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Wetter und Klima aus einer Hand

German Climate Observing Systems

Inventory report on the Global Climate Observing System (GCOS)

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The editorial team

Foreword

For their work, decision-makers in policy and business need robust climate information on which to rely their judgements. Profound knowledge of the state of the climate system in the past, today and in the future is the basis for any decisions to be made about measures for climate adaptation and climate protection.

To further develop the state of knowledge and understanding, robust data and information are equally important for research. The provision of such information requires long-term, scientifically sound collection and pooling of data.

Continuous long-term observation of all climate system components and the scientific processing of the data gathered are indispensable for identifying changes in the climate, deepening the understanding of the causes and being able to warn in good time of any extreme events or wide-ranging impacts.

▲ *Stefan Schnorr, State Secretary at the Federal Ministry for Digital and Transport (BMDV)*

Long, uninterrupted measurement series alone make it possible to identify any changes in the climate system and all related changes in the frequency and intensity of extreme weather events at an early stage.

I am very happy that this new edition of the Inventory Report on Climate Observing Systems provides an up-to-date summary of the ongoing measuring and observation programmes that are in place in Germany to monitor the climate and, through this, gives an overview of Germany’s contribution to the Global Climate Observing System (GCOS). The responsibility for monitoring the various components of the climate system is distributed between national/federal and regional/federal-state authority. I thank everyone involved for their valuable contributions.

Summary

◀ *View from the DWD weather station towards the summit of the Zugspitze*

The foundations for all observation of meteorological phenomena worldwide were laid in 1780 with the foundation of the Mannheim Societas Meteorologica Palatina.

This is why Germany has a very long tradition of climate observation, with the world›s oldest mountain station run on Mount Hoher Peissenberg and a continuous time series of near-surface temperature and air pressure observations since 1781. Systematic weather observations began in Germany in 1881, with recordings taken at 144 stations throughout the whole country. In 2022, the measuring network operated by the Deutscher Wetterdienst (DWD) included 1946 precipitation stations and 472 climate stations.

Accordingly, Germany has recourse to long time series of atmospheric and hydrological climate variables, the continuity of which is largely secured long into the future. The biggest problems for sustainable continuation of the observation series and in securing the availability of observation series exist for ocean observations and for some of the terrestrial observation programmes in Germany as well as internationally.

Even though not all relevant data are available at national level in a standardised form, the wealth of data gained by measurement allows for amply accurate statements on the climate in Germany and its development.

The challenges ahead are to further standardise measuring systems and to ensure the availability of Germany-wide data while fulfilling the Herculean task of digitising existing historical paper data.

A necessary prerequisite to efficiently and sustainably implement the German Action Plan for Adaptation under the German Adaptation Strategy of the Federal Government is to have an integrated view of all relevant climate variables. Here the German Climate Preparedness Portal (KLiVO) offers the possibility to bring all relevant institutions together.

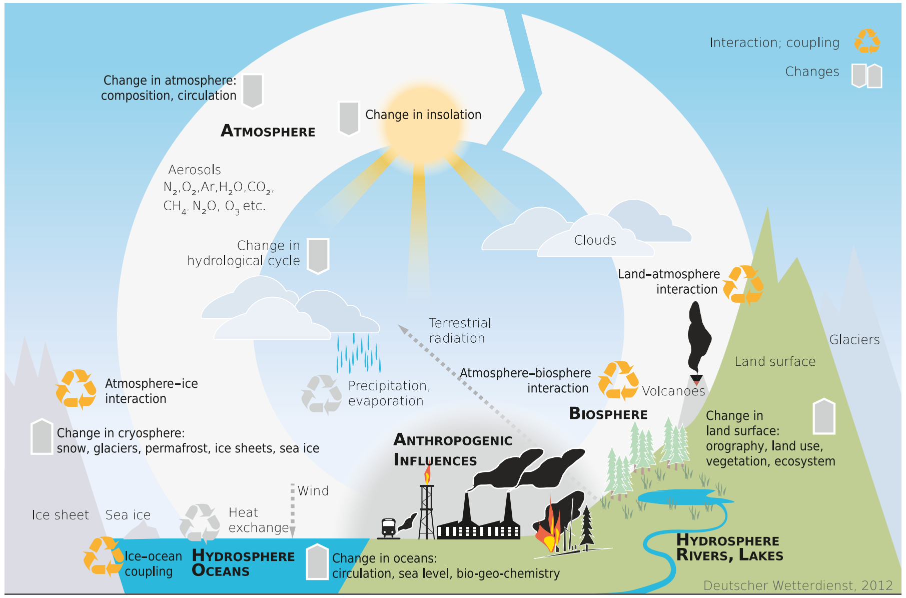
This Inventory Report on the German Climate Observing Systems is a revised and updated edition of the report published in 2013. It gives a detailed overview of climate-relevant variables of the atmosphere, ocean and land that are measured in Germany. It thus is an up-to-date, broad compendium of German climate observation addressing climate research and everyone in decision-making. The conclusions regarding the sustainability of the observation programmes aim to call the attention of decision-makers to the potential risks that might arise from a lack of long-term observation of the climate system.

Contents

1 Introduction

Introduction to the report

More than thirty years have passed since the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) at the Earth Summit in Rio de Janeiro in 1992. At first, the main focus of public attention was on climate protection. In recent years, however, the realisation has grown that adaptation to climate change has also become an inevitable fact. It has also become increasingly clear that climate-informed decisions require long-term, high-quality time series of the main climate parameters. These time series, however, often are incomplete. Considering all this, the Global Climate Observing System (GCOS) was established shortly after the Rio Earth Summit, tasked with the global co-ordination and documentation of such climate observations.



▲ *Figure 1-1: Components of the climate system and their physical, chemical and biological interactions (Source: DWD)*

Climate system and climate observations

»Climate« is generally understood as the average of weather conditions observed at a certain place over a sufficiently long period of time so that it can be described using statistical values. The internationally agreed period of time over which statistical values, such as means and averages (e.g. of near-surface temperature), frequencies (e.g. of exceedance or non-exceedance of thresholds) or extremes, are calculated is 30 years. As a rule, the longer the periods under examination, the more representative the statistical statements will be.

The climate in a certain place depends on a number of processes and developments. To understand the interrelationships that make up the climate system, the state of the atmosphere needs to be observed and described over long time periods, just as much as the state of both oceans and land surfaces as well as all related changes. The climate system consists of the atmosphere, oceans and land surface. With many changes regarding these components being influenced or, even more, triggered by human activity, socio-economic facts must also be taken into consideration. Figure 1-1 gives an overview of the physical, chemical and biological interactions in the climate system. ■ ■ ■

Observations – here to study the climate system – enable research to develop model-like visions of the interplay and its effects. Understanding this is the prerequisite to be able to reconstruct the observations by means of mathematical/physical models (i.e. climate models), validate visions and, on this basis and taking into account certain assumptions, come to produce reliable projections of future developments.

The six assessment reports (1990, 1995, 2001, 2007, 2014 and 2021) by the Intergovernmental Panel on Climate Change (IPCC) give evidence of how our knowledge of the climate system and climate modelling has developed over the last decades. Many of the new findings in understanding the climate system as well as the ensuing model improvements result from the availability and extensive analysis of observational data.

The IPCC's first assessment report had already pointed out the necessity of improving systematic observation of climate-relevant parameters at global level (IPCC 1990). The participants to the Second World Climate Conference (WCC-2) in 1992 called for the establishment of a global system for climate observations (WMO 1990). As a result, the Global Climate Observing System (GCOS) was jointly established in 1992 by the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO) and the International Science Council (ISC). Since then, various reports have been compiled within the scope of GCOS to analyse the state of global climate observing systems, elaborate plans how to overcome shortcomings in the observing systems and document the progress made in the implementation of these plans.

Requirements for climate observations

The basic requirements to be met by the GCOS programme were specified at the time of the system's foundation in 1992. A more sophisticated definition of these requirements was presented in a detailed report on the adequacy of global climate observing systems (WMO 2003b). This list of requirements includes:

1. **Characterising the state of the global climate system and its variability**
   In order to describe the climate system, a wide variety of atmospheric, oceanic and land variables need to be collected. To obtain exact estimations of temporal parameter variability and attribute the causes, the measurement series must be highly accurate, with good homogeneity and long-term continuity.
2. **Monitoring the forcing of the climate system, including both natural and anthropogenic contributions**
   In the past centuries and millenniums, climate variability resulted from variations in natural factors, such as solar radiation and volcanism. Today, anthropogenic causes add to these, including greenhouse gas emissions and air pollution as well as land-use changes.
3. **Supporting the attribution of the causes of climate change**
   Climate monitoring as described in Requirements 1 and 2 also helps to obtain a better understanding of the interactions between different elements and attribute the causes of changes. This is done by developing models which, based on the observational data and in model experiments, can be used to explore causes and relations of changes and enable the differentiation between anthropogenic and natural causes.
4. **Supporting the prediction of global climate change**
   Climate prediction requires to not only look at the development of the factors referred to in Requirement 2 but also at the initial state of the climate system. In addition, long data series of the main climate variables help to assess and further develop climate models.
5. **Projecting global climate change information down to regional and national scales**
   The effects of climate change and climate change adaptation require action particularly at national and regional level. This is why

▲ *Photo 1-1: Halo phenomenon over the DWD's measuring field on mount Fichtelberg*

Climate component	Subcomponent	Essential Climate Variables
Atmosphere	Surface	Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget
	Upper air	Temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget, lightning
	Composition	Carbon dioxide (CO_2), methane (CH_4), other long-lived greenhouse gases, ozone, aerosol, precursors for aerosol and ozone, *pollen*
Oceans	Physics	Sea surface and subsurface temperature and salinity, currents, surface currents, sea level, sea state, sea ice, ocean surface stress, ocean surface heat flux
	Biogeochemistry	Inorganic carbon, oxygen, nutrients, transient tracers, nitrous oxide (N_2O), ocean colour
	Biology/ecosystems	Plankton, marine habitat properties
Land surface	Hydrology	River discharge, groundwater, lakes, soil moisture
	Cryosphere	Snow, glaciers, ice sheets and ice shelves, permafrost
	Biosphere	Albedo, land cover, fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire, land surface temperature, *phenology*
	Human use of natural resources	Water use, greenhouse gas fluxes

▲ *Table 1-1: Essential Climate Variables (ECVs) according to the GCOS Implementation Plan, including the two variables Pollen and Phenology, additionally observed in Germany (Source: DWD, modified from WMO 2016)*

additional, more detailed information is needed at this level to complement the variables mentioned for Requirement 1 in order to develop regional climate models and better understand how the climate affects natural systems.

6. **Characterising extreme events for the assessment of impacts, risk and vulnerability**
   Climate observation data are meant to enable characterisation of extreme events, such as flooding, heat and storms, in order to run corresponding impact analyses and work out guidelines and adaptation strategies as well as action plans.

In order to satisfy these requirements, GCOS, in co-operation with the IPCC and the World Climate Research Programme (WCRP), has defined a number of Essential Climate Variables (ECVs, see Table 1-1).

Further to the scientific requirements, the selection has also taken into account the extent to which observation of these ECVs is possible to be implemented at global scale for the purposes of climate monitoring. As a result of new findings from research activities, advancing measurement technology and new user requirements, new variables can be included if needed.

Along with the global ECVs, which where first defined in 2003, other climate variables may need to be observed at a national level that are not part of the ECVs but have been recorded for a long time on a systematic basis and have been of significance for characterising the climate and its variability at local levels. In Germany, these include pollen and phenological parameters.

To make sure that long time series of national in-situ observations take account of large-scale changes only, if possible, and that these are comparable at international level, GCOS has laid down ten basic principles for monitoring the climate, known as the GCOS Climate Monitoring Principles (see Table 1-2; Karl et al. 1995, WMO 2003b).

Germany has a long tradition of climate observation. The foundations date back to Alexander von Humboldt (1769–1859) and to around 1780, when the Societas Meteorologica Palatina, also known as the Meteorological Society of Mannheim, came into existence. Since then, German institutions have contributed to systematic observation of the climate system at national and international level.

Systematic observation activities relevant to Germany currently comprise almost all ECVs (see Table 1-1).

The data are generally subject to strict quality checks and are, for the most part, transmitted to international data centres, some of which are operated by German institutions. From there, they are available to international research groups for integrated global studies, notably on climate change, and to operational institutions. German institutions thus help to improve international collaboration and standardisation of measurement data.

In order to co-ordinate national commitments to GCOS and support the organisation's international activities,

GCOS Climate Monitoring Principles

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e. metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.
6. Operation of historically-uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.
10. Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

▲ *Table 1-2: The ten Principles were considered at the 5th Conference of the Parties (COP 5) to the United Nations Framework Convention on Climate Change (UNFCCC 2000) and adopted by the 14th WMO Congress in May 2003. (Source: DWD, modified from Karl et al. 1995, UNFCCC 2000 and WMO 2003a)*

a national GCOS Secretariat for Germany was established at the Deutscher Wetterdienst (DWD) as early as in autumn 1992 immediately after establishment of the GCOS programme. Shortly after that, the brochure »GCOS – The German View« was published in 1993, giving a first overview of the German contributions to GCOS. The first German national inventory report for GCOS was submitted in 2013 entitled »German Climate Observing Systems. Inventory report on the Global Climate Observing System (GCOS)«. Since 1998, regular national GCOS meetings have taken place to enhance co-operation between all institutions in Germany that are responsible for making climate observations and to co-ordinate German contributions to GCOS.

The purpose of this report

The collection of climate data registered over many decades represents a veritable treasure trove of historical data, with great scientific significance for the responsible climate research institutions and bodies at national and international level. These data belong to our cultural assets which, if lost, can never be recovered again. Preserving and continuing long time series of observations is a continuous challenge for all those responsible for decision-making. Particularly at risk are those observation series the collection of which depends on temporally limited research funds.

Another, different kind of risk results from the fact that many data still only exist in paper form or on old data carriers and thus are not available for modern analysis. Without any counter measures, there is the risk of losing these historical data forever. In addition, the monitoring of climate-related parameters in Germany is distributed among multiple research institutions and authorities at federal and regional levels. Therefore, the purpose of this report is to provide an overall overview of the current situation and inform about the sustainability of these observations into the future.

Methodology of the report

Under the commitments of the UNFCCC, the Federal Government regularly draws up national inventory reports on the activities undertaken by Germany towards the implementation of the Convention. The reports all contain a chapter describing research and systematic observation measures in Germany. The Third Report of the Federal Government in accordance with the Framework Convention of the United Nations (Bundesregierung 2002) was Germany's first national communication to give a more detailed presentation of the German contribution to systematic climate observation. The latest (eighth) report was submitted in early 2023 (Bundesregierung 2023). The national communications only give a very broad overview of Germany's climate observation activities and follow a strict structure to enable comparison at the international level. With a view to providing the first ever comprehensive and descriptive survey of climate observation in Germany, it was agreed at the 6th national GCOS meeting held in March 2011 to publish a special brochure on climate observations in Germany. The inventory report of the Swiss government, entitled »National Climate Observing System. Global Climate Observing System – GCOS Switzerland« published in 2007 (Seiz and Foppa 2007) stood model for this. The Swiss report was last updated in 2018 (see www.gcos.ch).

Structure of the report

Based on the 2016 GCOS Implementation Plan (WMO 2016), the Essential Climate Variables that are relevant for Germany are described separately but are embraced in the same section if closely related. Chapters 2 to 4 deal with the atmospheric and oceanic variables and terrestrial observations. The description of each parameter, if possible, is complemented by information about the legal framework, climate signals, international context and scientific significance as well as the required resources. Chapter 5 presents the international data centres in Germany, Chapter 6 follows with descriptions of Germany's observation activities abroad or outside the German territory and territorial waters. Ocean observations that are carried out in international waters are included in the various articles of Chapter 3. Chapter 7 closes the report by summarising the major findings and conclusions; it also includes an outlook on the future of Germany's national climate observing system GCOS-DE.

Several lists at the end of the report provide an overview of the authors who have contributed to the report, the literature references, the picture credits and all the abbreviations used throughout the report. Where possible, figures were reworked and translated with a view to uniformity and accessibility.

Results of COP 27 in Sharm el-Sheikh

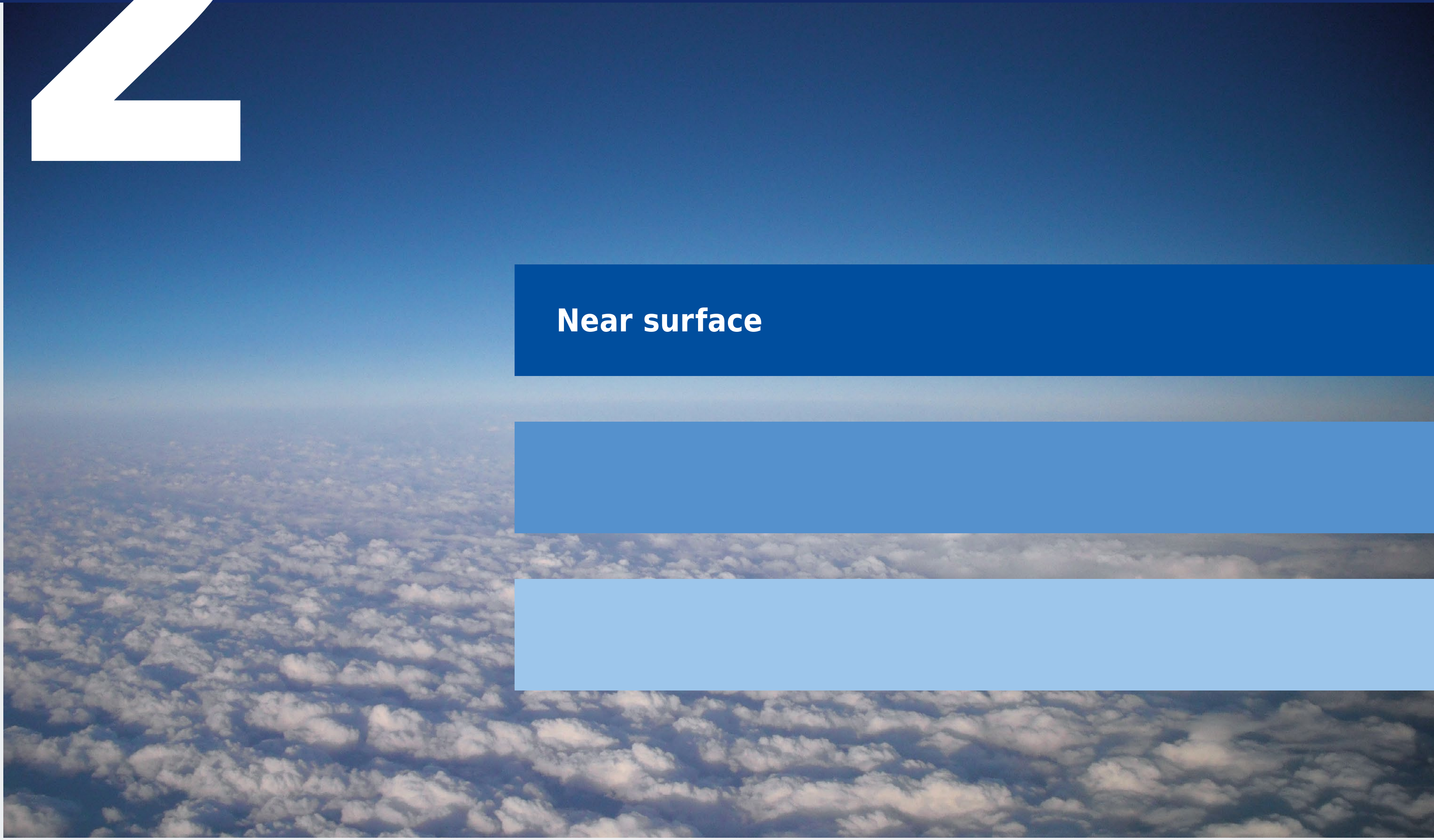
GCOS' regular reports on the state of climate observing systems as well as its implementation plans for overcoming shortcomings aim towards improving global climate observations, taking into account user needs.

A new version of the GCOS Implementation Plan (WMO 2022) was published in September 2022 after the editorial deadline for the Chapters 2 to 6 and then presented to the 27th Conference of the Parties to the Framework Convention on Climate Change (COP 27). This is why the newly adopted ECV Terrestrial Water Storage Anomaly could not yet be taken into account for this report.

One outcome of COP 27 is the decision of the Subsidiary Body of Scientific and Technological Advice (SBSTA) to encourage the Parties and relevant organisations to work towards the implementation of the 2022 GCOS Implementation Plan (UNFCCC 2022b). In their corresponding decision, among other things, the Parties to the UNFCCC emphasise the need to address gaps in observing systems (UNFCCC 2022a).

2 Atmospheric observations

2 Atmospheric observations

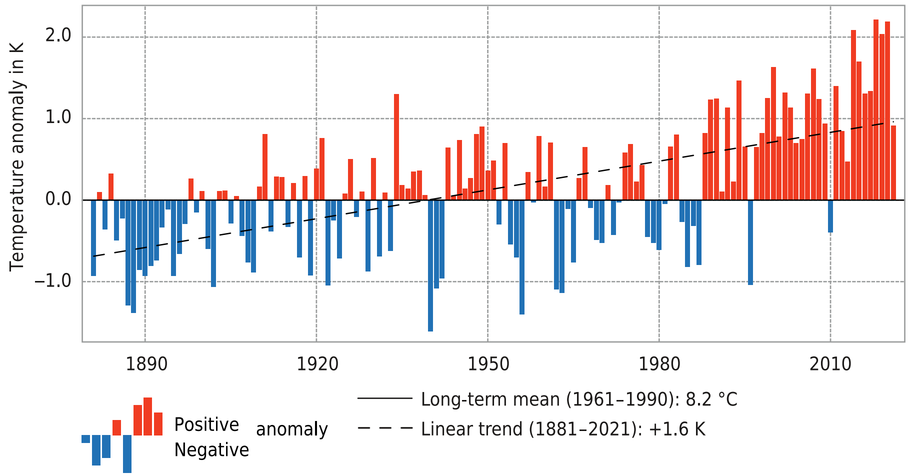


Near surface

2.1 Temperature and humidity

Temperature is one of the main indicators for describing the climate and its variability. Therefore, observing and analysing this parameter is of key importance at both the national and global level. The existing data series provide clear proof of progressing anthropogenic climate warming also in Germany.

Time series of mean annual temperatures in Germany (1881–2021)



▲ *Figure 2.1-1: The time series shows a clear temperature increase, with a largely linear development especially from 1970 onwards; this development is consistent with the global temperature increase. (Source: DWD)*

Climate signals

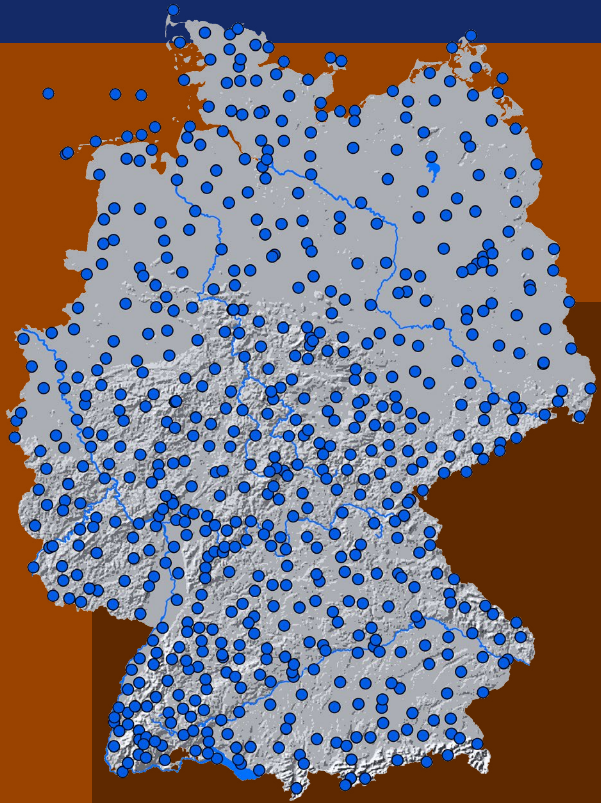
The time series of area averages derived from gridded fields allow meteorologists to discern climatological trends regardless of any lack of homogeneity that might exist in the records of single stations. They reveal a warming of about 1.6 K (linear trend) for the period 1881 to 2021. Especially in recent decades, there has been an increase in the trend, with the 2011 to 2020 decade, for instance, being as much as 2 °C warmer than the first 30 years of the evaluation period (1881–1910).

The temperature increase in Germany thus is consistent with the global trend, however with a stronger warming compared to the global average.

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems.

According to DWDG Section 6 and to the Ordinance Setting the Terms of Use for the Provision of Federal Spatial Data (GeoNutzV), the measurement series recorded at DWD stations are made available as open data.



▲ *Figure 2.1-2: DWD stations taking temperature measurements (Source: DWD)*

International context

The synoptic reports from 180 stations are disseminated worldwide on a routine basis. For a selected number of these stations, quality-checked monthly climatological information is made available in the form of CLIMAT reports. The stations at Frankfurt, Hamburg, Hohenpeissenberg and Lindenberg are part of the GCOS Surface Network (GSN).

Worldwide, there are several data centres that collect international temperature records and evaluate these independently of each other. The independent evaluations uniformly confirm the global temperature rise in recent decades. The evaluations enter into the reports of international organisations, especially into the annual status reports of the World Meteorological Organization (WMO) and assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

Required resources

Because of the legal mandate given to the DWD, the operation of the existing measuring stations can generally be considered as secured. In order to meet the requirements to save resources, the DWD has optimised and automated its measuring network. Selected climate reference stations secure the continuation of long time series and examine the comparability of the measurement technologies.

Ongoing digitisation activities (Kaspar et al. 2015) must be continued with a view to opening the historical data up for use and making additional long time series available.

Measurements in Germany

The Deutscher Wetterdienst (DWD) operates a network of weather and climate stations, of which about 500 currently measure temperature. Area-covering measurements date back to around 1951. All stations where temperature measurements are taken also measure humidity.

Alongside the DWD stations, additional measurements of temperature are carried out by other institutions and individual persons. However, only minor parts of these series are included in the DWD's database as they often do not meet the high standards regarding representativeness, measurement methods or continuity of operation.

Before 1950, the number of stations was considerably lower and often only monthly data exist, which have been digitised up to World War II. While many of the daily values have been lost, monthly values are available from a relatively dense network of more than 130 stations with data records back to 1881. This enables grid fields to be interpolated and spatial mean values to be computed (Kaspar et al. 2013). Before that time, only a few single data series exist, which often lack homogeneity due to differences in measurement methods and observation programmes. The longest of such station data series (Berlin) dates back to 1719.

A first uniform and well documented network was established in 1781 by the prince-elector of the Palatinate in the context of the Societas Meteorologica Palatina. Although this network collapsed after about ten years in the turmoil of the French Revolution and the following wars, a few single time series could be continued. One of these, for instance, is the uninterrupted time series of Hohenpeissenberg near Weilheim in the Alpine foothills, which was started in 1781 and has been homogenised to a large extent.

Between 1995 and 2005, in the context of the general automation of the networks, the measurement equipment widely changed from conventional mercury thermometers and bimetal recording instruments to digital electronic devices. Parallel measurements taken at the climate reference stations have revealed that this change has not led to any relevant inhomogeneity in the temperature time series (Kaspar et al. 2016).

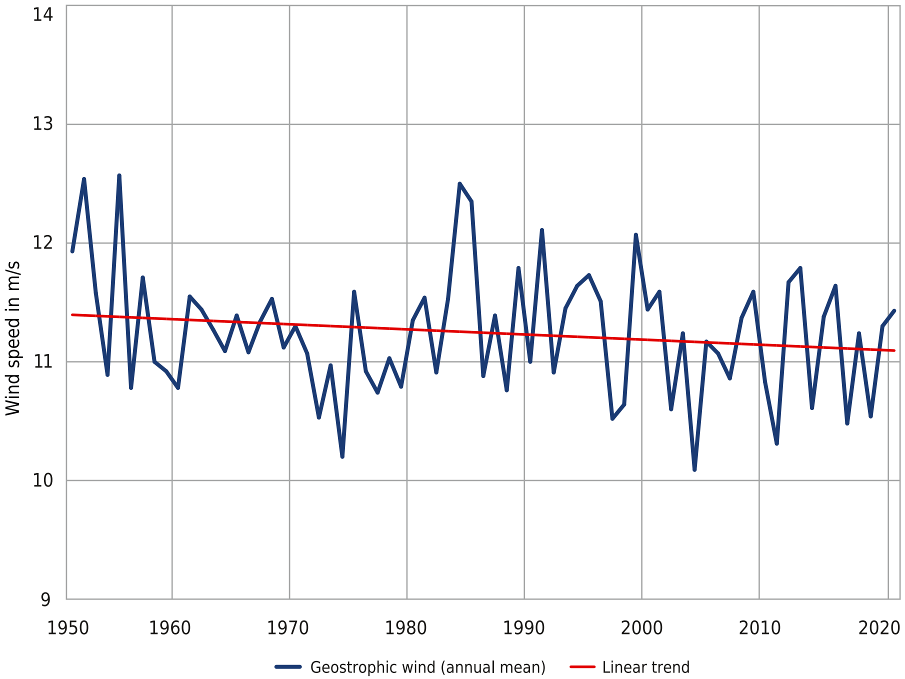
For such comparisons between the different generations of measurement technology, the DWD currently operates ten climate reference stations, all of which are situated in different climate regions in Germany and for which long series of measurements exist (Hannak and Brinckmann 2020). At these stations, conventional analogue readings were carried out in parallel to the automated digital measurements over a period of ten years.

dwd.de/zeitreihen **cdc.dwd.de/portal** **opendata.dwd.de/climate_environment/CDC**

2.2 Wind

Wind is an essential climate variable with high relevance for different areas of application. It is particularly important in the context of the use of renewable energies but also because of the potential for damage during extreme storm events.

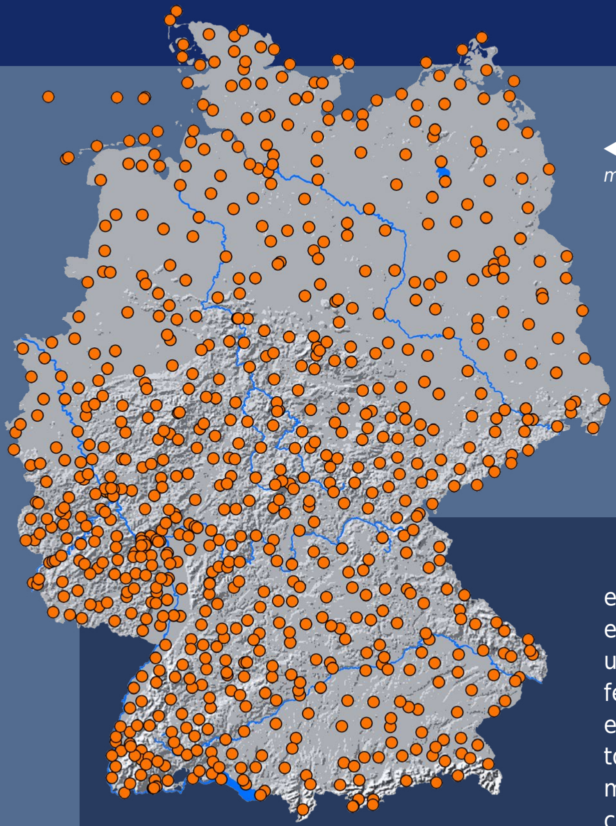
Mean annual geostrophic wind in the German Bight



▲ *Figure 2.2-1: Mean annual geostrophic wind, calculated from surface pressure data of Hamburg, Emden and List stations. The graphic shows the period from 1950 to 2020. The linear trend is shown as red line. (Source: DWD)*

Climate signals

There are no clear trends to be seen from the station time series for wind speed. Longer time series derived from air pressure measurements (geostrophic wind) equally show no significant trends. But it appears that Germany experiences a succession of weaker and stronger wind speed periods. For the area of the German Bight, there is evidence of a phase of low wind speed in the 1960s and 1970s while the 1980s and 1990s saw a slight increase in wind speed.



◀ *Figure 2.2-2: Map of DWD stations measuring wind (Source: DWD)*

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems.

According to DWDG Section 6 and to the Ordinance Setting the Terms of Use for the Provision of Federal Spatial Data (GeoNutzV), the measurement series recorded at DWD stations are made available as open data.

Measurements in Germany

The Deutscher Wetterdienst (DWD) operates a monitoring network of weather and climate stations, of which about 300 currently take wind speed and wind direction measurements at a height of typically around ten metres. This dense network has been in place for several decades. Going back to before that time, the coverage of wind measurements becomes gradually coarser. However, there are also wind estimates available from secondary stations. From before 1950, there exist only a few single measurement series. Some time series of wind estimates go back to the 19th century.

Due to differing measurement and evaluation methods and a strong influence of the surroundings and the measuring height, long time series often feature considerable lacks in homogeneity, which, however, can be corrected to some extent. Ongoing changes in the measurement technology, such as the change from cup anemometers to ultrasonic anemometers, are subject to studies carried out by the DWD at climate reference stations.

Measurements at greater heights and in offshore areas are of interest for applications targeting the wind energy sector in particular. Compared to near-surface wind measurements, considerably less data are available for the typical heights of modern wind turbines. Longer-term measurements at masts with heights of 100 m or higher exist from some single stations. The masts are run by different providers, among others at the Lindenberg Meteorological Observatory. Wind measurements are also conducted as a complement to standard recordings at the measuring masts operated at currently eight sites in Germany as part of the Integrated Carbon Observation System (ICOS). In the North and Baltic Seas, wind measurements are taken at the masts of the three research platforms (FINO1, -2, -3). Due to the limited availability of data at the application-relevant heights (> 100 m) and to the limited homogeneity of wind measurements, many applications use indirect, derived data sets that rely on model-based global or regional atmospheric reanalyses (Kaspar et al. 2020). The available wind measurements are used to assess the quality of the data sets, and the production of the data sets benefits from all observations used for data assimilation in the numerical weather models in use.

International context

The synoptic reports (including wind measurements) from 180 stations are distributed worldwide on a routine basis. For a selected number of these stations, quality-checked monthly climatological information is made available in the form of CLIMAT reports. The stations at Frankfurt, Hamburg, Hohenpeissenberg and Lindenberg are part of the GCOS Surface Network (GSN).

Required resources

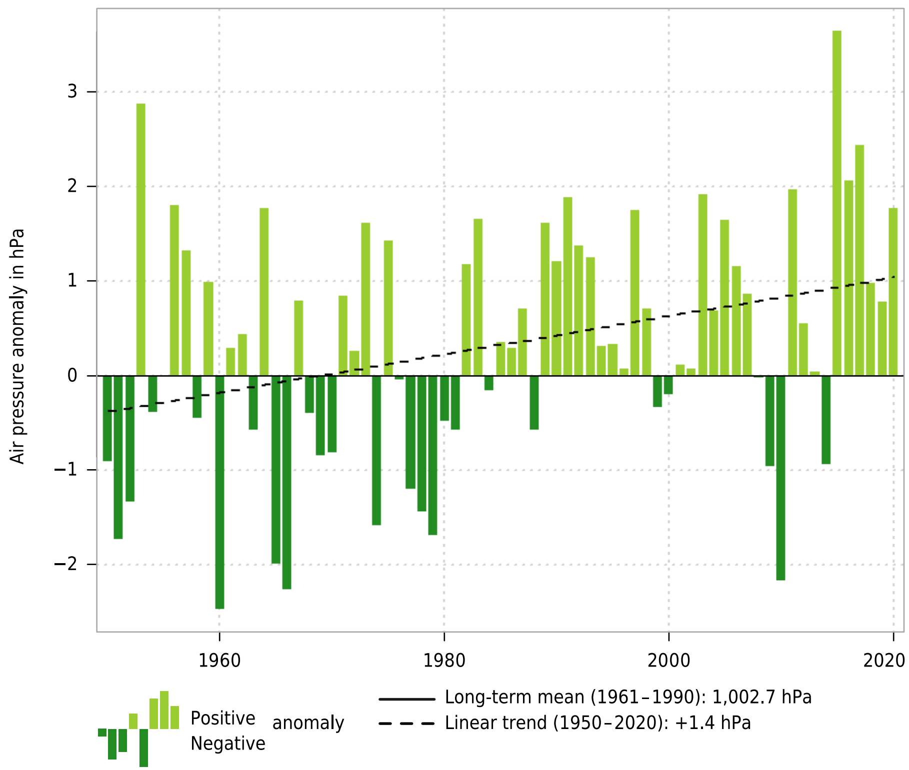
The operation of the existing measuring stations can generally be considered as secured.

opendata.dwd.de/climate_environment/CDC cdc.dwd.de/portal dwd.de

2.3 Air pressure

Air pressure is one of the main indicators for describing the climate as its spatial distribution determines the general circulation of the atmosphere. It is the variable which characterises the high and low pressure areas that influence the weather.

Mean annual anomaly in air pressure at Frankfurt am Main (1950–2020)

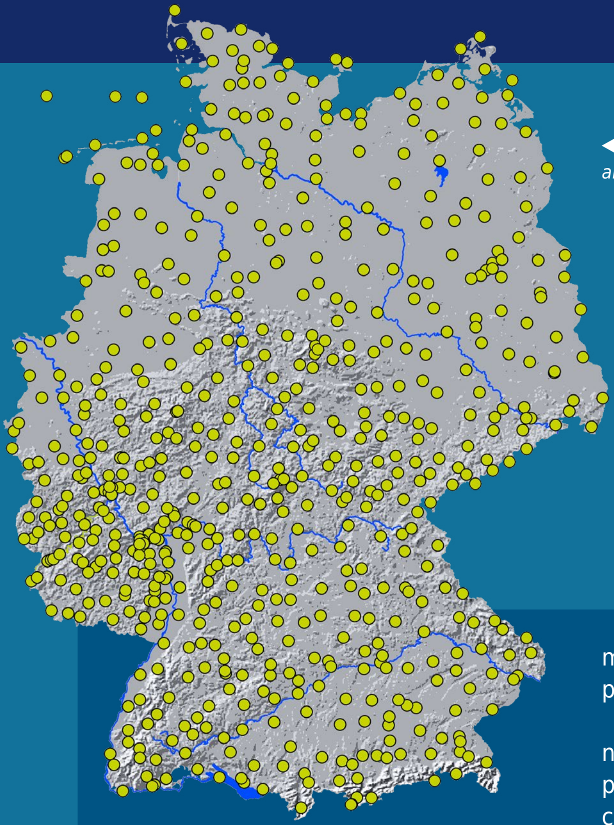


▲ *Figure 2.3-1: The graphic shows both the negative (dark green) and positive (light green) air pressure anomalies compared to the long-term mean for 1961–1990. (Source: DWD)*

Climate signals

Climate monitoring activities do not include the systematic, area-covering analysis of the trends in German air pressure data. During the past three decades, relatively high air pressure values have been recorded (for example at Frankfurt station, see Figure 2.3-1).

Air pressure changes are often manifested through changes in the frequency and intensity of large-scale weather patterns (known as »Großwetterlagen«). For example, periods of dry weather are usually associated with high pressure systems, rainy periods with low pressure activity. A trend in the climate variable air pressure can therefore justify changes in other climate variables, but it does not explain the causes.



◀ *Figure 2.3-2: Locations in Germany where air pressure is measured (Source: DWD)*

Measurements in Germany

As the spatial distribution of air pressure generally is quite homogeneous, the network of measurement stations requires here a lower density than for other climate variables. The Deutscher Wetterdienst (DWD) operates a network of weather and climate stations, of which currently around 180 take air pressure measurements. This network has existed for about 70 years.

Going back to before 1950, the station density was much coarser. From before about 1930, only a few single measurement series exist, which often lack homogeneity due to differences in measurement methods and observation programmes.

A first uniform and well documented network was established in 1781 by the prince-elector of the Palatinate in the context of the Societas Meteorologica Palatina. Although this network collapsed after about ten years in the turmoil of the French Revolution and the following wars, a few single time series could be continued. One of these, for instance, is the uninterrupted time series of Hohenpeissenberg near Weilheim in the Alpine foothills, which was started in 1781.

Between 1995 and 2005, in the context of the general automation of the networks, the measurement equipment widely changed from manually operated mercury or analogue aneroid barometers to digital recording devices. Fortunately, no significant inconsistencies in the time series were found.

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems.

International context

The synoptic reports from 180 stations are disseminated worldwide on a routine basis. For a selected number of these stations, monthly climatological information is made available in the form of CLIMAT reports. The stations at Frankfurt, Hamburg, Hohenpeissenberg and Lindenberg are part of the GCOS Surface Network (GSN). A collection of international air pressure observations is available from the International Surface Pressure Databank, of which updated versions are published at irregular intervals.

Required resources

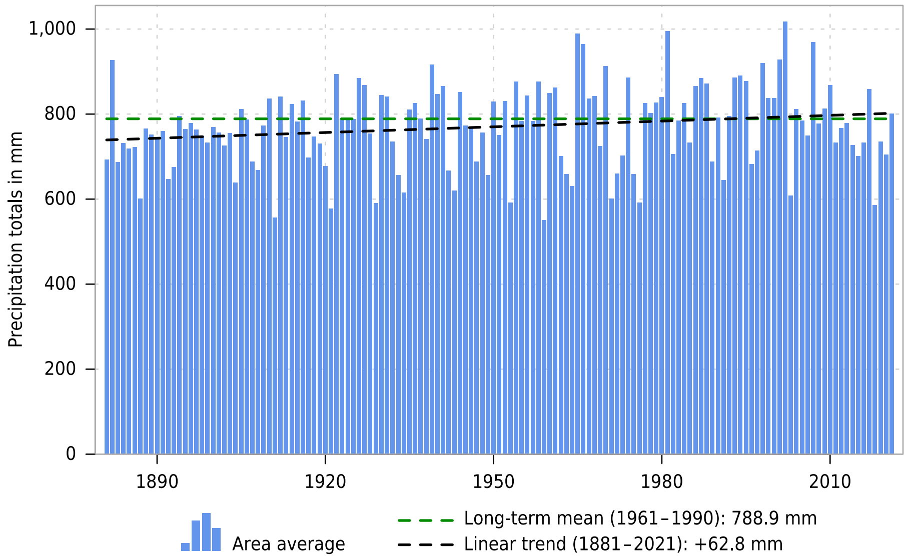
Because of the legal mandate given to the DWD, the operation of the existing measuring stations can generally be considered as secured. Persistent data digitisation activities are required in order to make further long-term data series available as a basis for scientific studies and for long-term model-based reanalysis.

opendata.dwd.de/climate_environment/CDC **cdc.dwd.de/portal**

2.4 Precipitation

Alongside temperature, precipitation is one of the key indicators for describing the climate and its variability. It is also an important parameter for both water cycle and water budget, with an accordingly high relevance for agriculture and water management. The Deutscher Wetterdienst (DWD), thanks to its climate data archive, can provide reliable analyses of the spatio-temporal behaviour of precipitation back to the year 1881 also in the context of anthropogenic climate change. For the most recent time, precipitation data collected by remote sensing add to the ever-growing number of in-situ measurements of high temporal resolution.

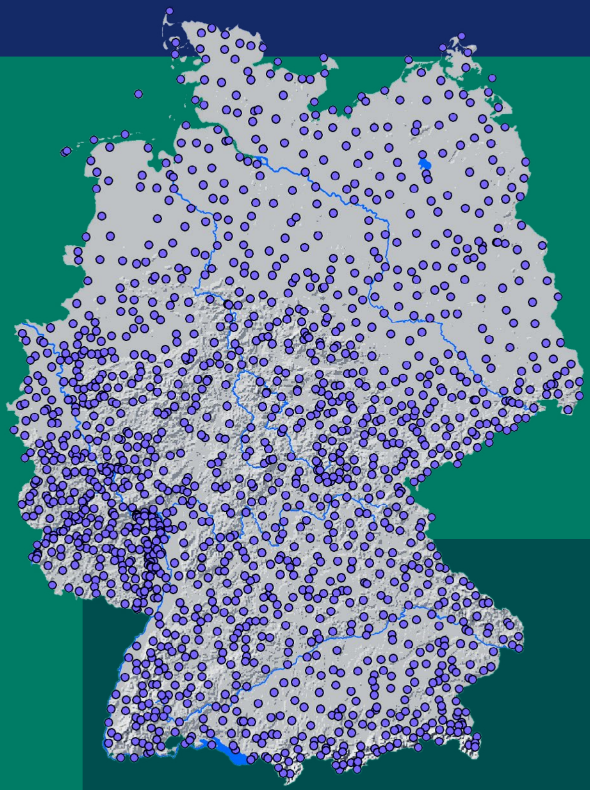
Average annual precipitation in Germany (1881–2021)



▲ *Figure 2.4-1: Average annual precipitation based on an ensemble of about 400 German precipitation stations (Source: DWD)*

Climate signals

The grid-based reanalysis of in-situ precipitation measurements allows discerning climatological trends since 1881 irrespective of any inconsistency that might exist in the time series of single stations (see Figure 2.4-1). The average annual precipitation in Germany shows an increase of close to 8 % over the last 140 years. The increase is more pronounced in the western and north-western, maritime influenced parts of Germany than in the eastern and southern, continental influenced parts. The increase is concentrated seasonally, with 26 % registered in winter and still positive values of 7 % and 5 % in spring and autumn. The figures for summer, however, show a decrease of 4 %. The trend has slowed down over the last decade due to repeated deficiencies in precipitation, especially in spring, but also in summer and autumn. In combination with the continuing rise in temperatures, there is an increasing tendency towards drought conditions in the warm season from April through to autumn. Evidence is accumulating for an earlier start and a later end to the season with convective precipitation. At the same time, there are more pronounced heavy rainfall events.



▲ *Figure 2.4-2: Active precipitation stations contained in the DWD archives (Source: DWD)*

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems.

International context

Besides other data centres, all data registered at the precipitation stations are forwarded to the Global Precipitation Climatology Centre (GPCC), which is hosted by the DWD (see Item 5.1). Moreover, precipitation is one of the Essential Climate Variables (ECVs) for which the DWD operates a Regional Climate Centre on Climate Monitoring (RCC-CM) for WMO Regional Association VI (RA VI Europe). The DWD is actively involved in international organisations, bodies and working groups (such as the WMO, the Copernicus services C3S, CAMS, CEMS, and GEO), which reflects its significant status in the fields of European and global climate monitoring.

Measurements in Germany

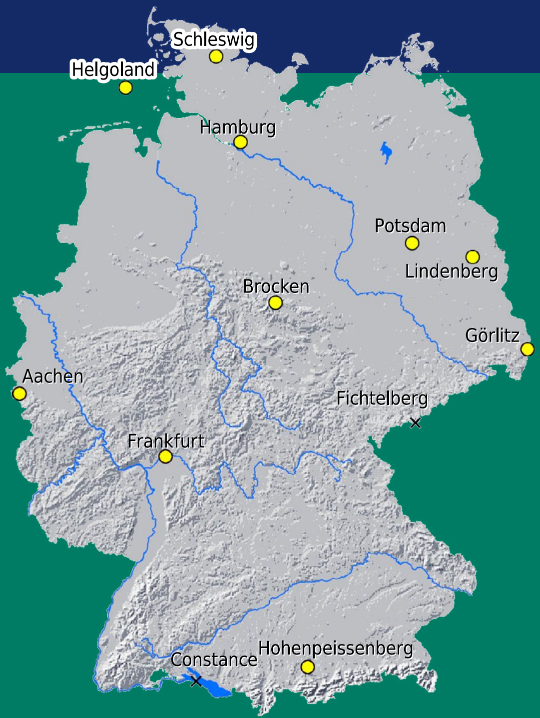
The DWD operates a network of around 2,000 weather and climate observation stations (see map above), where precipitation data are collected at least in the form of daily totals. Since around 1995, precipitation has been increasingly measured by digital systems allowing for improved temporal availability and resolution – even into the minute range (see purple area in Figure 2.4-4). More than 1,000 of the stations have already been changed to automatic measurement methods. Non-automated stations used to take (and often still continue to do so) only one measurement a day (at 7:00 a.m.). Before the year 2000, as many as three daily measurements (7:00, 14:00 and 21:00 LMT) were at least available from the climate stations (nearly 500 in number). Since that date, all climate stations have successively been automated. In addition to these, several hundred analogue rain gauges provide hourly precipitation totals.

This dense daily precipitation measurement network has been operated this way for approximately 70 years and comprised from 1951–2004 (1969–2000) more than 3,000 (4,000) stations (see Figure 2.4-2). Most of the stations, however, were manned, which made a high demand on human resources. If only monthly totals are required, the DWD has recourse to a network of more than 2,000 stations with data records going back the last 100 years; to find fewer than 1,000 stations, one has to return more than 130 years back to 1891. Extending the period for another ten years back to 1881, there is still a network of several hundred stations available, dense enough to interpolate reliable monthly gridded fields and derive area totals. Before that date, only a few single time series exist, which often lack homogeneity due to differences in measurement methods and observation programmes.

Alongside the DWD stations, additional precipitation measurements are carried out by other institutions or individuals. However, only minor parts of these time series are included in the DWD database, as they often do not meet the high standards of representativeness, measurement methods or continuity of operation nor does the DWD have access to the data or the authority to use them.

Required resources

The operation of the existing measuring stations can be considered as largely secured. However, the level of automation must be driven further. In this context, the personnel-intensive operations were gradually reduced and ultimately discontinued even at airports/aerodromes and climate reference stations. Precipitation monitoring in the era of climate change needs to work at high levels of availability and resolution and comprise Germany and its adjoining relevant river catchments. It requires at the same time the sustained operation of reference stations with essential (in other words long-term) measurement series. Persistent data digitisation activities are required in order to make further long-term data series available for scientific studies. Apart from this, two decades of precipitation data have so far been processed in the weather radar network of the DWD.



▲ *Figure 2.4-3: Locations of DWD climate reference stations. The network now comprises ten stations as Constance and Fichtelberg were given up in 2019. (Source: DWD)*

Significance of long data series

Systematic, station-based recording of precipitation in Germany and the operation of the corresponding station networks are closely connected to the institutions and bodies that operate them. The result is a heterogeneous picture in terms of space and time, given the fact that the first national meteorological service in Germany, the Reichswetterdienst, did not come into existence until 1934. Before then, and until the foundation of the DWD, precipitation observation was the responsibility of regional meteorological services or the meteorological services of the Länder, which was the reason for the existence of a multitude of regional networks. The longest uninterrupted precipitation time series exists for the weather station of Jena (Observatory) in Thuringia, with the first measurements taken in 1827.

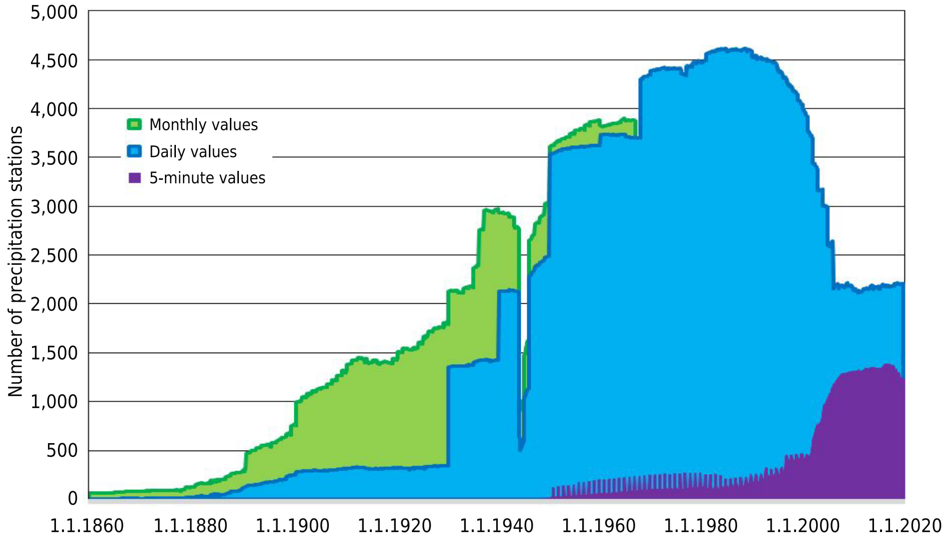
DWD climate reference stations

The progressing automation of weather observation calls for detailed investigation and quantification of the impact of this change to digital measurement techniques on the data series. At climate reference stations, manual observations by well-trained weather observers therefore continue to be carried out using conventional measuring and observation techniques in parallel to the digital measurements. The resulting comparative measurements over at least ten years prevent misinterpretation of the data series collected by the DWD with regard to climatological and climate change issues. With its climate reference stations system, the DWD has taken a pioneer role and is a renowned contact for many European meteorological services. The ultimate goal is to build a similar Europe-wide network of climate reference stations. The sites chosen by the DWD (see Figure 2.4–3) are characteristic of their geographic and climatic environment (Hannak and Brinckmann 2020).

Data rescue projects of the DWD

Since early 2005, the DWD has been running the KLIDADIGI project to digitise historical daily precipitation data that exist only on paper. The aim is to make these records available for climate monitoring and research, in particular with regard to climate change, and to rescue the data from ultimate disintegration and loss. The green area in Figure 2.4-4 illustrates the number of precipitation stations for which, in addition to monthly totals, there are also daily precipitation data available for digitisation. Digitisation of the paper documents from as many as 165,000 precipitation station-years plus 23,000 station-years from DWD climate stations would require a work force of around 790 person-years. Between now and 2025, the DWD plans to digitise, and thus rescue, about 25 % of these documents, with a major focus on the longest and most complete series.

Temporal coverage of precipitation data at monthly, daily and minute scale



▲ *Figure 2.4-4: Evolution of the availability of precipitation data from German stations from 1860 up to the end of 2019: monthly data (green), daily data (blue) and 5-minute values (purple) (Source: DWD)*

Within the framework of the analysis of short-duration heavy precipitation events, the DWD, since 2018 supported by the MUNSTAR project (investigation of methods for revising and updating heavy rainfall statistics in Germany), has scanned and digitally analysed the pluviograph records of around 250 stations and, on this basis, produced 5-minute values. The data series are of different lengths, mostly starting around the middle of the 20th century. However, the oldest strip charts found so far go back to 1903. To date, around 130 of the 250 station data series could thus be extended until 2020.

Further worldwide historical precipitation records from more than 2,200 overseas stations have been made available by the Hamburg-based Deutsche Seewarte (German Maritime Observatory). The majority of these data (mostly 12-hourly, taken twice per day) date from the periods 1830–1918 and 1930–1943. The stations are spread across all continents, mainly in the former German colonies and protectorates in Africa, China and the tropical Pacific (Bismarck Sea) and the southern Pacific. So far, 761 stations have been digitised, which makes up 34 % of the archive (June 2021).

New requirements due to anthropogenic climate change

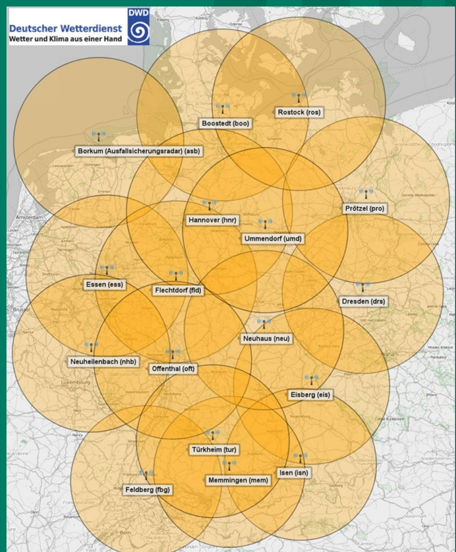
In the context of the discussions about anthropogenic global warming, the relevance and requirements of quality and spatio-temporal resolution for the monitoring of variability and trends in precipitation, regional particularities included, have further grown. For example, adaptation to changing hydrometeorological conditions constitutes one of the major challenges in enhancing the resilience of societies to the impact of climate change.

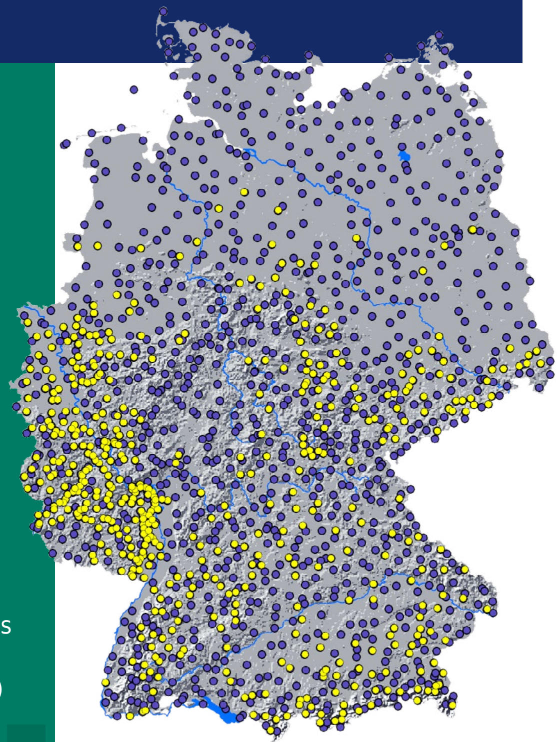
Due to their high accuracy and the length of time series, station-based precipitation data continue to be the backbone of precipitation monitoring. With station measurements, however, there is the problem of representativeness and homogeneity of the data. Moreover, even the national network of more than 4,000 stations that was operated in the years 1969–2000 was nowhere near dense enough to detect extreme, small-scale precipitation events. This problem of detection is worse in remote regions where inaccessibility leads to reduced density of stations. This is sufficient reason to use satellite- and radar-based precipitation measurements also for hydro-climatological applications, although at least the radar measurements had originally been introduced for real-time applications only. Meanwhile, both satellite and radar precipitation data have entered the era of multi-decadal and decadal coverage and exist at spatio-temporal resolutions in the hourly and kilometre scales, thus enabling high-resolution precipitation reanalysis for climatological purposes through averages, variances, extreme values and trends.

Radar-based quantitative precipitation monitoring

The DWD's RADOLAN system for real-time online adjustment of radar-based precipitation data by means of automated surface-based rain gauges supplies high-resolution quantitative precipitation data for the whole of Germany in real time. The real-time online adjustment takes place on the basis of precipitation data collected in the DWD's operational radar network of 17 C-band Doppler radar devices (see Figure 2.4-5) and the in-situ measurements from the network of automated gauges jointly

Figure 2.4-5: C-band radar network of the DWD (station radius: 150 km) (Source: DWD) ▼





▲ *Figure 2.4-6: Locations of automatic ombrometers of the DWD (violet dots) and those operated by partners (yellow dots) as of May 2021 (Source: DWD)*

operated by the DWD and the German federal states (see Figure 2.4-6). In standard mode, the »precipitation scan« provides precipitation data in 5-minute intervals, covering a radius of 150 km maximum around the radar site. The hourly in-situ precipitation totals of more than 1,000 automated DWD rain gauges and more than 500 auxiliary stations operated by the federal states are utilised for rain gauge adjustment of the radar data. The RADOLAN system has been in operation since 2005 and has since been enhanced several times. With the required input data being available since January 2001 already, the DWD performed a quantitative precipitation reanalysis at high spatial and temporal resolution for the entire period from 1 January 2001 until the present day. This has laid the foundation for a continuously updated, radar-based precipitation climatology and a catalogue of precipitation events in Germany since 2001.

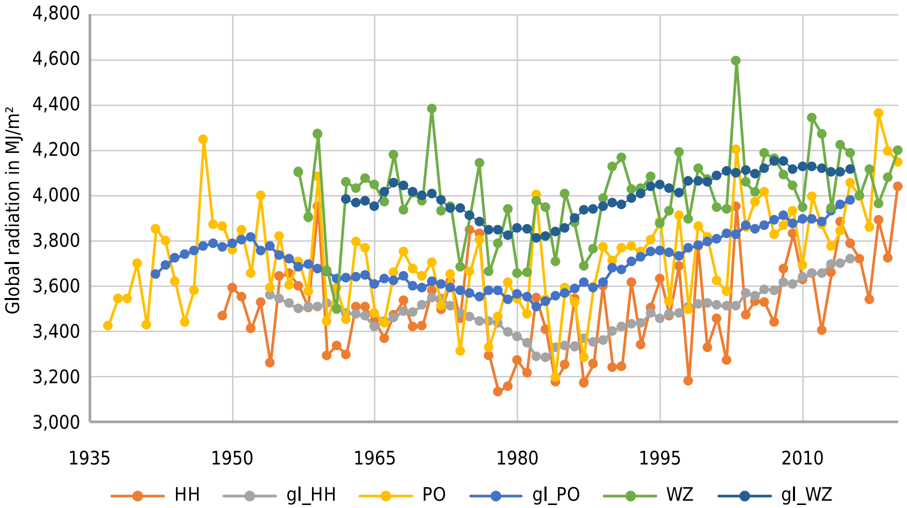
Measurements taken at sea

Although the code for the dissemination of meteorological data at sea includes precipitation as a parameter of observation, the fleet of voluntary observing ships, buoys and lightship substitution systems in the North and Baltic Seas does not register precipitation due to the lacking reliability of such measurements at sea. The continuous movement due to wind and waves distort the measurements, as does spray. Among the German research ships, POLARSTERN and METEOR are equipped with rain gauges, although their data records are also prone to error and too incomplete to be used for climatological assessment.

2.5 Radiation

The radiation balance at the Earth's surface is a key factor in the energy budget of the Earth–atmosphere system. Spatial and temporal differences in the radiation balance generate the weather and climate. Its most important and most commonly measured component is global radiation, which represents the amount of energy potentially received at the Earth's surface from the sun. The amount of available energy is modified by the solar radiation reflected back and by the long-wave radiation emitted from the Earth's surface and the atmosphere. Long-wave radiation is directly related to the greenhouse effect and thus constitutes an important variable for its monitoring.

Annual global radiation and 11-year moving averages

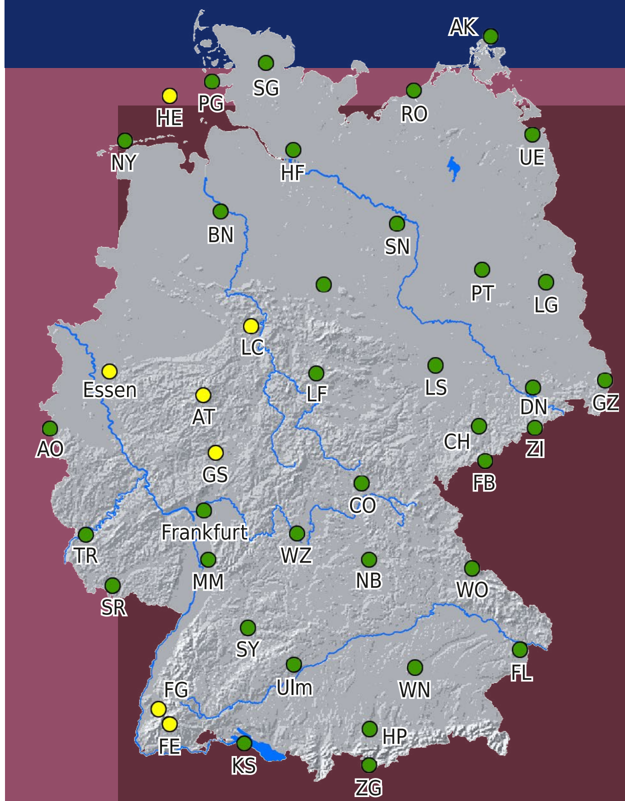


▲ *Figure 2.5-1: Annual global radiation and 11-year moving averages (gl) for Hamburg (HH: 1949–2020), Potsdam (PO: 1937–2020) and Würzburg (WZ: 1957–2020) (Source: DWD)*

Climate signals

Only continuous and accurate long-term observations of the radiative fluxes and ancillary atmospheric variables allow conclusions to be drawn about natural atmospheric variations and hence climate change. Measurement series of global radiation spanning 50 or more years are available from nine stations in Germany. Regional differences are clearly visible as well as a general decrease at all stations from the 1950s onwards. This phenomenon, resulting from the anthropogenic increase in atmospheric turbidity, has been observed in many regions of the world and is therefore referred to as »global dimming«. From the mid-1980s onwards, the aerosol load began to decrease again as a result of clean air measures, starting a recovery of global radiation known as »global brightening«, which still continues today. In fact, the highest values of global radiation have been recorded in recent years. However, the higher levels in global radiation can hardly be explained by a further decline in aerosol load as it has remained low for twenty years now. The reason rather is that there have been changes in the cloudiness. ■ ■ ■

◄ *Photo 2.5-1: Pyranometer for measuring global radiation at MOL-RAO*



▲ *Figure 2.5-2: Sites for radiation measurements in the DWD's surface observation network from 2024. The stations appearing in green are already in operation. (Source: DWD)*

Measurements in Germany

Continuous, comprehensive observations of global radiation are currently conducted using pyranometers at 35 stations of the DWD surface observation network. Apart from global radiation, the diffuse solar component is also measured at all stations using pyranometers in combination with a shadow ring. At 25 of the stations, further measurements are taken, carried out by means of pyrgeometers, in order to determine downwelling long-wave radiation. The data are stored in the database as »one-minute means«. They are subjected to an automatic and visual data check and are made available to the public free of charge via the DWD Climate Data Center.

Long-term series of radiation from the lower atmosphere, reflected short-wave radiation and long-wave radiation emitted from the Earth's surface are currently only available from the Lindenberg Meteorological Observatory – Richard Assmann Observatory (MOL-RAO). The observations are carried out round-the-clock on a continuous basis.

The earliest quasi-continuous measurements of global radiation were initiated in 1937 at the former Potsdam Meteorological Observatory. Subsequently, a radiation network comprising ten stations across Germany was established, which was further expanded over the years. In the framework of the Baseline Surface Radiation Network (BSRN), the MOL-RAO has also been collecting data on incoming short- and long-wave radiation parameters at high temporal resolution and low measurement uncertainty (≤ 2 %) since October 1994. The BSRN measurements are complemented by comprehensive spectral and spectroscopic measurements in the UV and visible wavelength range for the observation of atmospheric aerosols and gases. Furthermore, the MOL-RAO takes regular measurements of the vertical profiles of incoming and outgoing short- and long-wave radiation up into the stratosphere by means of a special radiosonde system. These measurements are unique in the world.

The global comparability of German radiation data is ensured by calibration of the radiometers at the National Radiation Centre at the MOL-RAO.

The spatial coverage of all components of the radiation balance and of many cloud parameters has long been improved as a result of the intensive use and processing of satellite data made available by the Satellite Application Facility on Climate Monitoring (CM SAF). In the new road map for radiation observations in the DWD surface observation network, which is currently being implemented, the use of satellite data takes an important role. For instance, they will be the basis for determining the spatial distribution of global radiation. The 42 surface stations, which all measure short- and long-wave radiation fluxes using very good, high-quality sensors, serve as ground truth stations for the validation of satellite data and their consolidation with surface observations.

Further long-term and high-precision measurements of radiation are conducted by various universities and institutions, such as the Jülich Observatory for Cloud Evolution, the Leibniz Institute for Tropospheric Research (TROPOS) and the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). The network for monitoring ultraviolet radiation is co-ordinated and supervised by the Federal Office for Radiation Protection (BfS).

▲ *Photo 2.5-2: Precision measurement devices for incoming radiation at Lindenberg BSRN station*

■ ■ ■

Monitoring these developments will be of crucial importance in the coming years as climate models may underestimate cloudiness and its possible changes.

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems. In this context, it is worth noting that complex climatological analysis is particularly reliant on long time series of relevant meteorological parameters measured at the climate reference stations.

International context

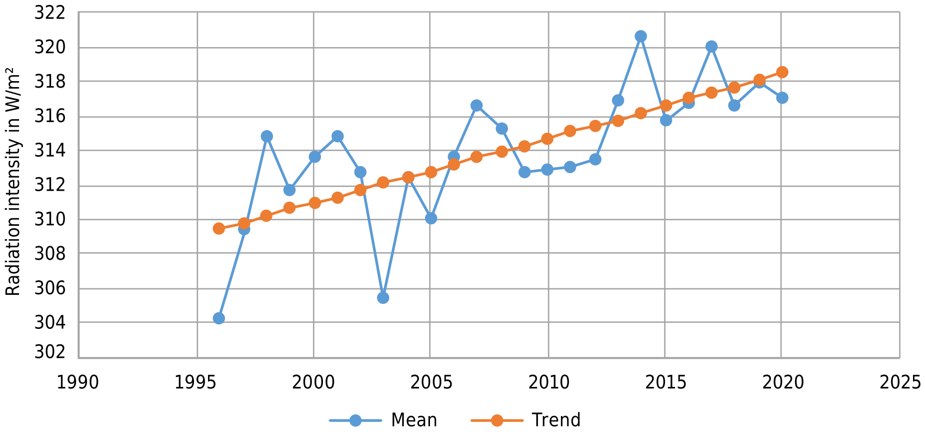
An important impetus for global co-operation in the radiation sector was provided by the International Geophysical Year (IGY) 1957–1958. Since 1964, radiation data obtained by the DWD network have been regularly delivered to the World Radiation Data Centre (WRDC) set up by the World Meteorological Organization (WMO) at the Main Geophysical Observatory in St. Petersburg.

Through the DWD station at Lindenberg and the Ny-Ålesund and Neumayer stations operated by the AWI, Germany makes an important contribution to the BSRN, which was established in the framework of the World Climate Research Programme (WCRP) and is now the reference radiation network for GCOS. The data obtained are also forwarded to the World Radiation Monitoring Center (WRMC) hosted by the AWI in Bremen (see 5.3).

The sets of high-quality radiation data derived from satellite measurements in the framework of the CM SAF are also highly significant for further research into climate change and the verification of observed changes, particularly because of the comprehensive coverage and growing availability of different radiation and cloud products.

Photo 2.5-3: Bird's eye view of the MOL-RAO site with the Regional Radiation Centre for WMO Region VI and the BSRN station in the foreground ▼

Annual means of incoming long-wave radiation (1996–2020)



▲ *Figure 2.5-3: Annual means of incoming long-wave back radiation (blue) with linear trend (orange) at Lindenberg BSRN station. Since measurements began, long-wave radiation has increased by nearly 10 W/m² due to the rise in temperature, humidity levels and greenhouse gas concentrations. (Source: DWD)*

Required resources

Both surface-based and satellite-derived radiation data are of vital importance for quantifying even the smallest changes in the radiation fluxes and for drawing conclusions about the causes of climate change for informed political decision-making. The prerequisite for this are accurate observations with low measurements uncertainties, which allow detection of mostly small natural variabilities.

This calls imperatively for continued operation of ground-based reference stations that already hold long time series of complex data sets, including radiation measurements. In future, their tasks should be extended to include the collection of spectral radiation data.

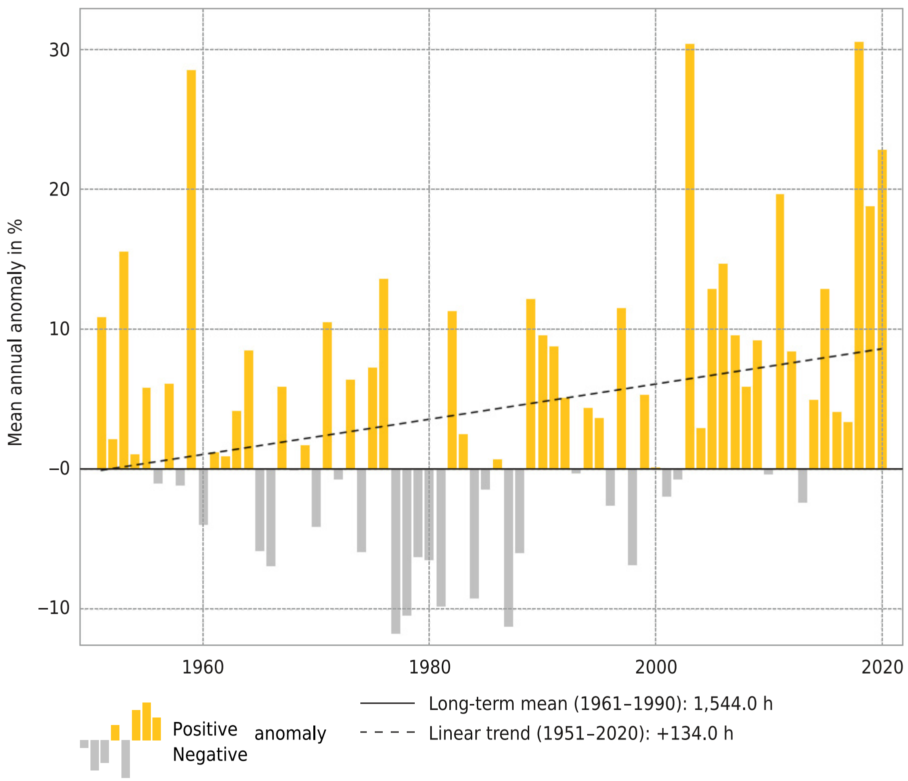
In addition, it is important to redress the current shortfall in professional capacity for analysis of satellite data and surface observations as well as combined data sets. Part of this problem is the inadequate basic funding for universities, which undermines their capacity for sustainable research.

dwd.de

2.6 Sunshine duration

Sunshine duration is a main indicator for climate monitoring. It has been used for this purpose for many years and is of great importance for many application areas. In particular, sunshine duration is also an approximate indicator of radiation, which in turn plays an important role in the context of the use of renewable energies. However, only few direct measurement series exist that cover several decades. Meanwhile, satellite data provide another alternative for obtaining radiation and sunshine data by derivation.

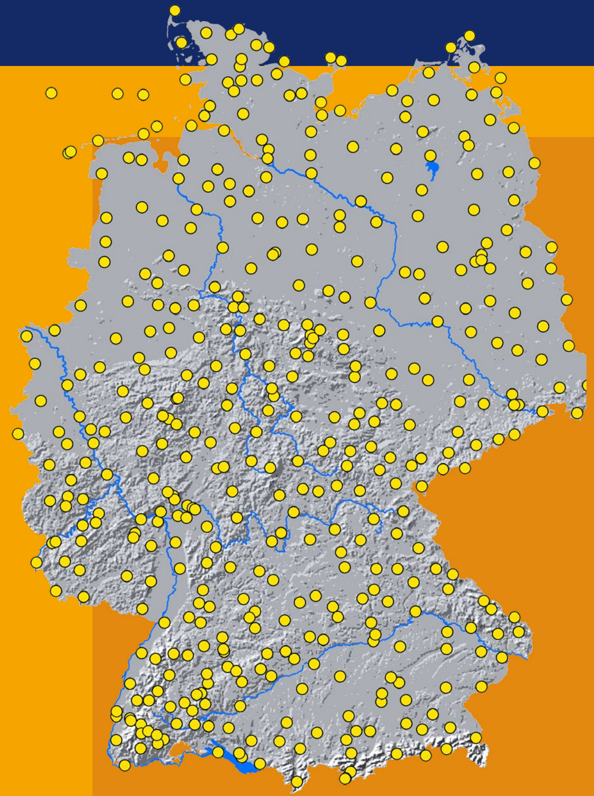
Annual mean sunshine duration in Germany (1951–2020)



▲ *Figure 2.6-1: Annual mean sunshine duration in Germany for the period 1951–2020 (Source: DWD)*

Climate signals

The measurements from the dense network of measuring stations were interpolated on a regular grid, allowing for the computation of area average series from 1951 onward. Based on these time series, it is possible to identify climatological trends, and this largely irrespective of any inhomogeneity that might exist in the time series of single stations. The results show considerable annual fluctuations and an increase in the annual sunshine duration of 134 hours over the period from 1951 to 2020 (linear trend).



▲ *Figure 2.6-2: Stations at which the DWD determines sunshine duration (Source: DWD)*

Measurements in Germany

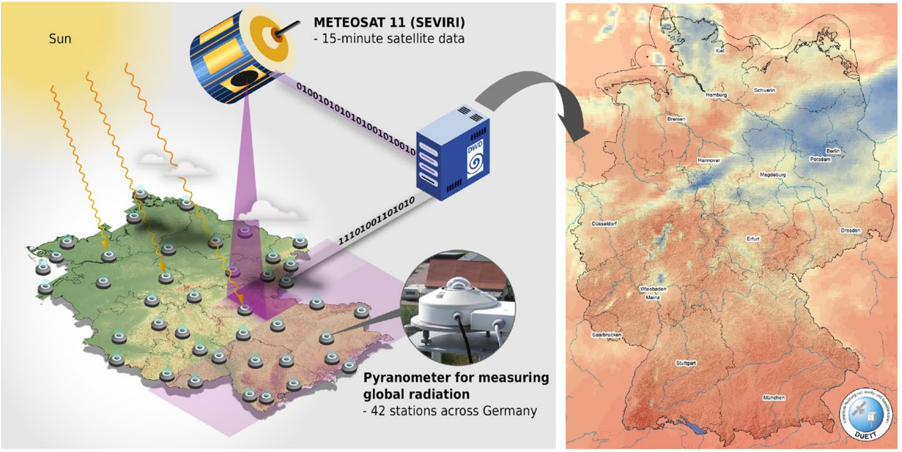
The Deutscher Wetterdienst (DWD) operates a network of weather and climate stations, of which currently around 270 register sunshine duration. Area-covering measurements date back to around 1951.

Before that time, only a few single data series exist, which often lack homogeneity due to differences in measurement methods and observation programmes.

Between 1995 and 2005, in the context of the general automation of the networks, most of the stations were changed from Campbell-Stokes instruments based on the magnifying glass effect to automatic measurement equipment (SONIe or SCAPP). Before this change, hourly data were available only after putting much effort into visual analysis and with much delay and partly also a high degree of uncertainty due to the subjective nature of the analysis. The new automated measurement technology now supplies digital data in near real time and at a high temporal resolution. The comparability of the measurements has been examined by means of parallel measurements at climate reference stations. Due to the differing measurement and evaluation methods, some considerable lacks in homogeneity were found in the data series (Hannak et al. 2019).

Meanwhile, the DWD has started switching its network to measuring radiation data. The intention is to obtain sunshine duration data by derivation from the radiation measurements. This type of radiation measurement offers a high level of quality but is planned to be carried out at only a reduced number of stations. In parallel, work is ongoing to develop procedures for combining station data and satellite-based measurements and deriving area-covering sunshine data.

DUETT – Combination of in-situ and satellite-based measurement data



▲ *Figure 2.6-3: Schematic representation of the combination of in-situ measurements with satellite-based data under the DWD project DUETT (Source: DWD)*

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems. According to DWDG Section 6 and to the Ordinance Setting the Terms of Use for the Provision of Federal Spatial Data (GeoNutzV), the sunshine series recorded at DWD stations are made available as open data.

International context

The synoptic reports (including sunshine data) from 180 stations are distributed worldwide on a routine basis. For a selected number of these stations, monthly climatological information is made available in the form of CLIMAT reports. The stations at Frankfurt, Hamburg, Hohenpeissenberg and Lindenberg are part of the GCOS Surface Network (GSN).

Required resources

The operation of the measuring network of the DWD can generally be considered as secured.

dwd.de/zeitreihen **cdc.dwd.de/portal** **opendata.dwd.de/climate_environment/CDC**

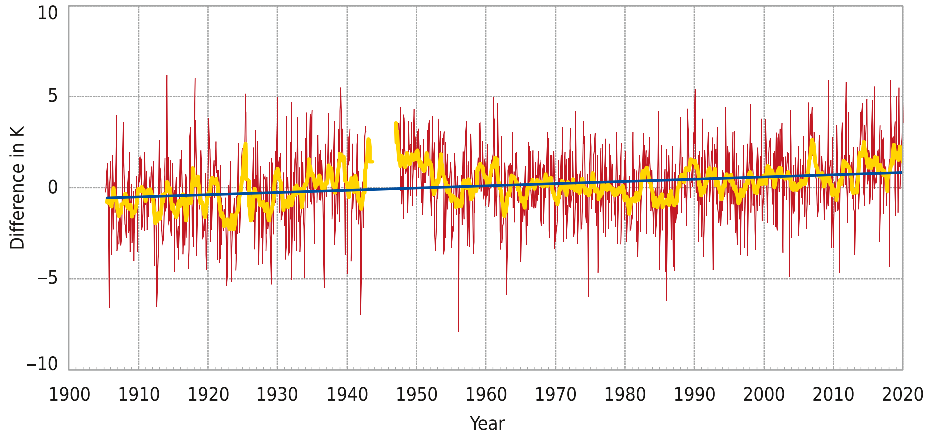
2 Atmospheric observations

Free atmosphere

2.7 Temperature, wind and water vapour in the atmosphere

The layer of the atmosphere relevant for weather and climate extends to an altitude of over 30 km. Throughout this range, temperature, wind, water vapour and pressure vary greatly and may be subject to abrupt changes over the time. Vertically resolved measurements of these parameters over this altitude range are essential not only for short-term weather forecasting but also for observing the long-term development of the climate.

Air temperature difference at 850 hPa relative to the long-term mean (1961–1990)



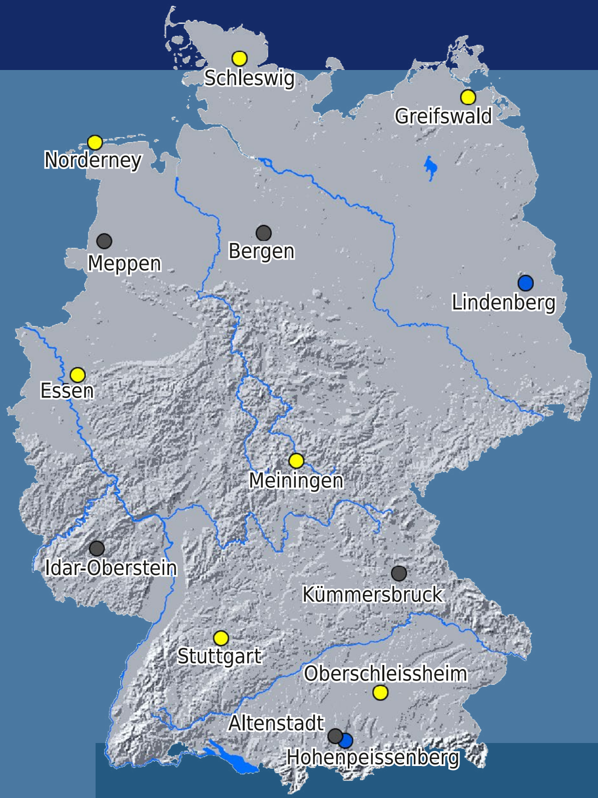
▲ *Figure 2.7-1: Time series of the air temperature difference at 850 hPa relative to the long-term mean for 1961–1990 (red: monthly values, yellow: 12-month running mean, blue: linear trend) (Source: DWD)*

Climate signals

Temperature trends in the troposphere and in particular in the stratosphere are of great importance for the long-term understanding of atmospheric processes. Figure 2.7-1 shows the time series for temperature at 850 hPa (including the data from kite ascents at the beginning of the 20th century) recorded at the DWD’s meteorological observatory in Lindenberg. Data for the lower stratosphere (at 100 hPa) rely on balloon soundings only and reveal a significant cooling of 0.5 K per decade (not shown in the graphic) as opposed to the clearly increasing trend in the troposphere, where the mean temperature trend shows a warming of roughly 0.1 K per decade. The yellow curve depicts the 12-month running mean temperature difference.

Historical trends in tropospheric water vapour are impacted by large uncertainties and only limited statements about temporal variations can be derived. Better estimates of changes in tropospheric water vapour are expected from the implementation of GUAN and in particular of GRUAN as well as from ongoing improvements in measurement technology. Long-term trends in stratospheric water vapour over several decades have been measured at only one station in the world. Special measurements, which began at several GRUAN stations more than ten years ago, form another anchor for estimations of trends in stratospheric water vapour.

◀ *Photo 2.7-1: Preparations for a radiosonde launch at the MOL-RAO*



▲ *Figure 2.7-2: Radiosonde-based measurements are carried out at the DWD's meteorological observatories (blue), the DWD's radiosonde stations (yellow) and several stations of the Bundeswehr Geoinformation Service (dark grey) (Source: DWD).*

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems. Within this context DWD supports numerous measurement programmes for long-term climate observations, defines climate reference stations and assures the continuity of long-term data series.

International context

The scientific investigations of temperature and water vapour at MOL-RAO are conducted in close co-operation with the international scientific community. The DWD's observatory plays a leading role in observation techniques, both internationally and in projects conducted in co-operation with other GRUAN and GUAN stations. Data are shared through a number of different data centres and are processed and analysed in close scientific partnerships. These observations are the basis of recommendations to decision-makers in policy and administration at national and international level.

Measurements in Germany

Vertical profiles of temperature, wind and water vapour are measured using radiosondes at 14 stations in Germany. Nine of these stations are operational radiosonde sites managed by the DWD alone; the other five are run in co-operation with the Bundeswehr. The standard observational programme of DWD requires two radiosonde launches per day. Only at the DWD's Lindenberg Meteorological Observatory – Richard Assmann Observatory (MOL-RAO), four radiosondes are launched each day operationally. Other sites may increase their sounding frequency to four soundings per day if needed during special weather conditions.

The MOL-RAO is the only station in Germany belonging to the GCOS Upper-Air Network (GUAN). It is also the Lead Centre for the GCOS Reference Upper-Air Network (GRUAN) and the only GRUAN site in Germany. Measurements in these networks strive for best possible homogeneity and continuity. As part of GRUAN, traceability to international standards and a vertically resolved quantification of the uncertainty of measurements are of great importance.

Changes in stratospheric water vapour have large impacts on the surface climate. Regular measurements within the altitude range from 10 km to 25 km take place only at MOL-RAO.

In addition, the MOL-RAO also measures vertical profiles of water vapour using a LIDAR, which under favourable meteorological conditions may provide data on the variability of water vapour at different altitudes with high temporal resolution.

Vertically resolved observations of temperature at Lindenberg started as early as 1905; however, only within the last twenty years have measurements of atmospheric humidity reached a level of quality sufficient for studying long-term trends in water vapour.

Required resources

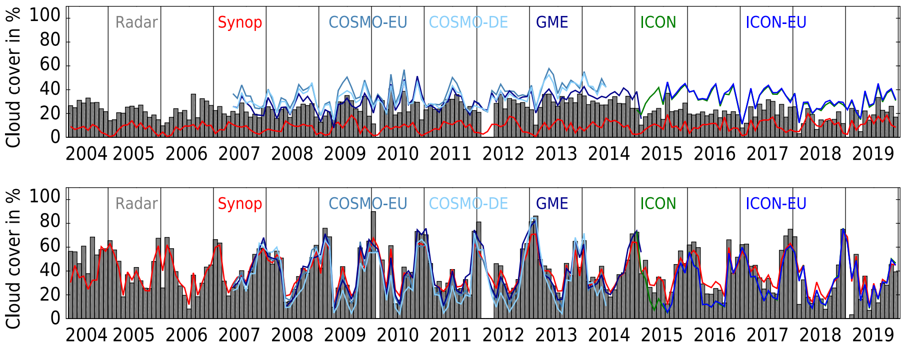
Long-term climate observations are currently threatened by austerity measures. The value of climate time series is strongly susceptible to interruption for which reason financial continuity of the observation programmes is required. Reduced funding particularly impacts observations of the free atmosphere through in-situ soundings, which so far are the only technology for climate reference data. These observations must be continued without interruption and with sufficient overlap when system changes occur, requiring continuous resource allocations.

dwd.de gruan.org

2.8 Clouds

Clouds are essential for the energy and water balance of the atmosphere and therefore have a significant impact on weather and climate. Classical visual observations of clouds have been carried out at many locations for more than 100 years in some cases. However, neither did they allow for the detection of small-scale spatial structures nor was it possible to infer the microphysical properties of clouds. For this reason, satellite-based measurements as well as ground-based remote sensing systems have gained increasing importance in the field of cloud observation and have now replaced visual observations almost completely.

Mean monthly high and low cloud cover



▲ *Figure 2.8-1: Data series derived from the measurements made with the 35 GHz radar at Lindenberg compared to the visual observations (synop) and simulations of the DWD's weather forecasting models COSMO-EU, COSMO-DE, GME, ICON and ICON-EU for high cloud cover (cloud base > 6 km) (upper diagram) and low cloud cover (< 2 km) (lower diagram) (Source: DWD)*

Climate signals

Only continuous monitoring over extended periods of time allows conclusions on climate change. Since these changes can be very small, the homogenisation of time series is very important, whereby changes in the methods of observation and measurement instruments must be considered.

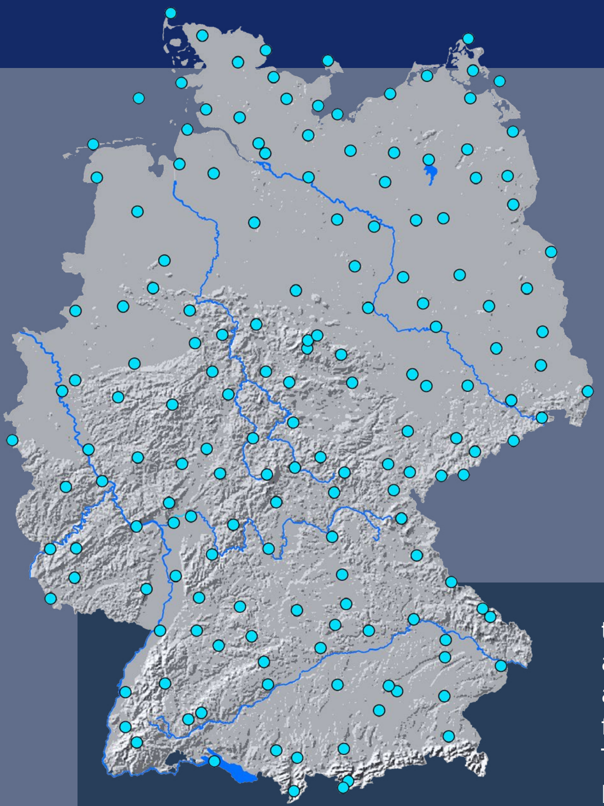
Consistent data sets can be obtained by running long-term comparisons between visual observations of cloud parameters and the parameter data derived from ceilometer measurements. Homogenisation of the data products that are derived from satellite-based measurements takes place by their reprocessing at the Satellite Application Facility on Climate Monitoring (CM SAF) of EUMETSAT.

Legal framework

Section 4 of the Deutscher Wetterdienst Act (DWDG) gives the German Meteorological Service (Deutscher Wetterdienst, DWD) responsibility for ensuring

- the short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere
- the operation of the measuring and observation systems necessary for the performance of the above listed duties
- the availability, archiving, documentation and release of meteorological and climatological spatial data and services.

To perform its duties, the DWD shall undertake scientific research in the fields of meteorology, climatology and related sciences and participate in the development of corresponding standards.



▲ *Figure 2.8-2: Network of DWD stations installed with ceilometers for cloud observation (Source: DWD)*

Measurements in Germany

For many decades, visual observations have been the only operational method for determining cloud parameters such as cloud type, cloud cover and cloud base. The time series go back to the 1940s, at some stations even to the 19th and 18th centuries. By mid-2022, visual observations were abandoned at all synoptic stations of the DWD and replaced by ground- and satellite-based remote sensing systems and procedures. Cloud base data, for instance, come from laser ceilometers deployed at the surface stations, just like cloud coverage data, which are obtained by means of temporal averaging. Widespread observation of clouds from space began about 60 years ago. The measurements from the various passive instruments on geostationary and polar-orbiting satellites (e.g. Meteosat, Metop, NOAA) are further exploited and reprocessed at EUMETSAT's CM SAF (which is co-ordinated by Germany) in order to derive essential climate variables, such as cloud parameters, land surface albedo and temperature, radiation fluxes as well as precipitation. Important cloud parameters determined operationally since 2004 are: cloud cover, cloud type, cloud optical depth, effective particle radius, cloud phase, cloud top pressure, cloud top height, cloud top temperature and vertically integrated cloud water content.

Continuous quality control is achieved by means of validation of the data against both ground-based in-situ measurements as well as indirect measurements. Since 2004, measurements of the fine structure of clouds have been carried out using a 35 GHz radar at the DWD's Lindenberg Meteorological Observatory – Richard Assmann Observatory (MOL-RAO). Due to the low attenuation of electromagnetic signals at this wavelength in both cloud-free and cloudy atmospheric conditions, the radar – in contrast to optical instruments – is able to scan multi-layered clouds through their full vertical extent; it can also identify structures (particles) above optically thick clouds. By comparing model-simulated cloud distributions and properties with visual observations, important insights can be obtained to improve cloud parametrisation in weather forecast and climate models.

International context

Germany makes the largest contribution to the entire range of European satellite programmes of ESA, EUMETSAT and other EU-relevant climate monitoring activities. The analysis of satellite data for the purposes of climate monitoring is done at EUMETSAT through the CM SAF. The World Data Center for Remote Sensing of the Atmosphere (WDC-RSAT) is located at the German Aerospace Center (DLR), from where the data are available to the scientific community.

To establish new satellite-borne and ground-based observation methods with active instruments (radar and lidar), Germany participates in numerous European research programmes, such as ACTRIS and EarthCARE. In addition, Germany is represented on numerous bodies and commissions of the World Meteorological Organization (WMO).

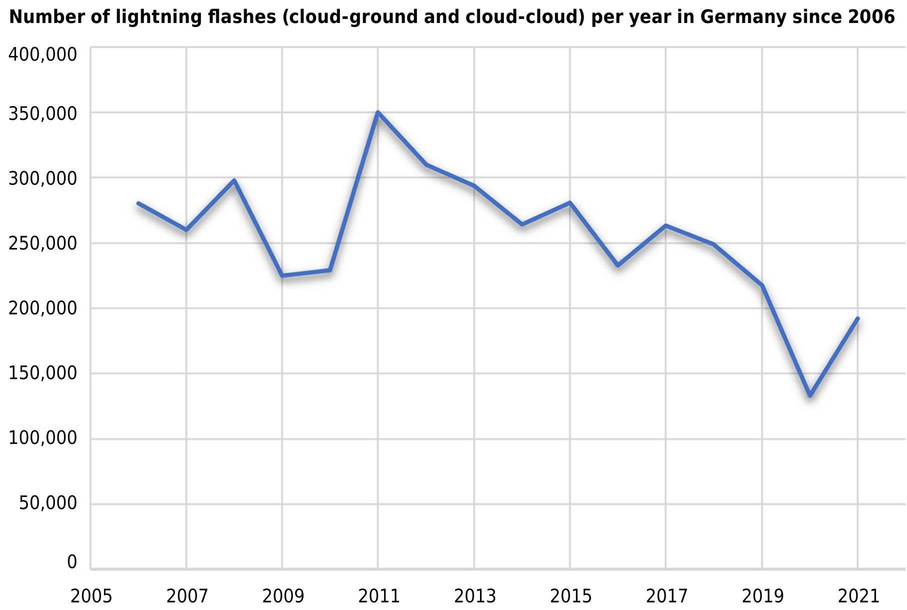
Required resources

Ground- as well as satellite-based measurement methods not only fill the gap in data coverage caused by terminating visual observation, they also deliver data on macro- and microphysical cloud properties, which visual observations would never be able to provide. In addition to investments in new systems, additional human resources are required for adequate maintenance of the systems as well as for development of appropriate retrieval methods, quality assurance over long time periods and the analysis and homogenisation of data.

dwd.de cmsaf.eu

2.9 Lightning observations

Lightning is a strong electrical discharge between clouds or between clouds and the ground that occurs in connection with thunderstorms. Lightning has a high damage potential as it can cause fires or damage to electrical infrastructure and equipment, for example, and also endanger human life. Lightning data are therefore not only used by meteorological services but also by aviation services, energy suppliers, insurance companies and industry. Lightning observations provide an additional information basis for the scientific study of convective systems, strong storms and similar meteorological events. However, due to the high temperatures, lightning also produces relevant amounts of ozone and nitrogen oxides. The occurrence of lightning can be measured and spatially assigned on the basis of the electrical discharge in the atmosphere.



▲ *Figure 2.9-1: Number of lightning flashes. Only lightning flashes with a minimum strength of 5 kA were analysed in order to exclude the effects from the continuously improving locating sensitivity of the monitoring network. Based on LINET data from nowcast GmbH. (Source: nowcast GmbH)*

Climate signals

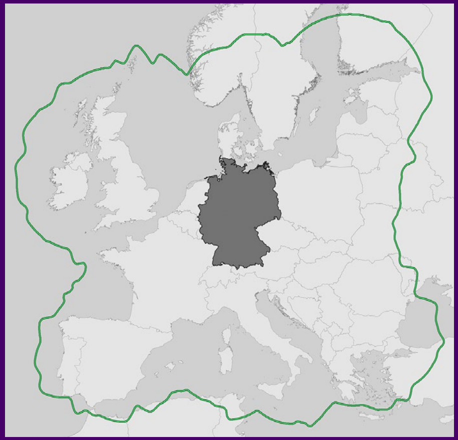
Position detection of lightning using current recording systems makes it possible to compile climatological information, for example about the geographical distribution of lightning or about typical annual and diurnal patterns (Wapler 2013). The time series taken from these lightning detection systems still tend to be too short to be used for any reliable statements about climate trends. As a result of changes in the detection of lightning, it has to be assumed that there are inhomogeneities in the time series. Recording global lightning is important for our understanding of climate change and its impact. Global lightning detection networks discover thunderstorms outside the range of radar systems or satellites. Still, there are unanswered questions about global climate change and its connection with global lightning or thunderstorm activity. Does global warming lead to increased lightning activity? Could the relationships between lightning and precipitation be used to improve our understanding of the relationship between global ■ ■ ■

◀ *Photo 2.9-1: Thunderstorm over Frankfurt am Main* climate change and global precipitation? These are just two of the many questions that can be answered if lightning activity on a global scale is recorded in the long term.

Over the past 15 years, there is no clear trend visible in the figures recorded for lightning in Germany. In fact, if anything, there has been less lightning over recent years. However, statements about trends in the frequency and strength of thunderstorms cannot be reliably derived from the amount of lightning. Further analyses are needed here, but currently none are available for Germany.

Legal framework

According to the Deutscher Wetterdienst Act (DWDG, Section 4), one of the tasks of the DWD is to operate the necessary measuring and observation systems, including for the purpose of issuing official warnings about weather phenomena related to imminent weather and climate events with a high potential to cause damage. In contrast to other parameters, the DWD does not operate a lightning observation system of its own but licenses the data from private-sector providers.



▲ *Figure 2.9-2: Coverage of nowcast's Europe-wide monitoring network with good to very good data quality (Source: nowcast GmbH)*

Measurements in Germany

Traditionally, the occurrence of thunderstorms was recorded by observers at the weather stations as one of several weather phenomena.

Today, lightning is recorded by measuring the electrical discharges with the aid of measuring networks of individual sensors located a few hundred kilometres apart. A flash of lightning generates an electromagnetic field that spreads out in all directions virtually at the speed of light. The sensors have antennae that register the signals. The location of the lightning is determined by analysing the differences in the arrival times of the signals at the various sensors (which is known as »time of arrival« procedure). With this method, the location can be detected down to less than 100 metres.

There are two local lightning detection systems with high location accuracy in Germany, both operated by private sector companies: Siemens' BLIDS lightning information service, which uses Vaisala sensors and technology, and the LINET Lightning Detection Network of nowcast GmbH (Betz et al. 2009), which has also been used by the Deutscher Wetterdienst (DWD) since 2006. The measurement network operated by nowcast GmbH consists of over 190 sensors, installed in 31 European countries, thus covering all of Germany and nearly all of Europe.

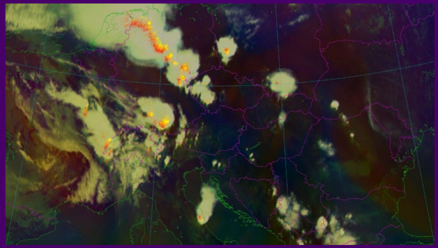
The DWD also uses global lightning data (GLD360) from Vaisala (Pessi et al. 2009, Said et al. 2013 and 2016, Pohjola and Mäkelä 2013).

The systems can detect other characteristics in addition to position, such as the strength and polarity of lightning strokes and the height of cloud-to-cloud lightning.

The private operators store the observations and now hold archives that go back over several decades.

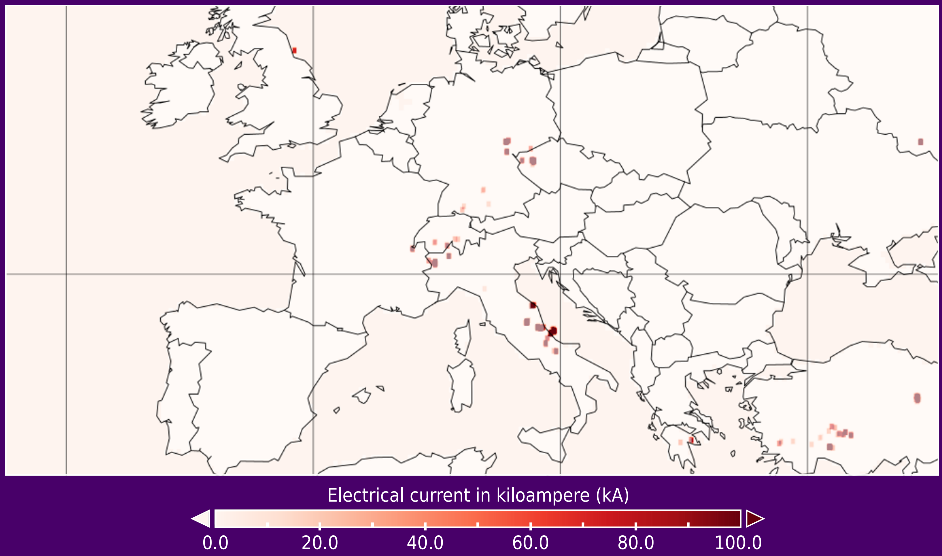
In addition to the local detection systems, data from several global lightning location networks (but with reduced data quality and a location accuracy > 1 km) are also available worldwide, including the GLD360 Global Lightning Detection data service operated by Vaisala (see Figure 2.9-4), the automatic lightning location network ATDnet of the UK's Met Office, the measuring network of the University of Washington (WWLLN) or nowcast's LINET global. The World Meteorological Organization's (WMO) »Guide to Instruments and Methods of Observation, Volume III – Observing Systems« provides a comprehensive description of existing measurement technology (see link at the end).

The new lightning imager sensing systems on Meteosat Third Generation (MTG) satellites will also be able to detect lightning, though they feature significantly lower spatial resolutions than ground-based lightning detection systems. The satellite-based lightning observations will be freely available and provide a valuable source of data for climate research.



▲ *Figure 2.9-3: Detected lightning on 20.06.2013 in the hour before 1500 UTC. The oldest lightning is shown in red, the youngest in yellow. (Source: Christo Georgiev/NIMH)*

Lightning incidents on 2 August 2020, between 1445 and 1500 UTC, GLD360



▲ *Figure 2.9-4: Lightning (cloud-to-ground and cloud-to-cloud strokes) and calculated current magnitudes on 2 August 2020 between 1445 and 1500 UTC, based on GLD360 data (Source: DWD, modified from Vaisala)*

International context

The extent of international observations depends on the commitment of private sector network operators. Data users obtain data directly from these operators. For these data, there is no systematic exchange between governmental organisations in place as is the case with other parameters. Apart from its Europe-wide network, nowcast GmbH operates other local lightning detection networks of high location accuracy in other countries of the world, covering all of the USA and Australia as well as parts of Asia, South America and Africa.

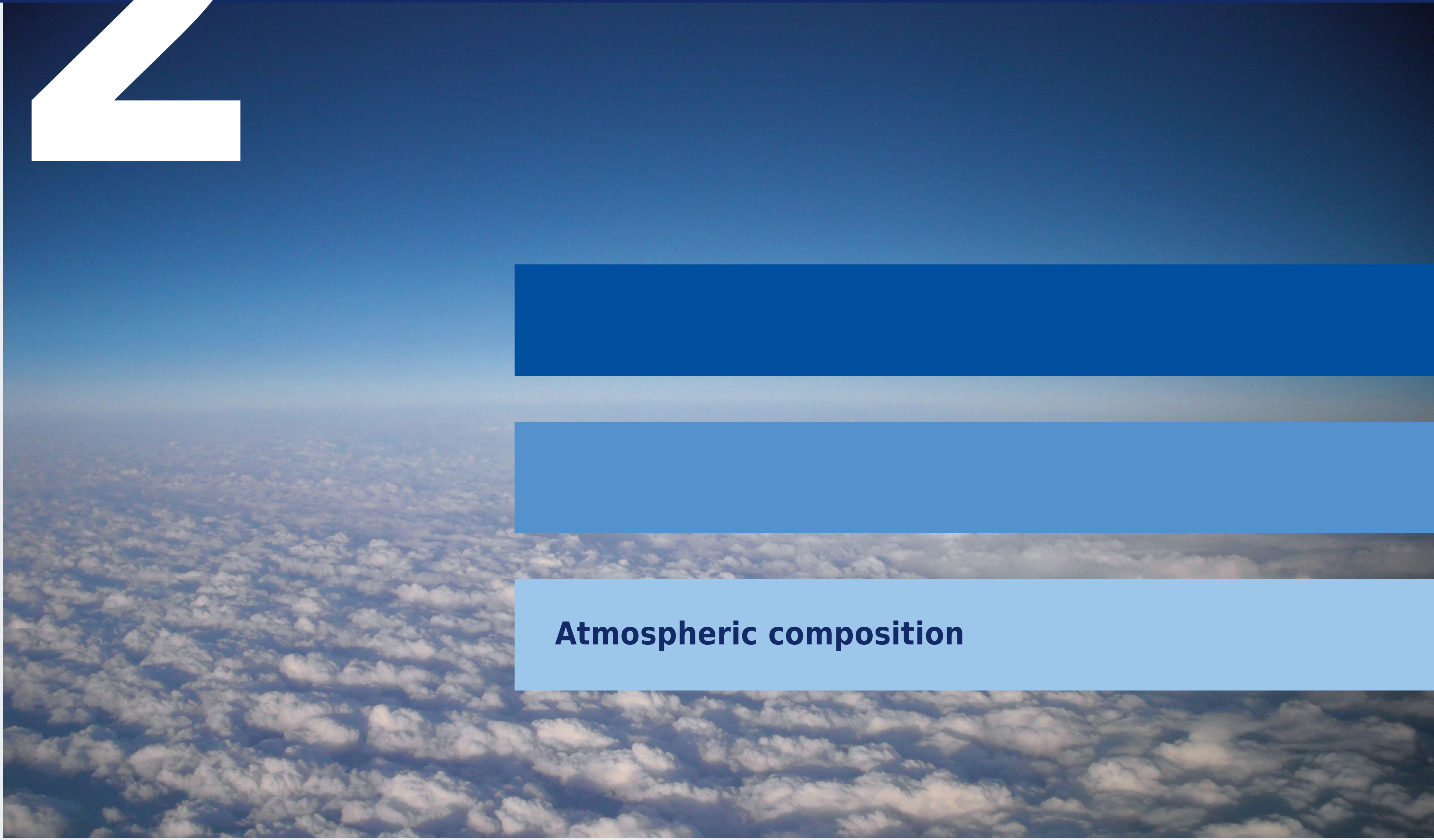
The EUropean Cooperation for LIghtning Detection (EUCLID) provides an additional framework for co-operation in Europe. Operators of lightning detection systems are also active in other European countries. Siemens' BLIDS, for example, uses over 155 connected monitoring stations and detects lightning all over Europe, including the Canary Islands and Madeira. The European states of the former Soviet Republics are not covered. The system uses the measurement networks of various national meteorological services and private operators, whose measurement antennae are connected to EUCLID's central computers.

Required resources

The lightning detection systems in Germany are operated by private companies and the data are licensed for use, in Germany for example by the DWD for official tasks. In many European countries, the systems are operated by the meteorological services themselves. As with other weather measurements, the data collected are made available to the general public free of charge.

community.wmo.int/activity-areas/imop/wmo-no_8 blids.de nowcast.de euclid.org

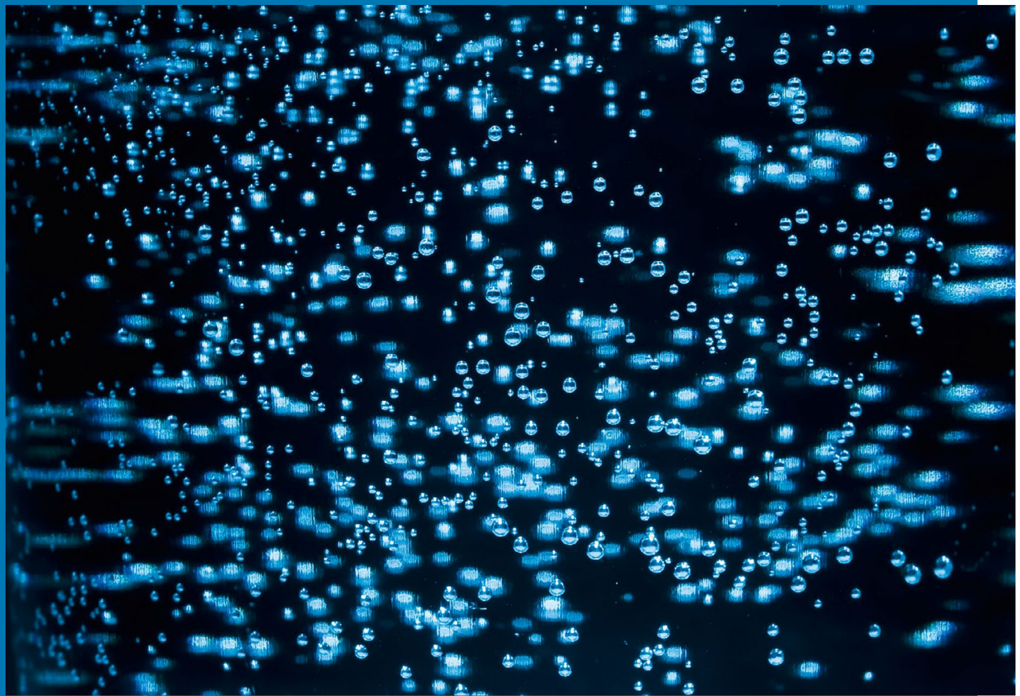
2 Atmospheric observations



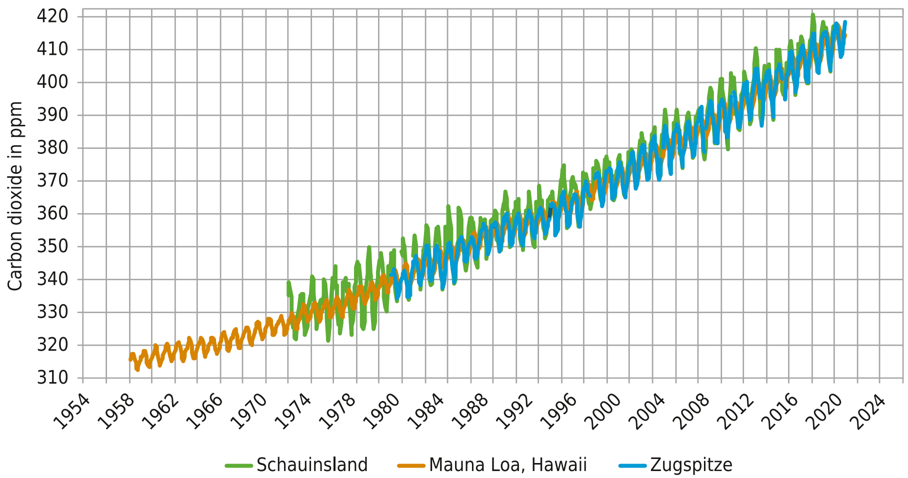
Atmospheric composition

2.10 Carbon dioxide

Greenhouse gases that are released from the burning of fossil fuels by humans are the main cause of global warming. Due to its high atmospheric concentrations, carbon dioxide (CO_2) is the most important among the controllable climate gases. Since the start of industrialisation around 1750, global concentrations of atmospheric CO_2 have risen by 47 %. In contrast, CO_2 concentrations were nearly constant over the previous 10,000 years. The current rate of increase in atmospheric CO_2 is about 100 times faster than at any time in the past.



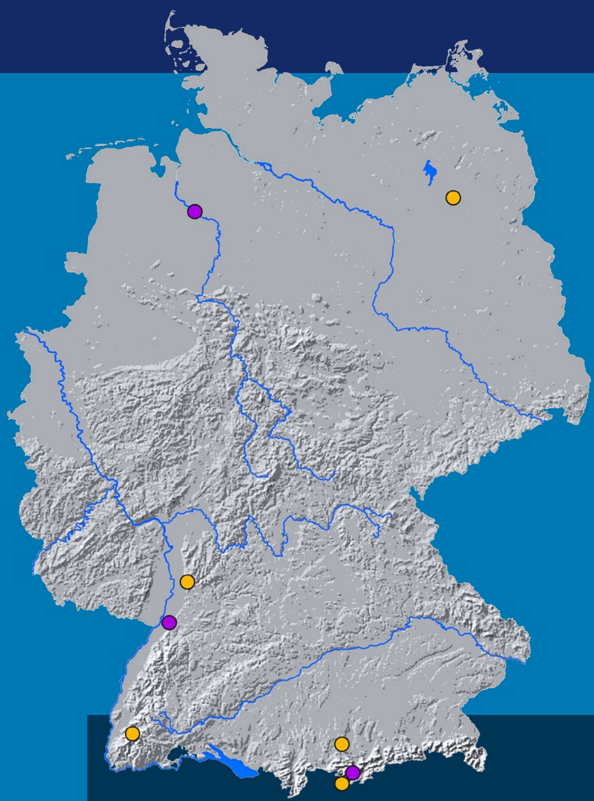
Carbon dioxide concentrations in the atmosphere (monthly means)



▲ *Figure 2.10-1: Time series of CO_2 measurements at the German GAW stations Schauinsland and Zugspitze in comparison with the world's longest CO_2 time series from Mauna Loa, Hawaii (Source: UBA, NOAA Global Monitoring Laboratory, Scripps Institution of Oceanography, WMO and WDCGG)*

Climate signals

Long CO_2 time series provide a reliable measure of the global increase in CO_2 and constitute a continuous record of the effect of fossil fuel burning on the atmosphere. Because of the high level of accuracy of the data, scientists are able to distinguish the effect of fossil fuel burning from the annual fluctuation of CO_2 in the biosphere. This provides a reliable basis for climate models to be used for analysing long-term changes in the atmospheric burden of CO_2 and calculating future scenarios. Whereas in the 1950s the mean annual increase in atmospheric CO_2 was still only 0.55 ppm, differences in mean annual values over the past decade point to an increase of about 2.2 ppm per year. This means that global CO_2 production has increased more than threefold compared to the 1950s.



◀ *Figure 2.10-2: The map shows the five locations (yellow dots) where CO_2 measurements are carried out in situ (i.e. in the ambient air), namely the three German GAW stations Neuglobsow, Schauinsland and Zugspitze/Hohenpeissenberg as well as Heidelberg University. The locations shown in purple, Bremen, Karlsruhe and Garmisch-Partenkirchen, are sites of the TCCON network for measurements of the total column of atmospheric CO_2. (Source: UBA)*

Photo 2.10-1: View towards Schneefernerhaus station (bottom left) and the buildings at the summit of the Zugspitze ▶

Measurements in Germany and abroad

High-precision in-situ measurements of atmospheric CO_2 in the ambient air, like those initiated by C. D. Keeling at Mauna Loa, Hawaii, in 1958, are taken everywhere in the world, for instance in Germany on mount Schauinsland since 1972, on the Zugspitze and at Neuglobsow since 1981 as well as at Hohenpeissenberg since 2006. Data from GAW stations in Germany are retrievable from the World Data Centre for Greenhouse Gases (WDCGG), which is based in Tokyo. Measurements of CO_2 concentrations using solar absorption spectroscopy have been carried out at approximately 20 stations around the world since 2004. This technique provides data on total column concentrations, i.e. from the observation point on the ground to the upper boundary of the atmosphere. The work is co-ordinated by the Total Carbon Column Observing Network (TCCON). In Germany, these measurements are carried out at stations in Bremen, Karlsruhe and Garmisch-Partenkirchen and contribute to the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO). Measurements to record the climate gas CO_2 in urban surroundings have been conducted by Heidelberg University since 1996. They show that long-term and high-precision time series of measurements from sites that are subject to additional pollution can be used for independent verification of statistics-based communications on regional greenhouse gas emissions, for instance the reports produced for the United Nations Framework Convention on Climate Change (UNFCCC). For the purposes of the German contribution to the GAW programme, Heidelberg University has been taking CO_2 flask samples at the Neumayer GAW global station in the Antarctic since 1994. TCCON measurements under German lead management are conducted in Spitzbergen in Norway, Białystok in Poland, Orléans in France and on Ascension Island. Since 2003, the global distribution of atmospheric CO_2 has also been determined by satellite. Although less accurate than ground-based measurements, satellite data give a representative overview of the large-scale spatial distribution of CO_2. A particular focus here is on determining natural CO_2 emissions as well as emissions caused by human activity on a global scale with the best possible spatial and temporal resolution. This requires satellite measurements that are highly sensitive to changes in CO_2 levels close to ground, i.e. close to the emission sources. The first satellite instrument to fulfil these requirements is the SCIAMACHY instrument, which, developed under German lead, is installed aboard the European environmental satellite ENVISAT.

Legal framework

Responsibility for the measurement of carbon dioxide as required in the context of the German contribution to the WMO's international Global Atmosphere Watch (GAW) programme lies with the Federal Environment Agency (UBA). Germany has further statutory obligations in the context of national emissions trading, for which precise statistical emissions surveys and reliable and accurate time series of existing CO_2 concentrations are needed. Amendments to the monitoring system for greenhouse gas emissions in place since 2005 were brought in by Regulation (EU) No. 525/2013.

International context

The GAW global station Zugspitze/Hohenpeissenberg, together with the GAW regional stations Schauinsland and Neuglobsow, makes the core German contribution to CO_2 data for GCOS. In the framework of the »D-A-CH« co-operation between Germany, Austria and Switzerland, the time series recorded at the mountain stations Zugspitze, Hohenpeissenberg, Hoher Sonnblick and Jungfraujoch are analysed together to enhance the reliability and spatial representativeness of the results. The measured data are transmitted to the WDCGG on a regular basis. The measurements are based on the GAW's standard reference scale provided by the agencies of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, USA, for carbon dioxide measurements. Quality assurance is reviewed regularly by round-robin tests carried out in the framework of the CarboEurope project and the GAW programme of WMO. The total column measurements contribute to the international activities co-ordinated by the TCCON.

▲ *Photo 2.10-2: Measuring instruments at Schneefernerhaus station*

Required resources

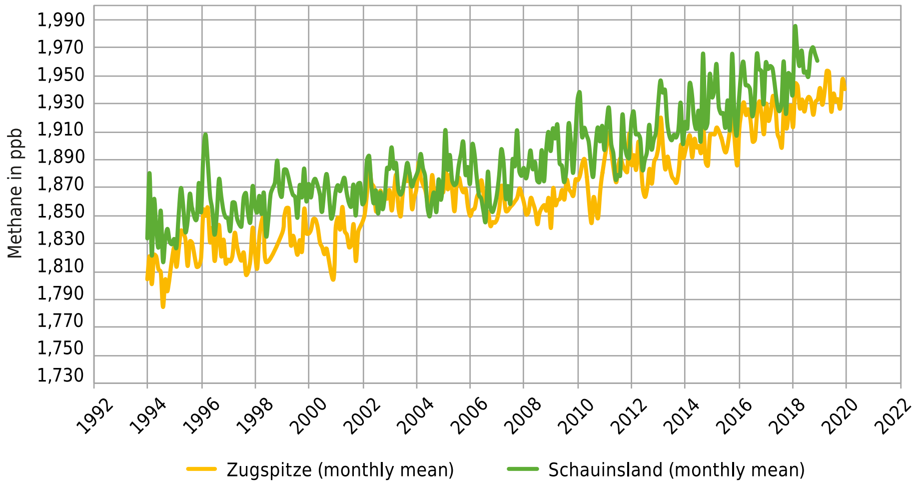
CO_2 measurements at the three GAW stations in Germany are covered by long-term funding from the UBA. The measuring sites are understaffed. At present, the cost of TCCON measurements is only partly financed by institutional funding and the activities are dependent on additional finance from third-party funded projects. Long-term funding is urgently required in order to ensure the continuity of operations.

dwd.de/gaw

2.11 Methane

Since the pre-industrial era, the presence of methane (CH_4) in the atmosphere has increased by more than 270 % as a result of human activity. Among the long-lived greenhouse gases, CH_4 makes the second largest contribution, after carbon dioxide, to global warming. CH_4 concentrations in the Earth's atmosphere are higher today than at any time in the past 650,000 years. Although the rise slowed after 1990 and concentrations remained stable at a high level until 2005, climate models again predict an accelerated increase in CH_4 concentrations with increasing global warming. Since 2007, global networks and satellites have been observing a renewed sharp rise in CH_4.

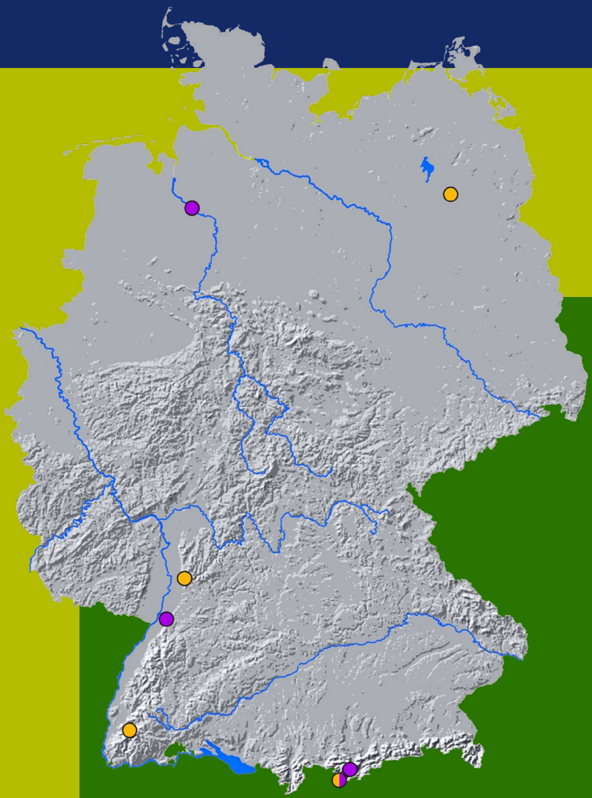
Methane concentrations in the atmosphere (monthly means)



▲ *Figure 2.11-1: Time series of CH_4 measurements at the Schauinsland (green) and Zugspitze (yellow) weather stations. The trend observed for the free troposphere is also visible in the measurements recorded at Schauinsland station, where CH_4 concentrations are generally higher due to the station's low altitude. (Source: UBA)*

Climate signals

Long high-precision time series provide a reliable picture of CH_4 concentrations, which are the overall result of interactions between all sources and sinks. Although the sources of CH_4 are known, their trends and their interaction with sinks cannot yet be fully explained. Even though the overall trend of CH_4 levels continues to show an upward trend, the rate of increase in CH_4 concentrations has steadily declined in the last two and a half decades. The reasons for this, as well as the consequences for future atmospheric global warming, are not yet sufficiently understood. Long and reliable time series are fundamental to improve our understanding of the interaction between sources and sinks.



◄ *Figure 2.11-2: Map of Germany showing the four locations (yellow dots) where methane measurements are carried out in situ (i.e. in the ambient air), namely the three German GAW stations Neuglobsow, Schauinsland and Zugspitze as well as Heidelberg University. The locations shown in purple, Bremen, Karlsruhe, Garmisch-Partenkirchen and Zugspitze, are sites where measurements of the total atmospheric column of methane are carried out for the TCCON network. (Source: UBA)*

Measurements in Germany and abroad

In Germany, in-situ measurements of atmospheric methane have been carried out on mount Schauinsland since 1991 as well as on the Zugspitze and at Neuglobsow since 1994. The measurements are complemented by flask sampling at Hohenpeissenberg, conducted there since 2006 in the framework of the worldwide programme co-ordinated by the National Oceanic and Atmospheric Administration's Earth System Research Laboratories (NOAA/ESRL). Data from GAW stations in Germany are retrievable from the World Data Centre for Greenhouse Gases (WDCGG), which is based in Tokyo.

Measurements to record CH_4 in urban surroundings have been conducted by Heidelberg University since 1996. They show that long and high-precision time series of measurements from such locations can be used for independent verification of statistics-based reports on regional greenhouse gas emissions, for instance reports produced for the United Nations Framework Convention on Climate Change (UNFCCC).

Measurements of CH_4 using new solar absorption spectroscopy devices have been carried out at approximately 20 stations around the world since 2004. This technique provides data on total column concentrations, i.e. from the observation point on the ground to the upper boundary of the atmosphere. From these data, it is possible to derive mean CH_4 concentrations in the troposphere. The work is co-ordinated by the Total Carbon Column Observing Network (TCCON). In Germany, these measurements are carried out at stations in Bremen, Karlsruhe and Garmisch-Partenkirchen. Further to this, long-term Fourier Transform Infrared Spectroscopy (FTIR) measurements in the traditional mid-infrared spectrum have been carried out on the Zugspitze since 1995. These form part of the activities of the Network for the Detection of Atmospheric Composition Change (NDACC) and also provide highly precise data on total column concentrations of methane. The measurements contribute to the WMO's GAW programme.

For the purposes of the German contribution to the GAW programme, Heidelberg University has been taking CH_4 flask samples at the Neumayer GAW global station in the Antarctic since 1987.

TCCON measurements under German lead management are conducted in Spitzbergen, Białystok, Orléans and on Ascension Island.

Since 2003, the global distribution of atmospheric CH_4 has also been determined by satellite.

Legal framework

Responsibility for measuring methane for the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) programme, which is the component of the GCOS network that monitors essential climate variables, lies with the Federal Environment Agency (UBA). Amendments to the monitoring system for greenhouse gas emissions in place since 2005 were brought in by Regulation (EU) No. 525/2013.

▲ *Photo 2.11-1: TCCON observatory at the California Institute of Technology (Caltech) in Pasadena, USA*

International context

The GAW global station Zugspitze/Hohenpeissenberg, together with the GAW regional stations Schauinsland and Neuglobsow, forms the core of the German contribution to methane data for GCOS. In the framework of the »D-A-CH« co-operation between Germany, Austria and Switzerland, the time series recorded at the mountain stations Zugspitze, Hohenpeissenberg, Hoher Sonnblick and Jungfraujoch are analysed together to enhance the reliability and spatial representativeness of the results. Data measurements are transmitted to the WDCGG on a regular basis. The measurements are based on the GAW's standard reference scale provided by the agencies of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, USA, for CH_4 measurements. Quality assurance is also reviewed regularly by round-robin tests carried out in the framework of the CarboEurope project and the GAW programme of WMO. The total column measurements contribute to the international activities co-ordinated by TCCON and NDACC.

Required resources

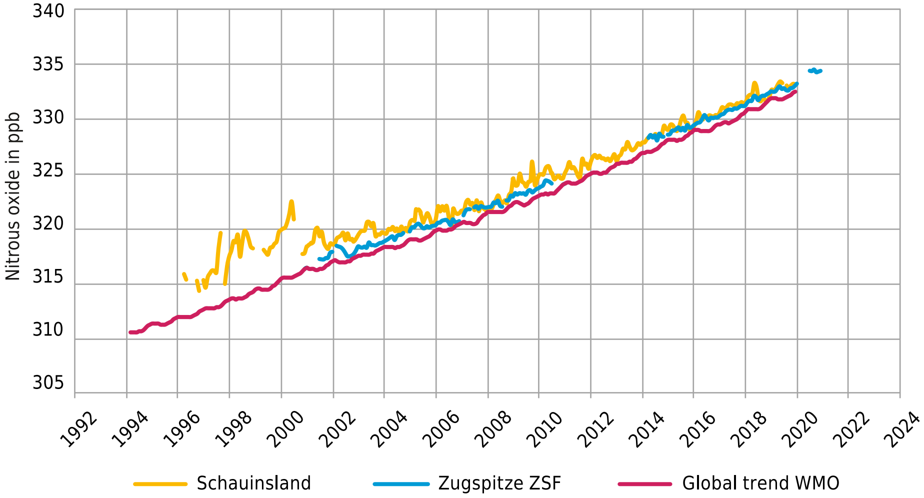
Methane measurements at the three GAW stations in Germany are covered by long-term funding from the UBA. The measuring sites are understaffed. At present, the cost of TCCON measurements is only partly financed by institutional funding and the activities are dependent on additional finance from third-party funded projects. Long-term funding is urgently required in order to ensure the continuity of operations.

dwd.de/gaw

2.12 Other greenhouse gases

Even if its most important members, carbon dioxide (CO_2) and methane (CH_4), are not taken into account, the group of long-lived climate forcers (LLCFs) still contributes significantly (around 18 %) to the greenhouse effect. The largest share comes from nitrous oxide (N_2O), sulphur hexafluoride (SF_6) and climate-forcing halogenated compounds. Among these, for instance, SF_6 and NF_3 are extremely long-lived with lifetimes of up to 3,200 years and 640 years, respectively, and thus will continue to affect the global climate long into the future.

Nitrous oxide concentrations in the atmosphere (monthly means)



▲ *Figure 2.12-1: Time series of N_2O concentrations at GAW regional station Schauinsland (yellow) and Zugspitze platform (blue) compared to the global trend (red) according to WMO (Source: UBA, WDCGG and WMO)*

Climate signals

Nitrous oxide makes the third-largest contribution to global warming from long-lived greenhouse gases. Compared to pre-industrial times (1750), the atmospheric abundance of N_2O has been increasing by just 20 %. At a time horizon of 100 years, however, N_2O has a global warming potential 300 times as large as that of CO_2. About 40 % of the amounts of N_2O emitted into the atmosphere result from human activity. The remainder comes from natural sources. Atmospheric N_2O concentrations show a slight north-south gradient, largely explained by the larger proportion of land area in the northern hemisphere and the use of artificial fertilisers in the mid-latitudes. Long high-precision series from both the northern and southern hemispheres are a key requirement for improved understanding of sources and forecasting of future trends. To do so, in-situ data of a very high degree of accuracy are required.

Measurements in Germany and abroad

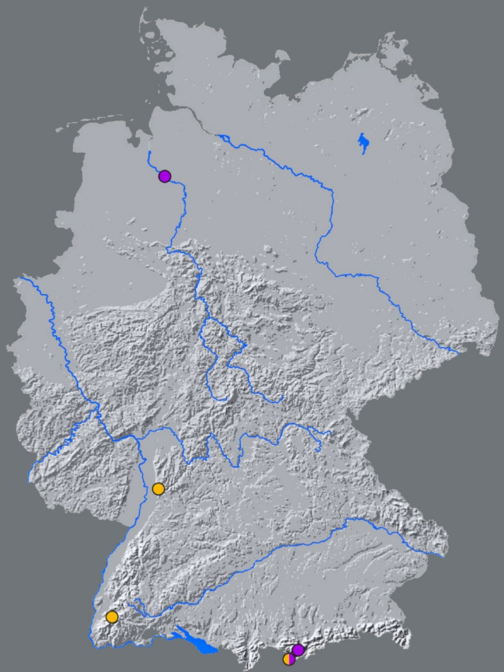
In Germany, in-situ measurements of N_2O, SF_6 and the indirect greenhouse gas hydrogen (H_2) are conducted by the Federal Environment Agency (UBA) at the GAW stations Schauinsland and Zugspitze and in an urban surrounding by Heidelberg University.

Data from German GAW stations are retrievable from the Tokyo-based World Data Centre for Greenhouse Gases (WDCGG).

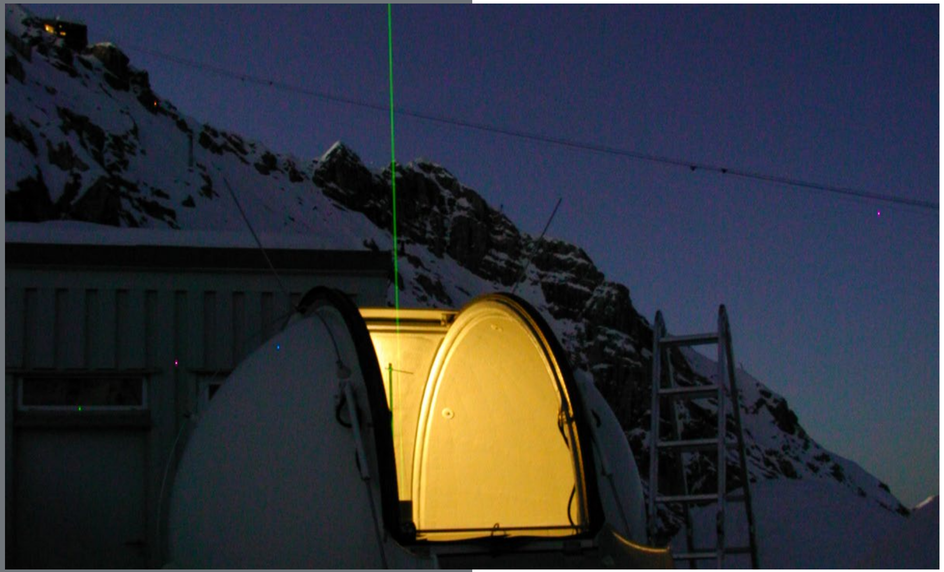
Since 2004, long-lived climate-relevant trace gases have been measured at about 20 stations worldwide using solar absorption spectroscopy. This technique provides data on total column concentrations, i.e. from the observation point on the ground to the upper boundary of the atmosphere. The work is co-ordinated by the Total Carbon Column Observing Network (TCCON). In Germany, these measurements are carried out at stations in Bremen, Karlsruhe and Garmisch-Partenkirchen. They make it possible to determine the total column of N_2O. The potential and limitations of this technique are currently being analysed.

Since 1990, similar measurements using solar absorption spectroscopy have been carried out in spectral ranges other than those used for TCCON purposes; this allows the detection of numerous other substances, including SF_6. The measurements are performed as part of the Network for the Detection of Atmospheric Composition Change (NDACC), among others at the German NDACC station Zugspitze.

The long-term influence of water vapour, which is the most important greenhouse gas, on climate change is being studied at the Zugspitze/Schneefernerhaus site. On clear nights, tropospheric water vapour profiles up to



▲ Figure 2.12-2: Map of Germany showing the two German GAW stations Schauinsland and Zugspitze and the urban surrounding site of Heidelberg University, all measuring N_2O, SF_6 and H_2 (yellow dots). Measurements of the total column of nitrous oxide (purple dots) are carried out at the TCCON sites of Bremen and Garmisch-Partenkirchen as well as at the NDACC site on the Zugspitze. Water vapour vertical profiles up to 12 km (extension to 30 km is under way) are measured regularly on the Zugspitze. (Source: DWD)



▲ Photo 2.12-1: Lidar instrument on the roof of the Environmental Research Station Schneefernerhaus (UFS)

12 km altitude have been measured at this site since 2007 using infrared (IR) differential absorption lidars (DIAL). Since 1996, Heidelberg University has taken measurements of the greenhouse gases N_2O and SF_6 and of the indirect greenhouse gas H_2 all in an urban surrounding. It has been shown that long and high-precision measurement series from such locations can be used successfully for independent verification of statistics-based reports on regional greenhouse gas emissions, for example for the United Nations Framework Convention on Climate Change (UNFCCC).

Legal framework

As part of its official participation in the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW), which is the component of GCOS that monitors essential climate variables related to atmospheric composition, Germany carries out measurements of N_2O, SF_6 and H_2 as well as climate-relevant halogenated compounds. With the signing of the Kyoto Protocol by the European Union, obligations to limit and reduce emissions have entered into force. To this aim, the monitoring system for greenhouse gas emissions in place since 2005 was amended by Regulation (EU) No. 525/2013. Important objectives are to improve the monitoring and verification of emissions by sources and their removal by sinks.

International context

The GAW global station Zugspitze/Hohenpeissenberg, together with the GAW regional station Schauinsland, forms the core German contribution to N_2O and SF_6 measurements for GCOS. The measured data are transmitted to the WDCGG on a regular basis.
The measurements are based on the GAW's standard reference scale provided by the agencies of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, USA, for N_2O and SF_6 measurement and on the reference scale for H_2 maintained by the Max Planck Institute in Jena. Quality assurance is reviewed regularly by round-robin tests carried out in the framework of the CarboEurope project and by WMO. The total column measurements contribute to the international activities co-ordinated by TCCON and NDACC. They are of particular importance as they can be used to validate satellite instruments, which have similar viewing geometry and also measure the total column. Airborne measurement campaigns were conducted to adjust the TCCON total column measurements to existing in-situ measurements. Both TCCON and NDAAC measurements are accepted by the WMO's GAW programme.

▲ *Photo 2.12-2: Measuring instruments on the terrace of the fifth floor of the Zugspitze measuring site*

Required resources

At present, the costs of TCCON and NDACC measurements are only partly covered by institutional funding, which makes these activities dependent on additional finance from third-party funded projects. Long-term funding is urgently required in order to ensure the continuity of operations. Until now, there are no continuous data series in Germany on halogenated greenhouse gases in the ambient air (in situ).

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2.13 Anthropogenic greenhouse gas fluxes

The anthroposphere, i.e. the habitat created or influenced by humans, releases, among others, the greenhouse gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. Both inputs into the atmosphere from various sources (e.g. the use of fossil fuels) as well as removals out of the atmosphere by sinks (e.g. vegetation) are called greenhouse gas fluxes.

◀ *Figure 2.13-1: A multitude of individual sources contribute to anthropogenic greenhouse gas emissions. (Source: DWD)*

Trends

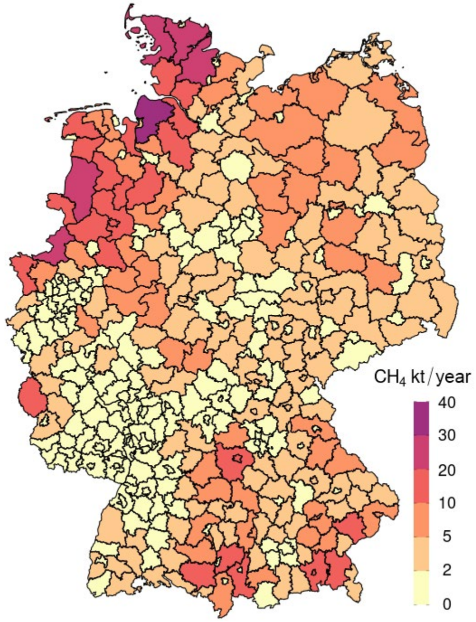
In order to stabilise greenhouse gas concentrations, the amount of emissions from the sources must correspond to the amounts removed by the sinks – which is referred to as »net zero». In many regions of the world, however, net greenhouse gas fluxes are far above zero, sometimes even increasing due to expanding anthropogenic activities.

In the case of the most significant greenhouse gas CO_2, the trend is driven by global increase in the use of fossil fuels, with the exception of a temporary decrease of approximately 7 % due to the COVID-19 crisis. A systematic downwards trend in anthropogenic CO_2 emissions over the last decades can only be seen on the European continent (Friedlingstein et al. 2021).

Global CH_4 emissions have increased by almost 10 % in the last 20 years for two main reasons: the increasing release of natural gas during the production and transport of oil, gas and coal, and the growing global meat production (Schiermeier 2020). In Europe, decreases in methane emissions have been achieved by reducing livestock farming, closing hard coal mines and implementing waste management measures.

N_2O emissions have increased over the last decades due to higher use of fertilisers (Copernicus 2019).

Agricultural CH_4 emissions per rural district (2018)

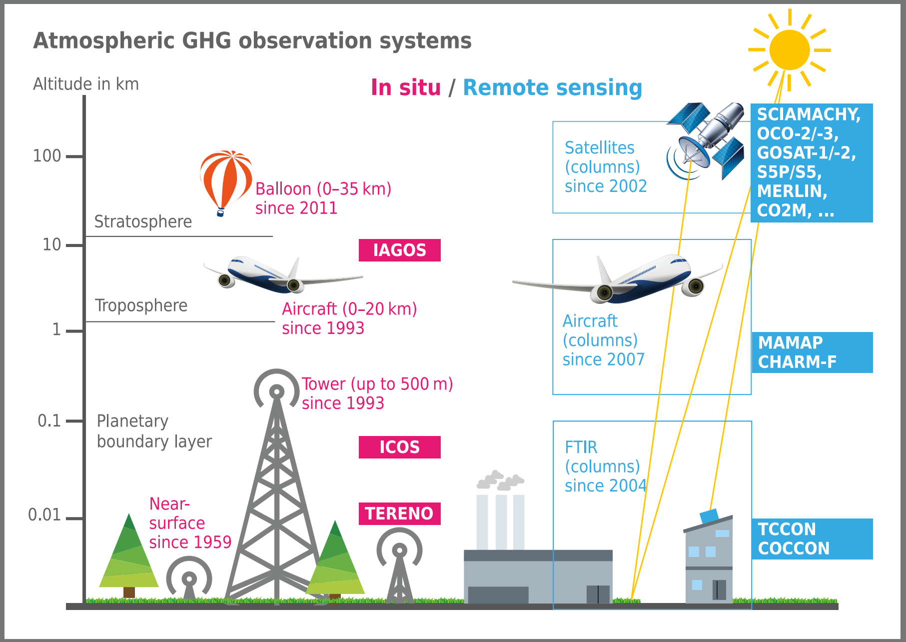


▲ *Figure 2.13-2: Germany's CH_4 emissions mainly stem from agriculture. (Source: UBA)*

In Germany, the Federal Environment Agency (UBA) records greenhouse gas emissions for each sector and reports their trends in the »National Inventory Reports« in line with the guidelines of the Intergovernmental Panel on Climate Change (IPCC). Ideally, these data, which are mainly derived from statistics (see e.g. Figure 2.13-2), can be supplemented by the observation-based GCOS Essential Climate Variables (ECVs) (such as in Figure 2.13-3).

Observation systems

In Germany, large-scale representative measurements are taken on nine high towers as part of the European research infrastructure Integrated Carbon Observation System (ICOS). In addition, measurements on masts and on the ground (e.g. at the Terrestrial Environmental Observatories, TERENO) show the typical fluxes for certain ecosystems. In respect of ground-based measurements, the UBA's measurement series at the Zugspitze and Schauinsland mountain stations are particularly important as they go back over many years and clearly show the trends in background concentrations. The international project In-service Aircraft for a Global Observing System (IAGOS) was set up to provide airborne in-situ measurements of greenhouse gas concentration. Remote sensing measurements using spectrometers, such as the COllaborative Carbon Column Observing Network (COCCON) and the Total Carbon Column Observing Network (TCCON) as well as the Methane Airborne MAPper (MAMAP), provide data on column concentrations. Further column data are provided by airborne laser devices (CH_4 Airborne Remote Monitoring, CHARM-F). Satellite-based measurements, including those taken with the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), the Orbiting Carbon Observatory satellites (OCO-2/3) and the Greenhouse Gases Observing Satellites (GOSAT-1/2) or as part of numerous missions (including Sentinel-5P and, in future, Sentinel-5, the Methane Remote Sensing Lidar Mission (MERLIN) and the Copernicus Carbon Dioxide Monitoring programme (CO2M)) continue to improve in terms of quality, resolution and coverage. The results expected from all these measurements will contribute to the determination of greenhouse gas emissions.

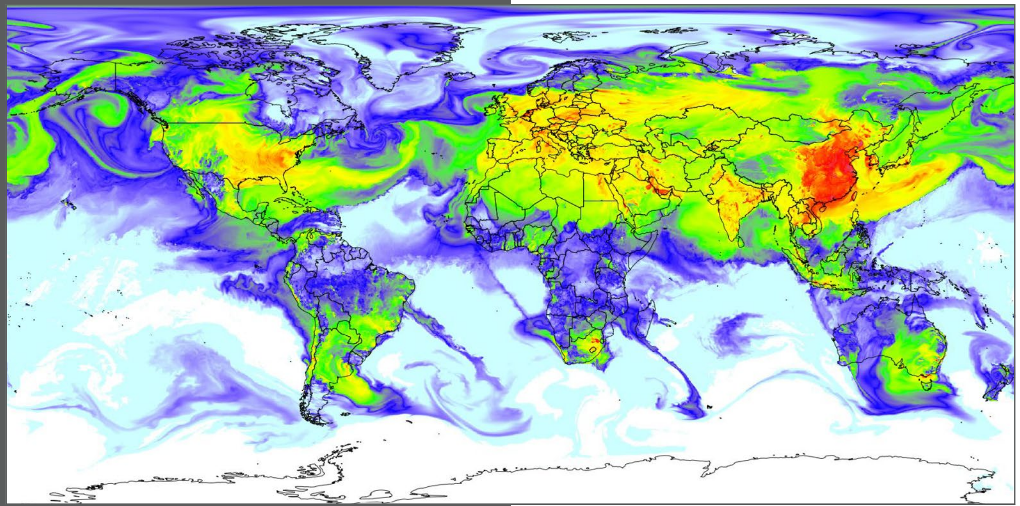


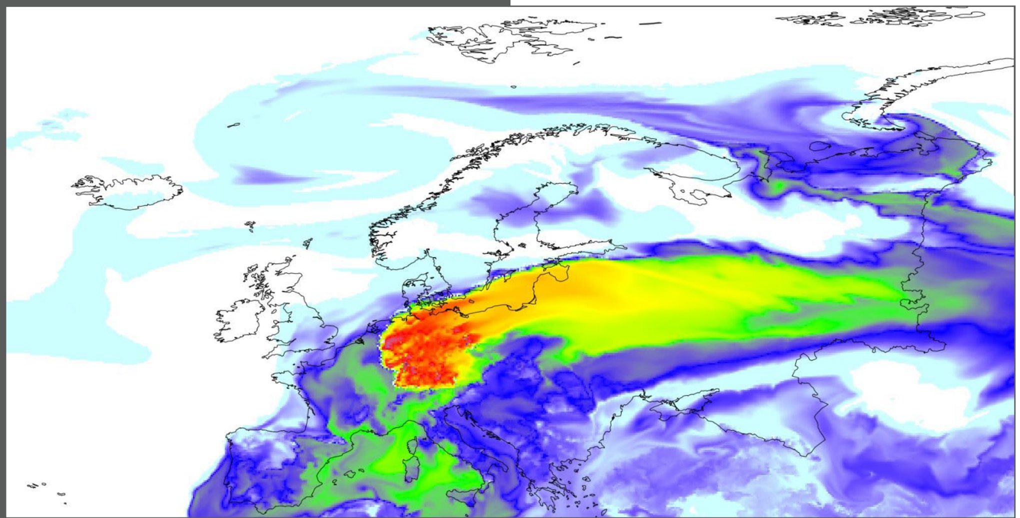
▲ *Figure 2.13-3: Atmospheric observation systems for greenhouse gas emissions (Source: University of Bremen and DWD)*

Recording greenhouse gas fluxes

Greenhouse gas fluxes are recorded in the atmosphere using national and international observation systems (see Figure 2.13-3). Oceanic fluxes are also recorded. The sources and sinks are inferred from the measurements with the aid of meteorological transport modelling and mathematical methods of data assimilation and inversion. In the case of long-lived greenhouse gases, a variety of factors must be adequately considered over longer periods of time. Since current measurements can only record partial aspects, so-called a priori information (i.e. estimates of sources and sinks made using other methods) is also taken into account, which allows conclusions to be drawn about the plausibility of the various components. The national system for the monitoring of integrated greenhouse gases focuses on Germany (Integriertes Treibhausgas-Monitoringsystem, ITMS) and uses the global results of the Copernicus Atmosphere Monitoring Service (CAMS) of the European Union as a boundary condition.

Figure 2.13-4: Global CO_2 emissions are distributed around the world via general atmospheric circulation. The example shows a concentration field modelled with ICON-ART at the height of the ICOS measurement towers, based on ten days of emissions outside Germany. (Source: DWD) ▶





▲ Figure 2.13-5: CO_2 emissions from Germany increase near-surface CO_2 concentrations over Europe, exemplified here by ICON-ART modelling. (Source: DWD)

Legal framework

The Paris Climate Agreement stipulates that greenhouse gas emissions are to be reduced in accordance with the countries' Nationally Determined Contributions. From 2023, the progress of climate protection will be recorded every five years in so-called Global Stocktakes. In addition, Biennial Transparency Reports are planned every two years from 2024.

At national level, the German Federal Climate Protection Act (KSG) regulates the permissible annual emission levels for individual sectors, such as energy, industry and transport. The ruling of the Constitutional Court of 24 March 2021 (Bundesverfassungsgericht 2021) called for specific targets and greater transparency. Here, the above-mentioned GCOS ECVs can make a contribution by providing information.

International context

Five GCOS products are defined for anthropogenic greenhouse gas fluxes:

1. Emissions from fossil fuel use, industry, agriculture and waste sectors
2. Emissions/removals by IPCC land categories
3. Estimated fluxes by inversions of observed atmospheric composition – continental
4. Estimated fluxes by inversions of observed atmospheric composition – national
5. High-resolution CO_2 column concentrations to monitor point sources.

The various national initiatives are internationally networked in the World Meteorological Organization's (WMO) Integrated Global Greenhouse Gas Information System (IG³IS).

Required resources

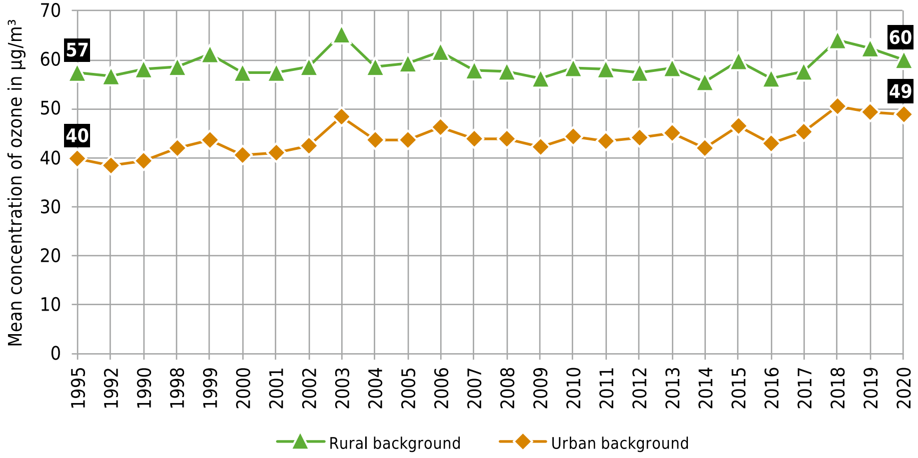
In Germany, the development of observation-based emissions verification is guaranteed through the Research for Sustainability strategy (FONA) and its ITMS greenhouse gas monitoring system for Germany as well as through various German, European and international research projects. To ensure that this commitment continues in the long term, further follow-up projects are required and the resulting system must be operationalised by the authorities and institutions involved.

umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen **dwd.de/EN/climate_environment/climatemonitoring/greenhousegas/greenhousegas_node.html**

2.14 Ozone

The colourless and poisonous gas ozone (O_3) is one of the most important trace gases in the atmosphere. Most of this gas (more than 90 %) is found in atmospheric layers above 10 km (stratosphere). The stratospheric ozone layer protects the Earth from harmful ultraviolet radiation from the sun. In lower atmospheric layers, the gas is present as »background ozone« as a result of hemispheric transport and natural ozone production, which makes it a focus of attention in this context. In strong sunshine, additional ozone forms chemically from precursor pollutants. Furthermore, ozone is a greenhouse gas and thus contributes to global warming of the Earth's atmosphere.

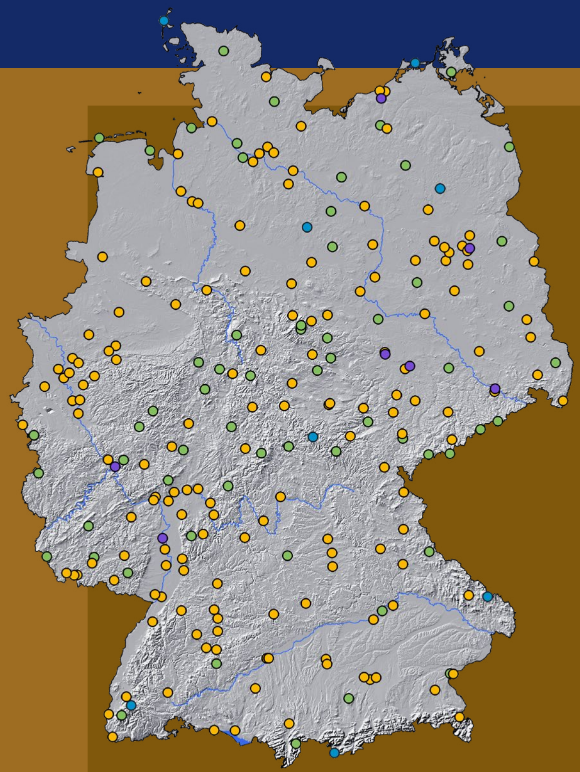
Trends in mean annual concentrations of ozone (1995–2020)



▲ *Figure 2.14-1: Evolution of mean annual concentrations of ozone at a selected range of stations of the site categories »rural background« and »urban background« (Source: UBA, based on data from the measurement networks operated by UBA as well as by the German federal states)*

Climate signals

Since the 1990s, there has been a notable decrease both in peak surface ozone concentrations and in the frequency of occurrence of very high ozone concentrations in surface air. This shows that the emission reduction measures taken against the so-called »summer smog« episodes have taken effect. Compared to the levels of 1990, ozone precursor emissions from nitrogen oxides and non-methane volatile organic compounds have declined until 2019 by 60 % and 71 %, respectively. However, the target level for the protection of human health continues to be exceeded. In contrast to the trend observed for peak ozone concentrations, the mean annual concentrations at urban background sites, i.e. in typical residential areas, have risen over the period from 1995 to 2020. At rural background sites, mean ozone concentrations show no significant increase (Figure 2.14-1). During the observation period, there has been a shift from low to medium concentration levels. The cause of this trend is the reduction in nitrogen oxide emissions: as nitrogen oxide is predominantly emitted in the form of nitrogen monoxide (NO), ■ ■ ■



▲ *Figure 2.14-2: Map showing all ozone measuring sites in Germany in operation in 2021: blue dots represent UBA stations in remote rural locations, green dots stand for stations in rural areas, yellow dots for stations in urban background and purple dots for traffic-near measuring sites. (Source: UBA and measuring networks of the federal states)*

Measurements in Germany and abroad

Measurements of ground-level ozone concentrations in Germany were initiated in the mid-1970s. In 1990, there were already 194 ozone measurement stations distributed over the whole of Germany; in 2020, ozone concentrations were measured at 274 sites in towns/urban agglomerations and rural areas. As set out in the Federal Immission Control Act (BImSchG), responsibility for monitoring air quality lies with the German federal states, who operate measuring networks for this purpose. In order to monitor any large-scale, transboundary transport of air pollutants and to supervise international activities and compliance with clean air strategies, the Federal Environment Agency (UBA) operates its own network consisting of seven measuring sites. The stations are located as far away as possible from local sources of air pollution.

DWD ozone measurements at Hohenpeissenberg and Lindenberg

The key focus of the ozone measuring programme of the Deutscher Wetterdienst (DWD) is on stratospheric ozone and ozone profiles from the ground up to 50 km altitude. The measurements are carried out as part of the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO), under which in particular the DWD's Hohenpeissenberg Meteorological Observatory (MOHp) also conducts extensive near-surface measurements of trace gases and aerosol. Since the late 1960s, ozone profile measurements at the MOHp and at the DWD's Lindenberg Meteorological Observatory (MOL) (at first located in East Berlin) have consisted in one to three regular ozone soundings per week. The sounding ensemble is transported by a balloon to an altitude of more than 30 km, continuously recording ozone partial pressure, temperature and wind as well as tropospheric humidity. In addition to ozone profiles, complementary spectrometer measurements of the total ozone column have also been carried out since the late 1960s. At Hohenpeissenberg, LIDAR measurements have been taken in clear nights since late 1987 to register profiles of ozone between 15 and 50 km altitude.

The long series of ozone measurements by the two observatories document the evolution of ozone in the different layers of the atmosphere. For the stratosphere, they clearly depict the phase of ozone depletion due to chlorofluorocarbons (CFC) from the late 1960s until the mid-1990s. Since the beginning of the 2000s, the ozone layer has been recovering, but at a very slow pace. It will take many more decades until full recovery is reached. As regards to tropospheric ozone, the measurements of both observatories, MOHp and MOL, confirm the values registered by the UBA with its much denser surface network.

The MOHp measurement series of ozone are part of the WMO's GAW programme.

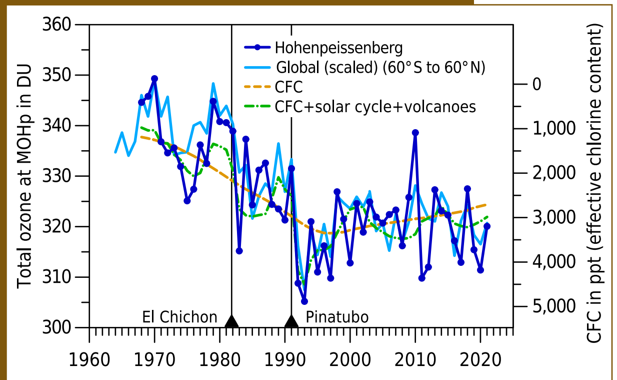


Figure 2.14-3: Long-term development of the stratospheric ozone layer based on total ozone column measurements at Hohenpeissenberg and global data (scale on the left). The data reflect a clear decrease in ozone from the end of the 1960s until the mid-1990s and a slow recovery since then. The ozone column follows the earlier increase in ozone-depleting chlorofluorocarbons and their decrease after the international ban imposed by the Montreal Protocol of 1987 (inverted scale on the right). The 11-year cycle of solar activity and large volcano eruptions also play ◄ *a role. (Source: DWD)*

reduced NO emissions lead to a weakening of the titration effect, a depletion process which breaks down ozone and, by oxidation with locally emitted NO, converts it to nitrogen dioxide. The consequence of this is an increased lifetime of ozone. In cities, the rise in mean annual ozone concentrations results from the falling number of low ozone values and a parallel rise in the number of medium ozone concentrations. In addition, it is assumed that the impact of hemispheric transport on ozone pollution in Germany and Europe is increasing due to industrial emissions in Asia and North America.

Legal framework

In Germany, monitoring of air quality – including ground-level ozone – is carried out according to the air quality regulations of the European Union, which have been incorporated into German law through the Thirty-ninth Ordinance on the Implementation of the Federal Immission Control Act (39. BImSchV). This regulation sets ozone target values for the protection of human health and vegetation. Information and alert thresholds are established in order to counter the risks to human health that are associated with short-term exposure to high ozone concentrations.

Required resources

Due to the legal obligation to monitor ground-level ozone concentrations in Germany, long-term continuity of these programmes is secured.

◀ *Photo 2.14-1: Launch of a balloon-borne ozone sonde at the MOHp*

International context

All ozone data collected in Germany in the framework of European air quality guidelines are transmitted to the air quality data portal of the European Environment Agency (EEA). From there, the data are available for use all over Europe in research, statistical analysis and projects, and as a source of real-time data. The UBA's measurement stations are also part of the European Monitoring and Evaluation Programme (EMEP) for the investigation of pollutant concentrations in air masses transported over long distances and across national frontiers. In addition, the data from the GAW's global station Zugspitze/Hohenpeissenberg and regional stations Schauinsland and Neuglobsow contribute to the GAW programme. Under a co-operation with the Czech Hydrometerological Institute (CHMI), the MOHp operates the WMO's Regional Dobson Calibration Center (RDCC) for Europe.

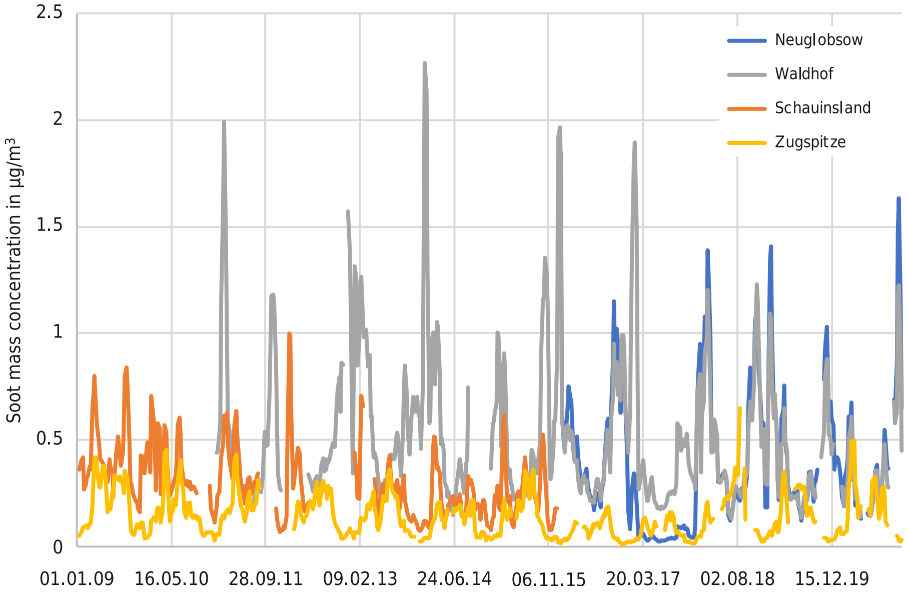
In addition to the GAW programme, the ozone data gathered by the DWD also feed other international programmes for monitoring the atmosphere and for the validation of satellite-based data. Examples for such programmes are the Network for the Detection of Atmospheric Composition Change (NDACC) or the Copernicus Atmosphere Monitoring Service (CAMS).

umweltbundesamt.de/en/topics/air/air-pollutants-at-a-glance/ozone **dwd.de/ozon**

2.15 Aerosols

Aerosols have a predominantly cooling effect on the atmosphere. The exception is black carbon (BC), also referred to as soot, which is a major contributor to global warming because of its radiation-absorbing properties. Soot arises mostly from anthropogenic combustion processes. Generally, however, the effects of aerosols are not yet understood well enough, which is why adequate measurement series of ultrafine particles (UFP) and soot are highly important.

Soot mass concentration in µg per m³



▲ *Figure 2.15-1: Soot mass concentration in µg per m³ at background stations (Source: UBA)*

Climate signals

Similar to the particle mass, there is a great difference in the levels of soot measured at urban stations and in rural surroundings. One well-known source of soot is traffic (especially from diesel vehicles), which is the reason for the high values measured at traffic-near stations, with mean values of around 2–4 µg/m³ in the period 2009–2011. Soot concentrations recorded at background stations are considerably lower, amounting to a quite constant figure of 0.02 µg/m³ on the Zugspitze over the same time period. The level of soot at a specific measuring site, just as the number of ultrafine particles, functions as a sensitive indicator of the influence of local combustion sources.

Analogous to particle mass, the observations reveal a similarly strong annual variation in the concentrations of soot. In flat country, the highest values occur in winter whereas the mountain stations register maximum values in summer. The reasons for this are the annual variation in the height of the mixing layer and the heating period in winter (Sun et al. 2021).

From 2009 onwards, soot concentrations decreased nationwide until 2018, with an annual linear trend around 1.7–13.1 %. This reduction agrees well with the decrease observed for all BC emissions as a whole, proving the success of statutory reduction measures, such as the introduction of low-emission transport and heating systems. The daily curve of soot concentrations also reveals that reduced emissions from traffic have led to lower soot figures during the day. When looking at seasonal trends, it is domestic heating that has the largest influence on soot concentrations in the winter months (Sun et al. 2020).

Legal framework

Directive 2008/50/EC of the European Parliament and the Council of 21 May 2008 on ambient air quality and cleaner air for Europe has superseded the previous Council Directive 96/62/EC of 27 September 1996 on ambient air quality assessment and management and its three subsidiary directives (1999/30/EC, 2000/69/EC and 2002/3/EC), in which threshold values for SO_2, NO_2, NO_x, and PM10 as well as further gaseous air pollutants had been given. Accordingly, in the entire EU, up to now no directives exist that set threshold values for climate-forcing aerosols such as short-lived black carbon. Threshold values exist only for PM10 and PM2.5, and it must be stated that so far no definite connection with temperature warming is known for this type of aerosol (Kuttler 2011).

◀ *Figure 2.15-2: Locations of the 19 stations of the GUAN network. The colours indicate the category of the sites: red = traffic, orange = urban background, green = rural background, light blue = alpine surrounding. (Source: UBA)*

Measurements in Germany

In addition to observing particle size distributions, continuous measurements of soot concentrations have been carried out within the framework of the German Ultrafine Aerosol Network (GUAN) at 19 different sites in Germany since October 2008 in order to determine ultrafine particles (UFP) and investigate the chemistry of aerosols. The GUAN network was established by the Leibniz Institute for Tropospheric Research (TROPOS) on behalf of the Federal Environment Agency (UBA) for the purposes of a project to determine the representative exposure of the population to fine and ultrafine particles. Numerous measurements of BC are furthermore made within the networks operated by the German federal states. In addition to measuring BC in Germany, continuous nephelometer measurements are carried out at both sites of the GAW global station Zugspitze/Hohenpeissenberg to record forward and backward scattering from aerosols at three wavelengths. Those data also serve for determining single-scattering albedo, which can be used to detect transport events of volcanic ash or Saharan dust. Elemental carbon as well as organic carbon have been measured by the UBA since June 2011 at the GAW regional stations Schauinsland and Neuglobsow as well as at the UBA's own measurement sites Schmücke and Waldhof. PM10 and PM2.5 concentrations in ambient air are measured in Germany at the three official GAW measurement sites Neuglobsow, Schauinsland and Zugspitze and at all other stations of the UBA's air measurement network (Westerland, Zingst, Waldhof and Schmücke). PM10 and PM2.5 are also measured in the air-quality monitoring networks of the German federal states at more than 370 stations, most of which are situated in more densely populated or urban areas.

International context

The GUAN observation network is part of the air monitoring programmes and projects that exist in Europe and are continuously developed further. These include the European Monitoring and Evaluation Programme (EMEP), the project European Supersites for Atmospheric Aerosol Research (EUSAAR) as well as the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS). Provided that the given guidelines for data access and restrictions of use are respected, GUAN data can be retrieved from the EBAS database of the Norwegian Institute for Air Research (NILU; see link at the end).

Required resources

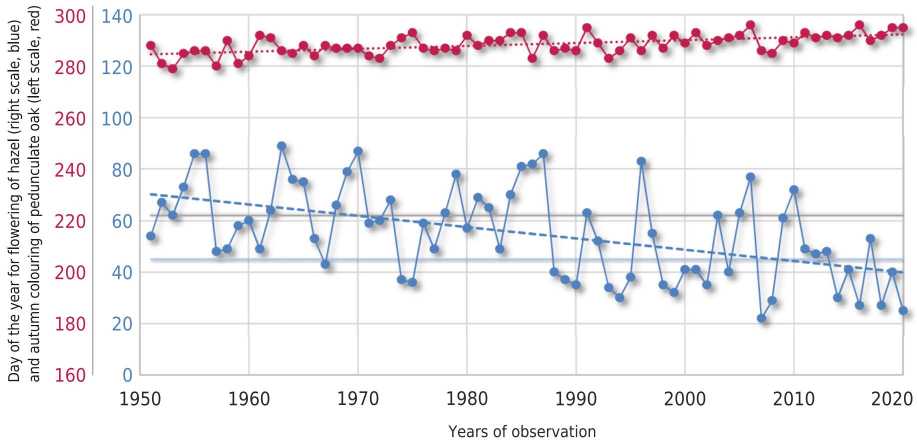
From 2008 until the end of 2013, the GUAN network was financially supported by the Federal Ministry for the Environment (BMU). At present, the stations are self-financed by the institutions by which they are operated. Accordingly, long-term continuity of the measurements is not secured, although this would be necessary and sensible because of the increasing interest in BC and UFP concentrations. However, the funding of current nephelometer measurements is secured permanently by the UBA and the Deutscher Wetterdienst (DWD), the funding of PM10 and PM2.5 measurements by the German federal states.

ebas.nilu.no **wiki.tropos.de/index.php/GUAN**

2.16 Pollen

Around 20 million people in Germany suffer from pollen allergies. This is about one quarter of Germany's total population, with a tendency to further increase. Pollen production and release by plants are decisively influenced by the weather with all its complex characteristics. Long-term continuous observation and analysis of pollen concentrations in the atmosphere, together with model calculations of amounts of pollen released, make it possible to identify possible shifts in the pollen season, changes in the counts of pollen or the occurrence of new types of pollen.

Onset of flowering of hazel and autumn colouring of pedunculate oak in Germany since 1951



▲ *Figure 2.16-1: Onset of flowering of hazel and autumn colouring of pedunculate oak in Germany since 1951 serve as indicators for the beginning and the end of the vegetation period, respectively. The consequence of a prolonged vegetation period is that the pollen season is also getting longer. (Source: DWD)*

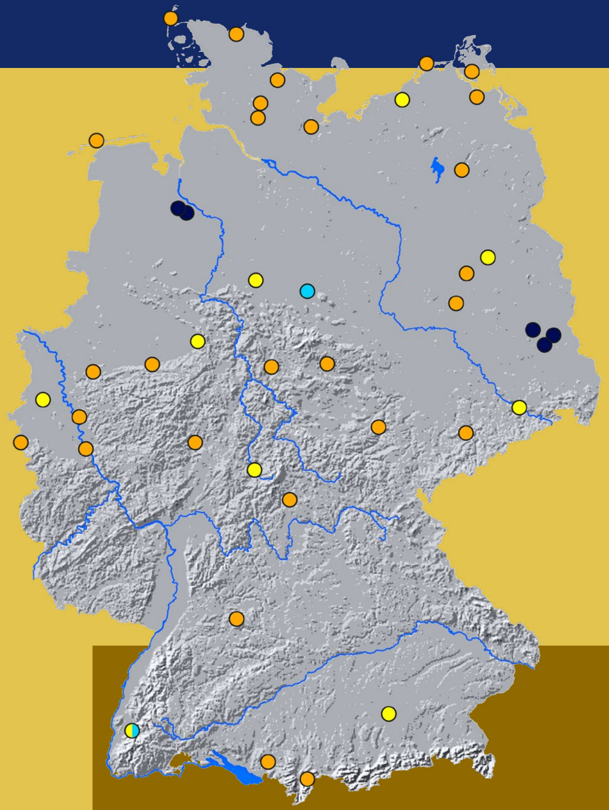
◀ *Photo 2.16-1: Male inflorescences of hazel*

Climate signals

Climate change is prolonging the vegetation period, and with it also the duration of the pollen season. An indicator for this is the period between the onset of flowering of hazel (pre-spring) and the onset of autumn colouring of pedunculate oak (late autumn). Based on this, the vegetation period for 1991 – 2020 is on average three weeks longer compared to the period 1961 – 1990 (Figure 2.16-1). The largest changes are observed in spring.

In addition to the advancement of the pollen season, observations show a trend towards increased pollen concentrations for certain plants (e.g. hazel, birch, ragweed). One reason, among others, is the increase in CO_2 concentrations and in temperature (Kaminski and Glod 2011, Augustin et al. 2017).

The global warming also leads to a shift in vegetation zones and changes in the range of plants. Plants that are adapted to cold climates could lose ■ ■ ■



◄ *Figure 2.16-2: Pollen monitoring network of the German Pollen Information Service Foundation (PID). The DWD (light blue dots) operates a pollen monitoring site at the ZAMF in Braunschweig and one of the reference sites (yellow dots) in the PID network. The latter is located at the DWD's ZMMF in Freiburg, where the pollen forecasts are produced. The network also includes seasonally operated stations (orange) as well as stations operated by co-operating partners (dark blue). (Source: DWD)*

Photo 2.16-2: Ragweed, a highly allergenic plant ►

Measurements in Germany

Concentrations of major airborne pollen have been measured in Germany since the mid-1980s. At present, the network of the German Pollen Information Service Foundation comprises around 35 stations. Ten of these monitoring sites are »reference stations«, at which pollen data are analysed throughout the whole year. All monitoring sites are equipped with Hirst pollen traps, with uniform operating procedures for the preparation and evaluation of the samples. The Deutscher Wetterdienst (DWD) has been publishing pollen forecasts for Germany since 1986. The forecasts consider the eight most allergenic pollen species: hazel, alder, ash, birch, grasses, rye, mugwort and ragweed. Publication of pollen forecasts starts with the first occurrence of hazel and alder pollen, usually in January (or possibly as early as December depending on the weather conditions). They are issued until about the middle of October when ragweed has stopped releasing pollen. The pollen forecasts are available on the website and open data servers of the DWD and are distributed by newsletter as well as through the DWD's GesundheitsWetter app.

By now, there are several automated pollen monitoring systems available on the market. The Free State of Bavaria, for instance, operates a measuring network consisting of eight automatic pollen monitors. At present, the DWD is running tests to verify the operational suitability of the systems available on the market.

their habitat whereas thermophilous plants will probably expand further. An example is ragweed, which is a highly allergenic species and has already become established in several areas in Germany (Cunze et al. 2013, Lake et al. 2017). Other plants, such as olive, pellitory or cypress, which are among the main allergy triggers in the Mediterranean region, could equally come into greater focus. Continuous monitoring of pollen occurrence is therefore extremely important.

Legal framework

According to Section 4 of the Deutscher Wetterdienst Act (DWDG), one of the tasks of the DWD is to provide meteorological services for the general public as well as for individual customers and users in the field of public health. Apart from conducting pollen measurements at own sites, the DWD uses data it buys from the German Pollen Information Service Foundation (Stiftung Deutscher Polleninformationsdienst, PID). Daily pollen forecasts are created at the DWD's Research Centre Human-Biometeorology (ZMMF) in Freiburg based on pollen data as well as meteorological and phenological observations in combination with numerical pollen forecasts (ICON-ART).

International context

As pollen dispersal does not respect national borders, international data exchange is required. For this purpose, the European Aeroallergen Network (EAN) was established in 1988. The EAN database includes pollen data from more than 400 active pollen monitoring sites across Europe and 300 more sites for which historical data records are available. All the data are available for research purposes and provide valuable information about the spatial and temporal development of pollen concentrations in the air over Europe.

The AutoPollen programme of EUMETNET is aimed to define international standards for automatic pollen monitoring as well as minimum location requirements in order to ensure international comparability of pollen data. The DWD participates actively in the work of this programme.

◀ *Photo 2.16-3: Change of the drum from the pollen trap on the roof of the DWD branch office in Freiburg for analysing the pollen collected*

Required resources

The DWD operates two pollen monitoring stations, one at the ZMMF in Freiburg, the other at its Agrometeorological Research Centre in Braunschweig (ZAMF). The ZMMF site in Freiburg also serves as a reference monitoring site in the PID network, which means that pollen concentrations are measured all year round and that the data are passed on to the PID without charge. The vast majority of manual pollen monitoring sites are operated in the context of medical institutions. Ensuring the fail-safe operation of these sites depends on external conditions that are difficult to influence. Due to the high significance of pollen monitoring data, a guaranteed basic funding of the pollen network would be useful to ensure continuity of high-quality measurements. As manual evaluation requires a high level of human resources, the DWD aims to establish an automated pollen monitoring network for the whole of Germany as soon as suitable devices are commercially available.

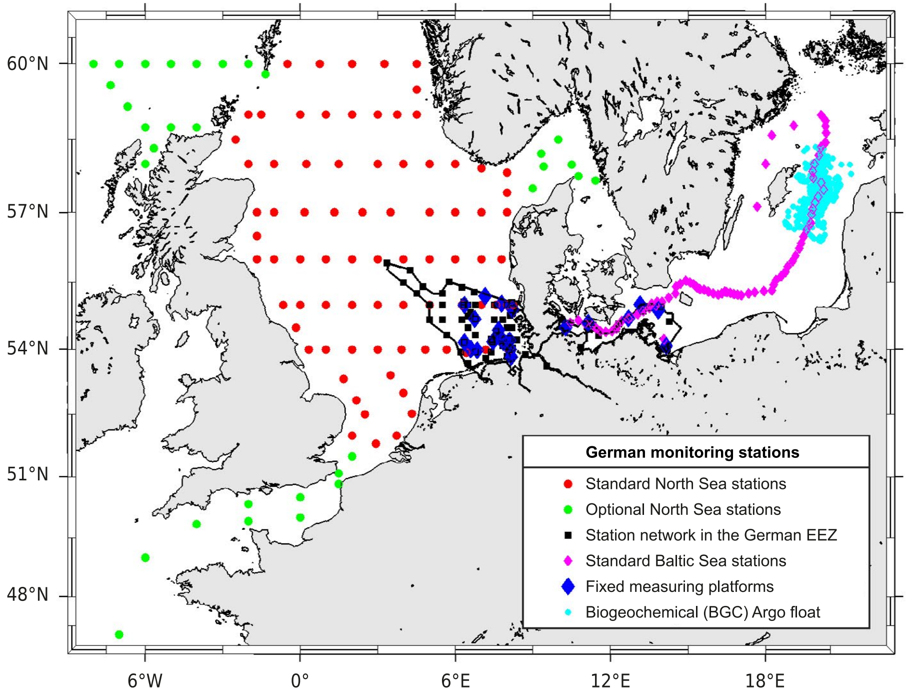
dwd.de/pollenflug **pollenstiftung.de**

3 Ocean observations

3.0 Impact of global warming on the oceans

Oceans and coastal waters are important components of the Earth's climate system. This is evident from the fact that the oceans have absorbed about 90 % of the additional heat caused by the anthropogenic enhancement of the greenhouse effect. In coastal areas, we humans can directly observe the impacts of climate change in the form of sea level rise, ocean acidification and changes in coastal ecosystems. Within the framework of the Global Climate Observing System (GCOS), German climate observations are carried out in the North and Baltic Sea with a special focus on the German Exclusive Economic Zone (EEZ) as well as in the open ocean.

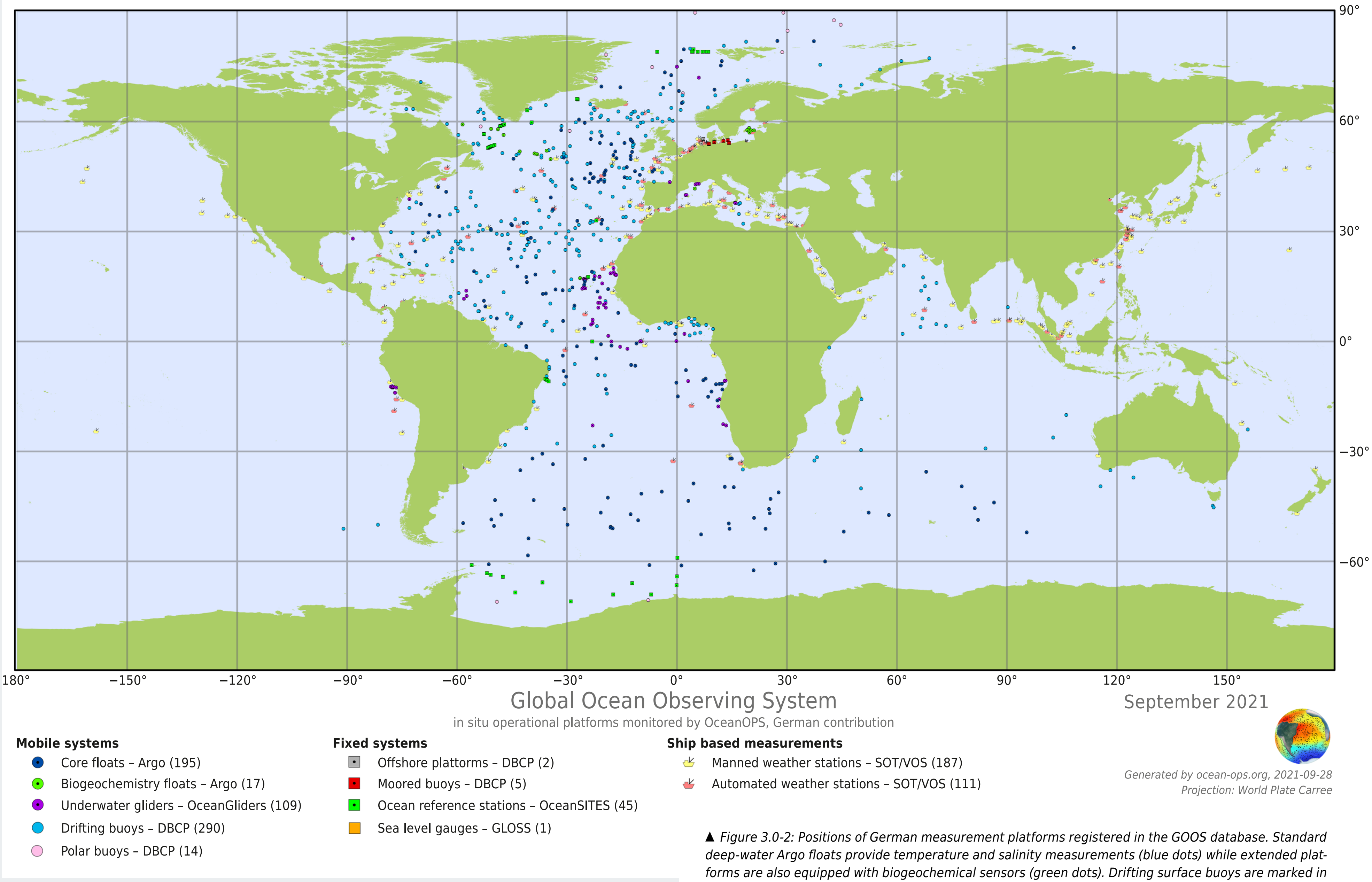
German monitoring stations in the North and Baltic Sea



▲ *Figure 3.0-1: Stations in the North and Baltic Sea with regular sampling intervals. Circles indicate stations where samples are taken yearly (red) as well as stations with longer intervals between visits (green). At stations belonging to the network in the German EEZ (black outlines and squares), samples are taken up to five times a year. The network is complemented by further monitoring stations in the Baltic Sea (magenta). In the Baltic Sea, an BGC-Argo float provides additional information on biogeochemical parameters (cyan). Blue diamonds indicate fixed measurement platforms, such as the research platforms in the North Sea (FINO stations) or the measurement buoys of the Marine Environmental Monitoring Network in the North and Baltic Sea (MARNET). These stations record time series of hydrographic and chemical parameters as well as the sea state. Not all stations record all parameters. (Source: BSH)*

Coverage, sustainability and context within GCOS

Monitoring programmes consisting of long-term observations in the North and Baltic Sea are carried out mainly by the Federal Maritime and Hydrographic Agency (BSH). In the Baltic Sea, the monitoring activities are supported by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW), which covers large parts of the range (Figure 3.0-1). The spatial measurement coverage and the range of observed variables are further improved in close ■ ■ ■



▲ *Figure 3.0-2: Positions of German measurement platforms registered in the GOOS database. Standard deep-water Argo floats provide temperature and salinity measurements (blue dots) while extended platforms are also equipped with biogeochemical sensors (green dots). Drifting surface buoys are marked in blue and pink. The German contributions include reference moorings at fixed locations (green squares), moored buoys and offshore platforms (red and grey squares) as well as missions with underwater gliders (purple dots). (Source: DWD, modified from OceanOPS)*

co-operation with university and non-university research institutes. In addition, there are a station measuring the sea state (operated by Schleswig-Holstein's Government-owned Company for Coastal Protection, National Parks and Ocean Protection (LKN.SH)) and the Bunkerhill station (operated by the Helmholtz-Zentrum Hereon).

EEZ observations are embedded in European initiatives and also contribute to the Marine Strategy Framework Directive (MSFD).

Most of the observations in the open ocean are carried out via research projects. An exception is the German contribution to the Deep Argo array, which receives permanent funding from the BSH as well as from the Federal Ministry for Digital and Transport (BMDV).

Regardless of the type or the length of the observation activities' funding, it is necessary to ensure the availability of the data for GCOS. At a national level, data sets are collected at the PANGAEA® data centre and at the German Oceanographic Data Centre (DOD), which exchange data with European data portals, such as SeaDataNet, the European Marine Observation and Data Network (EMODnet), the Copernicus Climate Change Service (C3S) and the Copernicus Marine Service (CMEMS).

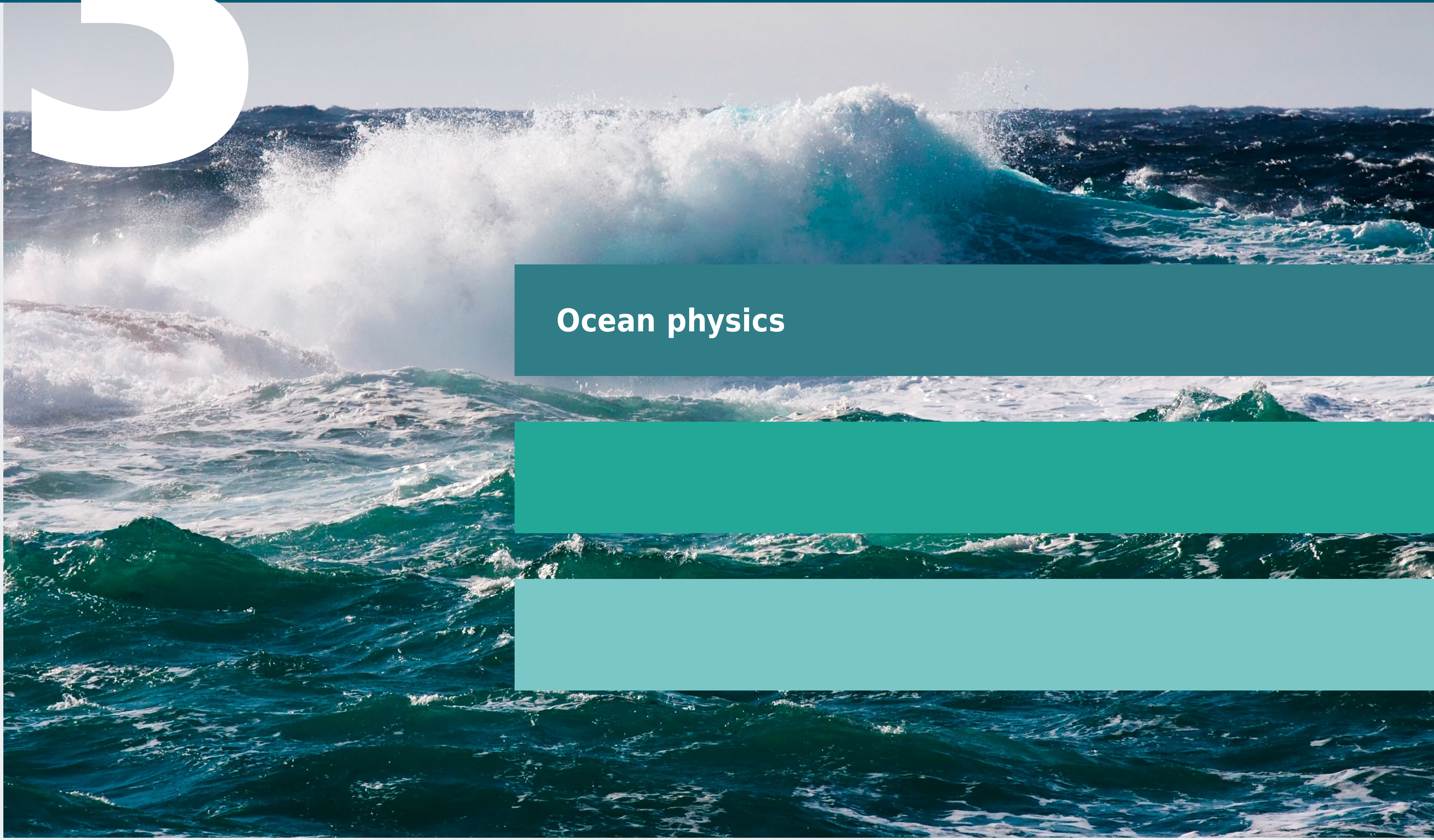
Networks and continuity of all required data sources can be harmonised through the individual co-ordination groups of the Global Ocean Observing System (GOOS). This, in turn, also ensures the connection with the climate observation system of the World Meteorological Organization (WMO), the WMO Integrated Global Observing System (WIGOS). The co-ordination groups include the operators of observation platforms (ships, autonomously drifting and navigating systems, moored systems, see Figure 3.0-2). A summary of the contributions of nations participating in GOOS and GCOS is available at a web portal (ocean-ops.org), which also serves as the basis for the yearly published GOOS Ocean Observing System Report Card.

◀ *Photo 3.0-1: Deck of the FS METEOR during preparations for the deployment of a time series station in the North Atlantic*

bsh.de/EN/DATA/Climate-and-Sea/Oceanographic_Data_Center/oceanographic_data_center_node.html

pangaea.de **emodnet.ec.europa.eu** **seadatanet.org** **climate.copernicus.eu** **marine.copernicus.eu**

3 Ocean observations

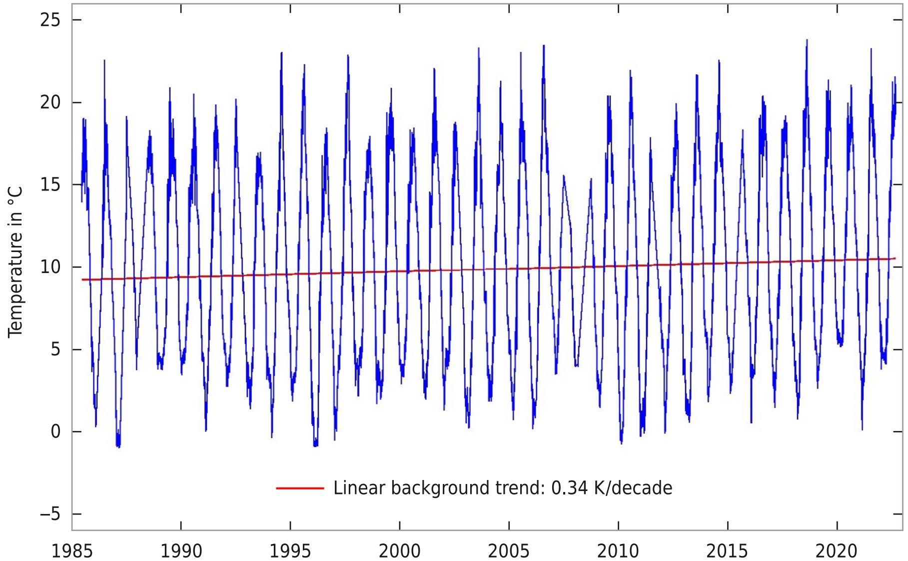


Ocean physics

3.1 Sea surface temperature

Temperatures at the sea surface are determined locally by latent and sensitive heat fluxes, mixing processes and the radiation balance. Large-scale currents can cause horizontal and vertical advection. However, most of the time, the sea surface is in near thermal equilibrium with the adjacent atmospheric layer, thus reflecting the seasonal fluctuation in temperatures. This allows an estimation of the temperature climate and its changes.

Sea surface temperature at 1 m depth at MARNET station LT Kiel (1985–2022)



▲ *Figure 3.1-1: Time series of sea surface temperatures from 20.06.1985 to 31.08.2022 at 1 m depth at the MARNET station LT Kiel, with adjusted linear background trend of 0.34 K/decade. At the depths of 0.5 m, 2 m and 4 m, the adjusted trends in the time series at this station are 0.5 K/decade, 0.35 K/decade and 0.30 K/decade, respectively. (Source: BSH)*

◀ *Photo 3.1-1: A drifting surface buoy at the beginning of its mission, usually lasting several years, during which it will take measurements of air and water temperatures, air pressure and currents, and transfer them onshore via satellite*

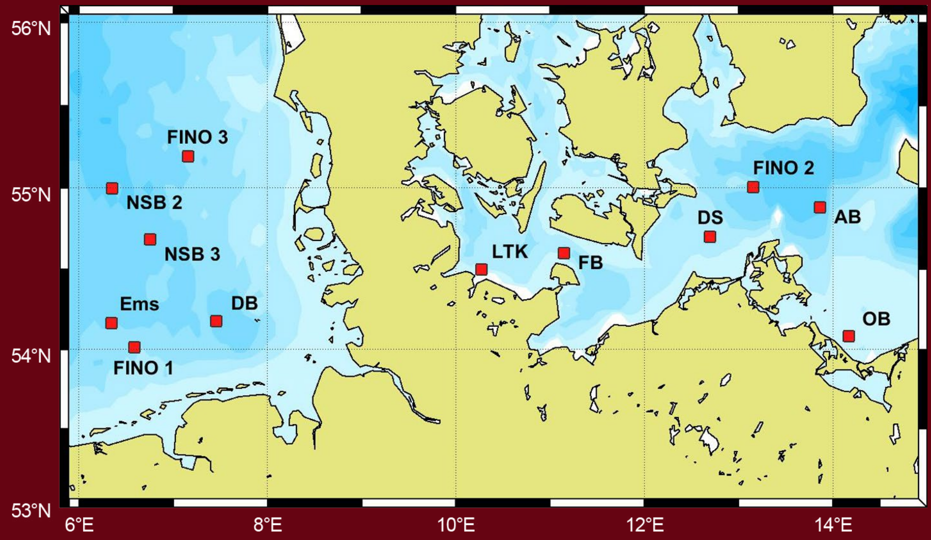
Climate signals

Depending on the temporal resolution, sea surface temperatures are mainly dominated by their seasonal cycle, in addition to the diurnal cycle (see Figure 3.1-1). This periodic natural variability is superimposed on the significantly smaller climatic changes, which consistently lead to increased temperatures. In the simplest case, the background trend is assumed to be linear. In line with this, the assumed trend for the whole of the North Sea is an increase of +0.3 K/decade for the period from 1969 to 2008 (Löwe 2009). For the German Bight, the estimated increase is at +0.4 to +0.5 K/decade during the period from 1983 to 2012 (Quante and Colijn 2016). Between 1990 and 2018, satellite data show a trend of +0.59 K/decade for the whole of the Baltic Sea (Siegel and Gerth 2019). For the south-western area of the Baltic Sea, the increase in temperature between 1990 and 2008 is ■ ■ ■

estimated to be around +0.7 K/decade (Lehmann et al. 2011). However, since the temperatures do not increase steadily, these figures always depend considerably on the time period chosen, in addition to the region and the method applied, and are therefore not always directly comparable. In the south-western Baltic Sea, for example, a linear trend of +0.06 K/decade has been found between 1856 and 2005 while the trend for the period 1978 to 2007, estimated based on the same data set and the same method, is roughly ten times larger (Kniebusch et al. 2019). This shows that the assumption of a linear background trend is a gross simplification, which only describes the average temperature increase in the time period under consideration. However, if a suitable reference period is chosen, extrapolation can provide a simple forecast of the evolution in the near future.

Where are the measurements taken?

Sea surface temperatures of German coastal waters are measured by the Federal Maritime and Hydrographic Agency (BSH) and, at the regional level, by the respective agencies in the federal states in accordance with their statutory tasks. In the context of climate research, the BSH's most important contribution are near-surface measurements conducted at the stationary platforms of the Marine Environmental Monitoring Network in the North Sea and Baltic Sea (MARNET, see Figure 3.1-2). The resulting high-resolution stationary time series are especially suitable for research purposes. Other regular stationary measurement activities take place under the responsibility of the various federal-state agencies, however at a much lower and thus less representative temporal resolution. On top of station data, the BSH produces surface temperature data sets from ship-borne measurements. These are taken at fixed locations during regular environmental monitoring cruises three to four times per year as well as by flow measurements when cruising between these locations. In addition, research institutes also provide surface temperature data sets, first of all those resulting from FerryBox data regularly collected by commercial ships on almost identical routes. The German Maritime Search and Rescue Service (DGzRS) also publishes daily sea surface temperatures from its staffed coastal stations. Further important sources of sea surface temperature data are the Voluntary Observing Ships (VOS) of the World Meteorological Organization (WMO), whose measurements are redistributed via the WMO-operated Global Telecommunication System (GTS), and satellite measurements, for example from NOAA satellites. These two data sources are used to produce, among others, the weekly BSH charts of sea surface temperatures. This product, however, is not the result of an exclusively German measurement programme.



◀ *Figure 3.1-2: MARNET measurement stations in the North and Baltic Sea. FINO 1, 2 and 3 are the names of the three research platforms in the North and Baltic Sea. NSB 2 and 3 refer to the two buoys operated in the North Sea. The other abbreviations stand for the two light vessels Ems (Ems) and Deutsche Bucht (DB), the measurement station at Kiel lighthouse (LT Kiel) and the measurement stations in the Fehmarnbelt (FB), at the Darsser Schwelle (DS), in the Arkona Basin (AB) and on the Oderbank (OB). (Source: BSH)*

International context and access to data

Essential parts of the captured sea surface temperature data are collected and distributed by the North West Shelf Operational Oceanographic System (NOOS) and the Baltic Operational Oceanographic System (BOOS), which both are regional alliances, referred to as Regional Operational Oceanographic Systems (ROOS), of the European component of the Global Ocean Observing System (EuroGOOS) and of GOOS itself. Through this, the activities are indirectly linked to GCOS. Given their availability in the Copernicus Marine Service (CMEMS), these data also feed into the work of the European Environment Agency (EEA) and, where not supplied directly, into reports for the Marine Strategy Framework Directive (MSFD). As part of Germany's obligations as a contracting party, the data of the respective monitoring positions in the North and Baltic Sea are also supplied to the OSPAR Commission and to the Baltic Marine Environment Protection Commission (also known as Helsinki Commission or HELCOM) for their assessments of the state of the environment. At a global level, especially the sea temperature measurements distributed via GTS feed into climate-relevant data sets, for example the International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

According to the EU's Open Data Directive, sea temperature measurements taken by the BSH and the federal-state agencies in their capacity as public bodies are freely available. The measurements feed directly into public data portals, for example the BSH's own infrastructure for marine-related data, which is part of the Spatial Data Infrastructure Germany (GDI-DE), which in turn is a component of the European Union's Infrastructure for Spatial Information in Europe (INSPIRE). In addition, some data, especially the MARNET station data, are also collected operationally via NOOS and BOOS and thus become available on the European data portals of CMEMS, the European Marine Observation and Data Network (EMODnet) and SeaDataNet. Data distributed via GTS are also freely available and used globally in many different ways. Due to the free availability and wide dissemination of the data, it is difficult, apart from the data collectors as first users, to capture the range of the users of sea surface temperature data; it is also not specified in any more detail at the time of the data's publication.

▲ *Photo 3.1-2: The German research ship MARIA S. MERIAN approaching parts of a long-term mooring in the Labrador Sea. The sensors are raised once a year for maintenance. In addition, a wide range of ECVs are measured on board of the ship.*

Where do the resources come from?

Under the Maritime Shipping Responsibilities Act (SeeAufgG), the Federal Maritime and Hydrographic Agency (BSH) has a legal obligation inside the German Exclusive Economic Zone (EEZ) to monitor the state of the marine environment. This includes in particular sea surface temperatures. The BSH fulfils this task by carrying out regular monitoring cruises and by taking stationary measurements at fixed platforms. Both of these activities are therefore fixed components of the BSH budget. The same applies for the operation of the nautical and hydrographic services. With the coastal monitoring activities of the federal-state agencies being part of their tasks, the funding of these activities is also secured, in this case by the agencies' budgets.

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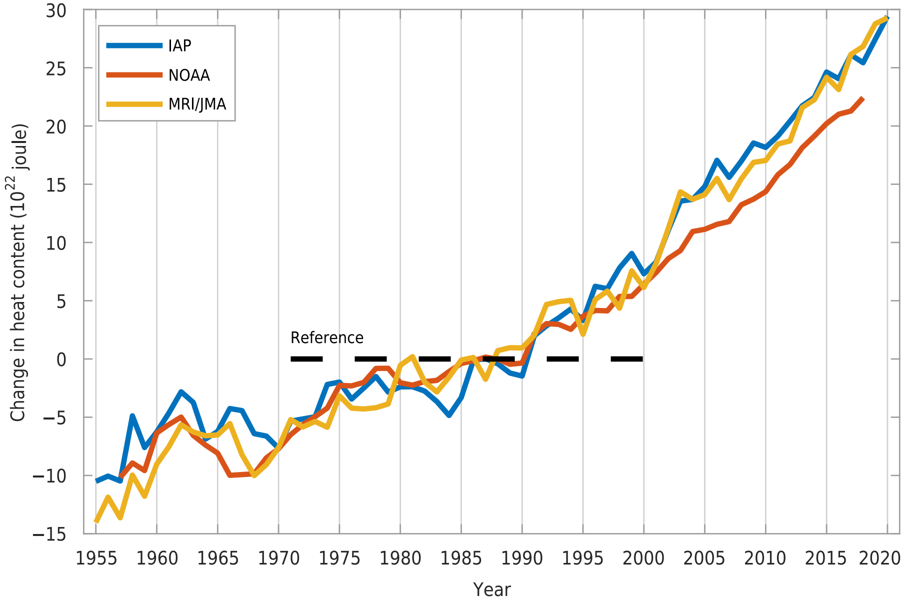
3.2 Temperature in the water column

Temperature is of fundamental importance for describing physical and chemical parameters of the ocean. It seriously affects the density of ocean water, general circulation patterns as well as the sea level, and serves as a control parameter for ecosystems. Measurement series of temperature allow statements to be made about the state of the climate and make it possible to determine the interrelations between terrestrial, atmospheric and oceanic processes. For climate assessments at both the national and global level, it is therefore most important to assure the continuation of long time series. The Essential Climate Variable (ECV) Temperature is required for determining other ECVs.

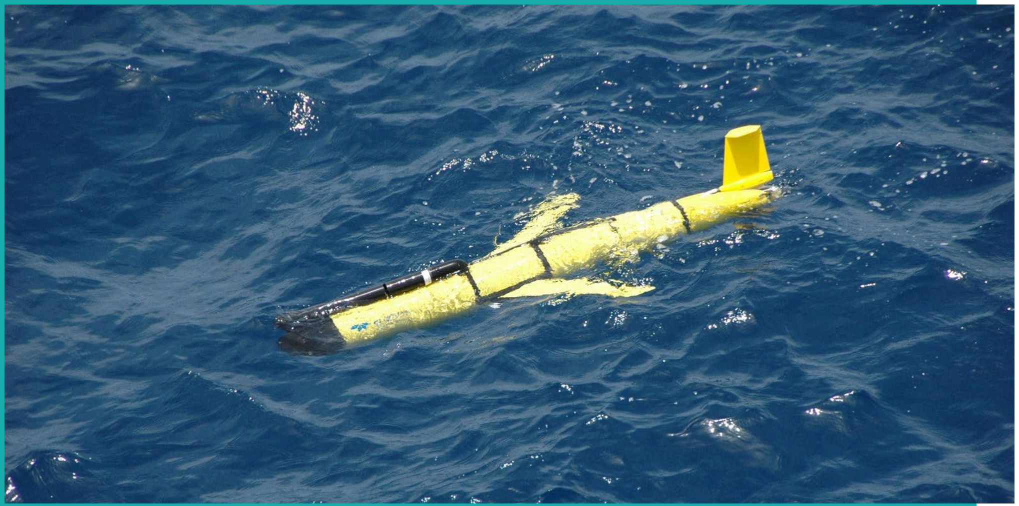
Heat content of the upper 2,000 m of the world's oceans (1955–2020)



▲ *Figure 3.2-1: Change in the heat content of the upper 2,000 m of the world's oceans in the period from 1955 to 2020 compared to the 1971–2000 mean (set as zero baseline). The ocean heat content is measured in joule, a measurement unit for energy. (Source: GEOMAR, modified from EPA)*

Climate signals

The oceans have absorbed about 90 % of the additional heat accumulated in the Earth system as a result of human activity. The warming affects the thermal expansion of sea water and thus the ECV Sea level. Regionally, the warming can lead to the melting of sea ice and to changes in the stratification of the ocean. This in turn affects ocean ventilation and marine organisms. Clear trends towards warming are identifiable in almost all marine and coastal regions and the influence on ecosystems, for example, can be clearly demonstrated. ▪▪▪



◀ *Photo 3.2-1: A glider sending measurements from its successful dive for transmission via satellite. During its months-long missions, a glider measures vertical profiles of a multitude of ECVs at hourly intervals down to a depth of 1,000 m.*

...

If one combines observation data from different sources, the resulting diagram reveals a marked increase in global ocean temperature, expressed in terms of ocean heat content, since the mid-1980s (Figure 3.2-1). The curves on the graph represent the data resulting from the calculations independently run by three different government institutions, namely the US American National Oceanic and Atmospheric Administration (NOAA), the Institute of Atmospheric Physics China (IAP) and the Meteorological Research Institute of Japan's Meteorological Agency (MRI/JMA) based on different methods. For better illustration, an increase of one unit in the diagram (1×10^{22} joule) corresponds to about 17 times the total energy consumption of the Earth's population in a year.

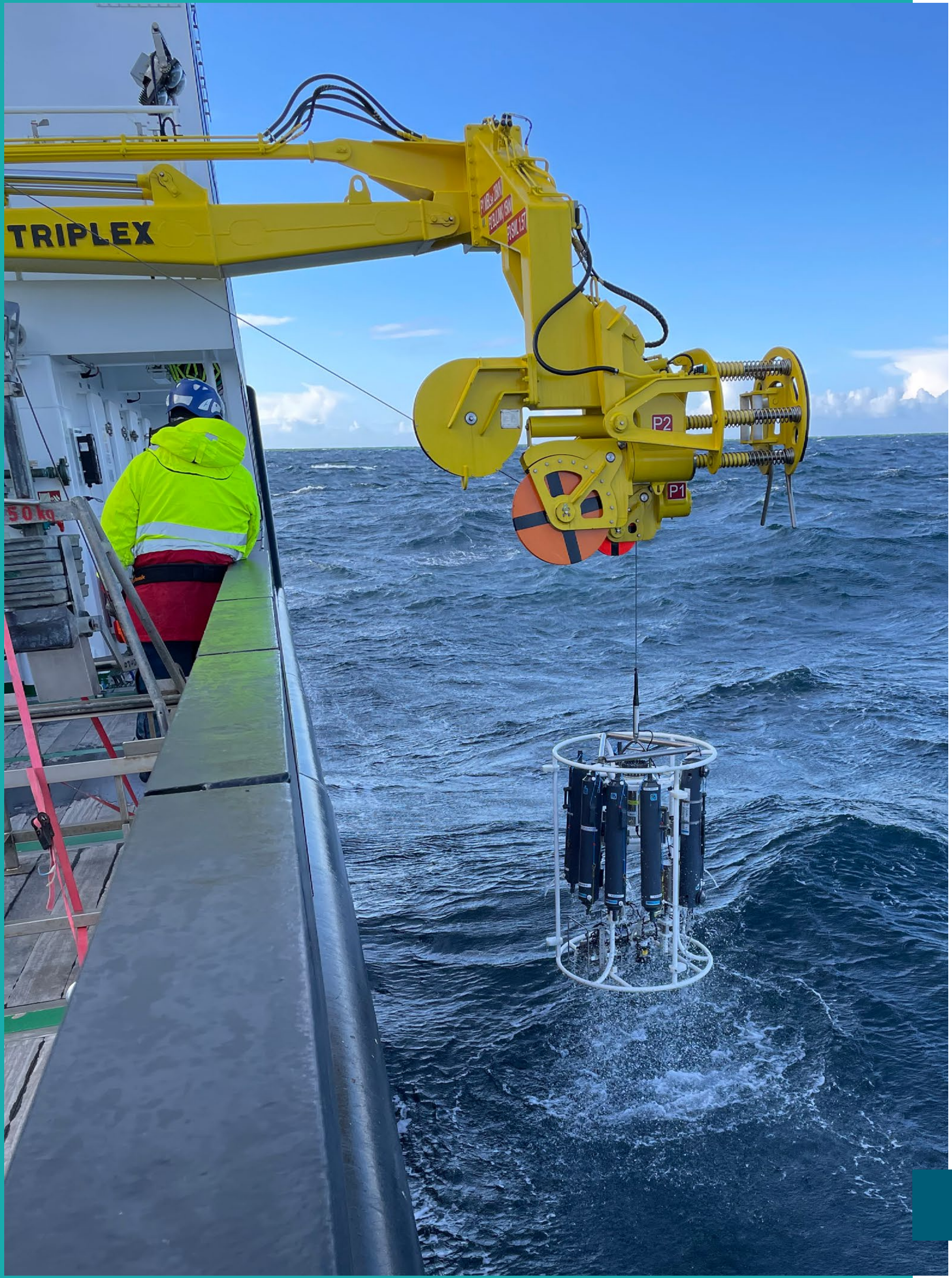
Where are the measurements taken?

Measurements of ocean temperature are carried out from ships and by autonomous as well as fixed platforms. The measurements are available in the form of vertical profiles and as point data. Since robust and cost-effective standard measurement methods are used, the measurement of temperature is included in almost all observation activities. For using temperature measurements for climate studies, it is important to have realistic estimates of measurement accuracy.

◀ *Photo 3.2-2: Launch of an Argo deep float into the sea. Once deployed for 3 to 5 years depending on the design, the float will collect vertical profiles of temperature and salinity from the surface down to a depth of 2,000 m as well as information about current flow at around 1,000 m down in the ocean every 10 days and transmit these to the global data centre for Argo. At present, the Argo observing network is being extended to measure biogeochemical variables and include applications for profiles down to a depth of 6,000 m.*

The network of measurements in the North and Baltic Seas (Figure 3.0-1) and in the open ocean (Figure 3.0-2) is complemented by measuring sites on the coast (harbour quays, piers/jetties, stilling wells), all together leading to the creation of long time series. During the monitoring cruises undertaken by the Federal Maritime and Hydrographic Agency (BSH) or its partners in the waters of the North and Baltic Seas, temperature profile measurements are analysed to derive metrics, for example seasonal variability, or long-term trends.

With regard to the open ocean, Germany provides important contributions to temperature measurements over the entire water column at regional and global level. An example is the monitoring of the ocean heat content. The heat content in the ocean is calculated from the ocean temperature and water depths. Changes in the heat content therefore provide more comprehensive information about climate warming in the ocean than sea surface temperature data as these do not allow any statements to be made about the depth of the warmed layers. In addition to measurements from ships, autonomous platforms, such as the globally operated deep floats of the Argo network, have become an essential pillar for heat content determination over the past 20 years. Germany's contribution to the Argo network consists in about 50 deep floats per year and is managed by the BSH. Determining the warming of the deep ocean requires high measurement accuracy and traceability to reference measurements. In this context, measurements along standard sections of the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) are of vital importance. GO-SHIP carries out surveys with a repeat rate of at least every decade. In addition, regularly calibrated sensors are anchored in key regions, where they register changes at very high resolution (< 1 hour). Co-ordination of the measurements takes place as part of the OceanSITES programme.



International context and access to data

Temperature measurements are archived by the German Oceanographic Data Centre (DOD) at the BSH and in the PANGAEA® database. From there, they can be retrieved via the data portals run by the German Marine Research Alliance (DAM) or the European Marine Observation and Data Network (EMODnet). If possible, the data are exchanged in near real time via the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO) for use in weather and ocean prediction models. Access to the data is also possible for the general public via various portals (see links at the end).

◀ *Photo 3.2-3: Profile measurement with a temperature/conductivity sensor returning aboard the surveying, wreck search and research vessel VWFS Atair*

Where do the resources come from?

Operation of the Marine Environmental Monitoring Network in the North Sea and Baltic Sea (MARNET) is a fixed component of the BSH budget. Ongoing BSH funding also includes provision for regular monitoring cruises and the operation of nautical and hydrographic services. In addition, with an own budget title allocated to it in the BSH's budget, participation in the international Argo programme is secured on a long-term basis. The contributions from the research institutes rely on project finance, which typically is limited to 3 to 5 years and, if continued in follow-up projects, can sometimes produce time series of several decades.

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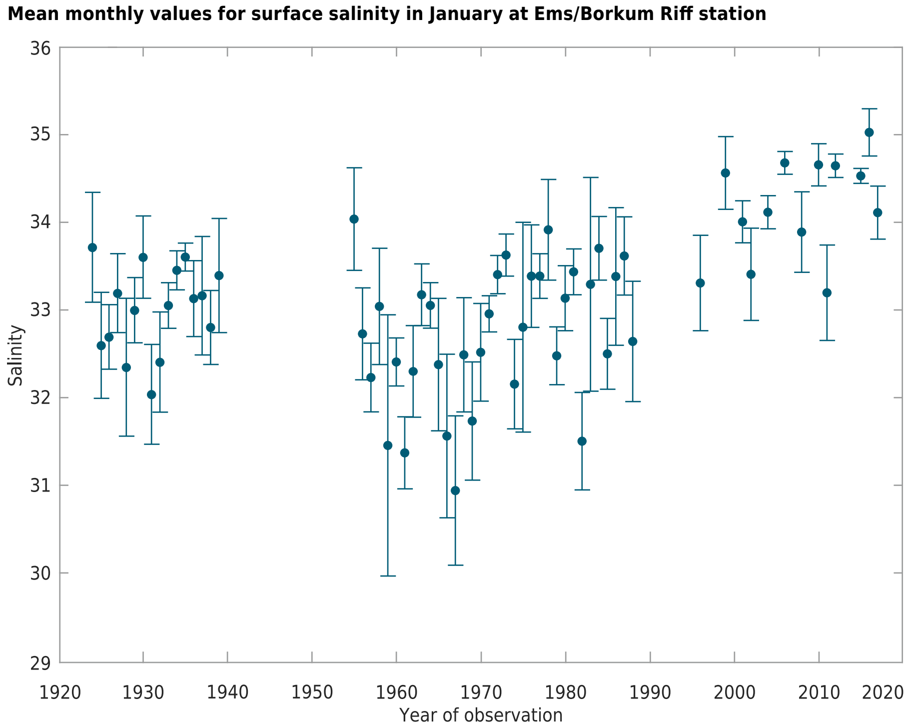
3.3 Salinity in the water column

The distribution of salinity in the ocean is closely linked to the global water cycle and ocean transport processes. Salinity, together with temperature and pressure, is the key variable for determining the density of seawater, which in turn controls ocean stratification and motion processes. Salinity data are used in many regional and global weather and climate applications. Measurements of salinity in the ocean have been taken for more than 100 years and with a relatively high degree of quality so that the resulting time series constitute a unique long-term archive for changes in the global water cycle and ocean circulation.

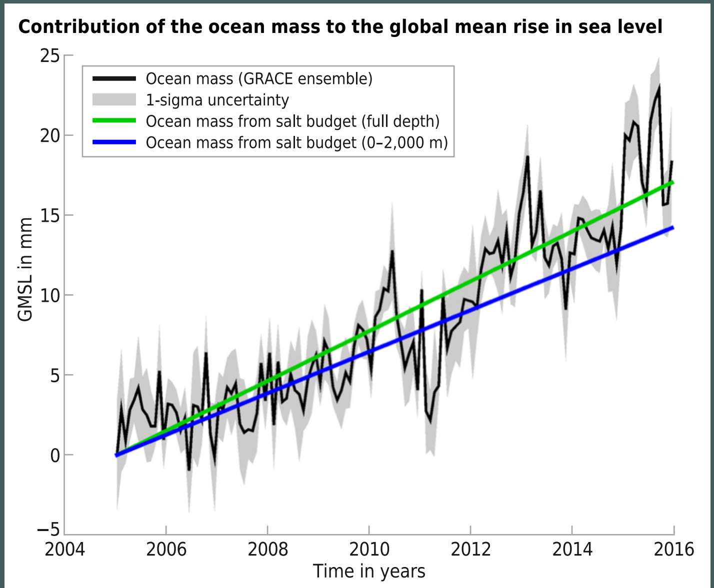


▲ *Figure 3.3-1: Ems/Borkum Riff station: monthly mean surface salinity for January from historical data (see link at the end) (Source: BSH)*

Climate signals

Comparatively long time series are available locally for for measurements in the German EEZ in the North and Baltic Seas. The sometimes high variability of near-surface salinity on short timescales at inshore stations, largely due to the influence of continental run-off, partly masks the determination of climatic trends. Helgoland Roads (sampled since 1873) and Ems/Borkum Riff (sampled since 1920) (Figure 3.3-1) are examples of decadal time series. In the Baltic Sea, the salinity in the water column indicates the efficiency of ventilation in the deep Baltic Sea through sporadic inflow events from the North Sea. These inflow events therefore have far-reaching consequences, for example for fisheries.

Thanks to international collaboration, signals could be extracted from data collected globally (ships and autonomous measuring platforms). They show, for example, changes in the hydrological cycle in response to global warming (see Figure 3.3-3). In addition, the decrease in salinity is a result of increased freshwater ■ ■ ■



◄ *Figure 3.3-2: Contribution of ocean mass to global mean sea level rise in millimetres derived from satellite data (Gravity Recovery and Climate Experiment (GRACE), black curve) and from analysis of salinity decrease in the global ocean (blue and green curves for 0–2,000 m and full depth). The shading indicates the 1-sigma uncertainty of each estimate. The curves are offset for clarity. (Source: BSH, modified from Llovel et al. 2019)*

Where are the measurements taken?

Salinity in the German Exclusive Economic Zone (EEZ) in the North and Baltic Seas is recorded by ship-based measurements taken during the monitoring cruises as well as by sensors permanently installed at long-term stations. Both these measurement series are part of the general marine monitoring activities of the Federal Maritime and Hydrographic Agency (BSH) and are carried out in co-operation with the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) within the framework of the MARNET partnership (see link at the end). The measurements are a continuation of those formerly taken on staffed weather ships. In addition, salinity data are collected by federal-state authorities as well as by research institutions of the coastal federal states of Germany; the collected data are archived in data centres. In recent years, data have also been collected from automatic measuring stations on offshore wind turbines.

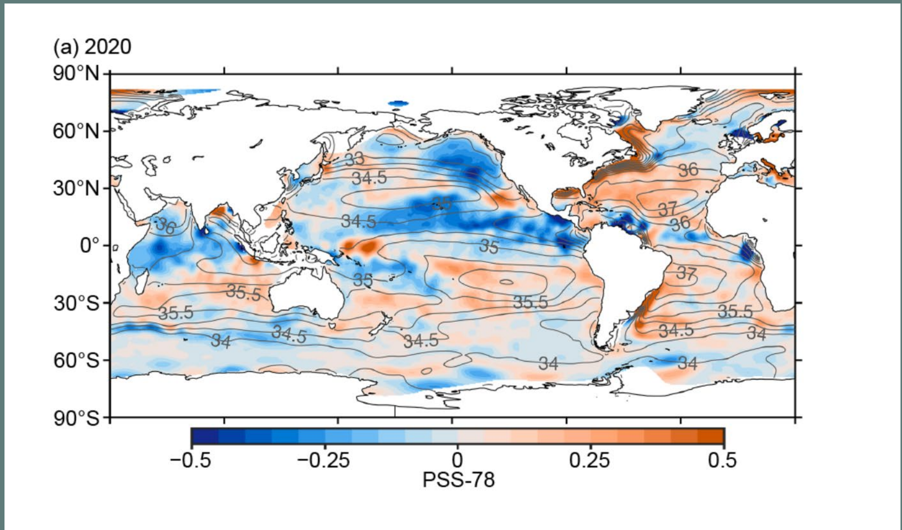
With the exception of the Argo array, the collection of salinity data outside the EEZ is performed purely in the interests of research. In principle, it is global and may also include long-term measurements (see Figure 3.0-2). To this end, ship expeditions and observation platforms operating autonomously (Argo floats, moorings, gliders) are used. There is a clear regional focus on the Atlantic, including the adjacent Arctic and Antarctic regions, but observations are also made in the Indian and Pacific Oceans. In the year 2000, Germany started contributing to the global Argo float programme, which now has approximately 4,000 floats throughout the world's oceans. The Argo floats are deployed for over four years. During this time, they also record the salinity distribution in the upper 2,000 m of the ocean. Germany contributes about 50 new Argo floats per year to maintain global measurement coverage.

■ ■ ■

input due to melting of continental ice, mountain glaciers and increases in river inputs. For example, these inputs lead to a net mass gain in the ocean, which is reflected in a rise in sea level (called the barystatic sea level change).

International context and access to data

The observations in the German EEZ listed here, as well as the global observations, are being collected both at the European level (North West European Shelf Operational Oceanographic System (NOOS), Baltic Operational Oceanographic System (BOOS) and Copernicus) as well as internationally through collaboration on portals (e.g. National Oceanographic Data Center (NODC) and PANGAEA®). In addition, collaboration takes place in various bodies (e.g. Global Ocean Observing System (GOOS), Global Climate Observing System (GCOS) and World Climate Research Programme (WCRP)) and in international observation networks, in particular in the Observations Coordination Group of GOOS/GCOS. ■ ■ ■



▲ *Figure 3.3-3: Surface salinity anomalies for the year 2020 in relation to the long-term climatological mean 1955–2012. From: Johnson, G.C., Lumpkin, R. (Eds.), 2021: Global Oceans. In: State of the Climate in 2020. Bulletin of the American Meteorological Society 102, 8, S143–S198, DOI: 10.1175/BAMS-D-21-0083.1, published 2021 by the American Meteorological Society. (Source: BSH, modified from Johnson and Lumpkin 2021)*

This group ensures the co-ordination of Argo deep floats, moorings (OceanSITES), ship expeditions (Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)) and glider measurements (OceanGLIDERS). A lot of research activities also take place within the framework of international alliances.

Links to selected data products on national and international websites are listed at the end of the article.

Where do the resources come from?

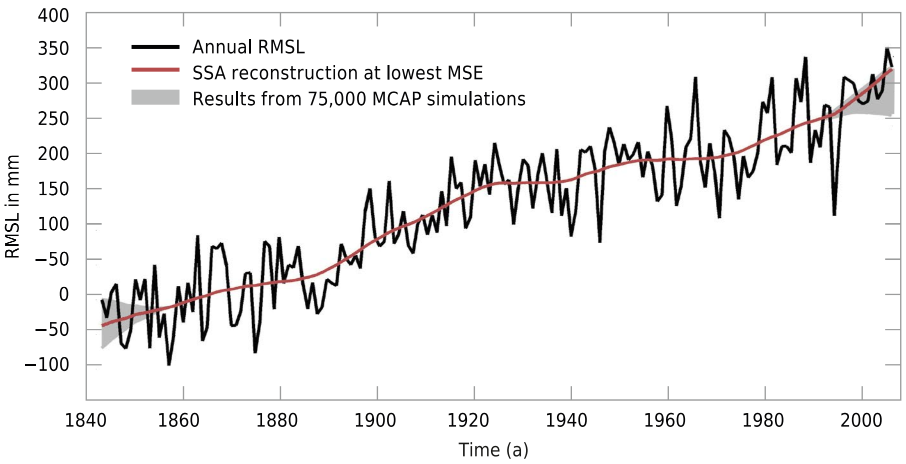
Operation of the permanent monitoring stations in the German EEZ requires a high level of organisational and human resources, which are provided through the BSH budget. With an own budget title allocated in the BSH's budget, participation in the international Argo float programme is secured on a long-term basis. The measurements in the EEZ and in international waters carried out by research institutes depend on project finance, which is naturally limited to a few years.

https://www.marine.csiro.au/~dunn/cars2009/
coriolis.eu.org
bsh.de/EN/DATA/Climate-and-Sea/Marine_environment_monitoring_network/marine_environment_monitoring_network_node.html
bsh.de/EN/DATA/Climate-and-Sea/Marine_environment_monitoring_network/Historical_time_series/historical_time_series_node.html

3.4 Sea level

Changes in the sea level provide an important indicator for changes in the climate of the Earth. The causes for climate-related sea level changes are complex and arise mainly from the interaction between thermal expansion of the water as it warms and any changes in the ocean water mass due to the melting of ice sheets and glaciers. Regional sea level changes can differ substantially from the global mean as a result of changing circulation patterns in the ocean, but especially because of vertical land movements resulting from the loss of terrestrial ice mass since the last ice age (glacial isostatic adjustment, GIA).

Synthetic time series of mean sea level (mm) in the German Bight (1843–2008)



▲ *Figure 3.4-1: The constructed time series is based on the high-quality, verified records from 13 selected tide gauge stations (Wahl et al. 2011). The graph shows the annual means (black) as well as the adjusted non-linear trend (red). The continuing sea level rise is relative to the land and takes account of the effects of uplift or subsidence. (Source: BSH, modified from Wahl et al. 2011)*

Climate signals

In view of the high internal variability in the sea level due to natural fluctuations in air pressure and wind forcing of ocean circulation, long-term measurement series are needed to derive statistically reliable data about anthropogenic sea level changes and exclude the influence of natural variability. For most regions, time series going back at least 50 years are required to properly take account of the ocean's natural decadal variability when analysing observations for trends (Haigh et al. 2009). Building on the results of the AMSeL project of the German Coastal Engineering Research Council (KFKI), under which the data from gauges along the German coastline were combined to a high-quality synthetic time series of sea level data in the German Bight, another KFKI project, MSL_absolut-A, was able to produce virtual time series of sea level in the North and Baltic Seas. Corrected by the relevant land motion, the time series show absolute rates of sea level rise along the coasts of Schleswig-Holstein of 1.9 mm/a (North Sea) and 1.6 mm/a (Baltic Sea), respectively, over the period 1900–2015. When looking at the period 1993–2015, however, the rates are as high as 3.2 mm/a ▪ ▪ ▪

(North Sea) and 2.4 mm/a (Baltic Sea), agreeing well with the data from satellite measurements. However, many of the existing individual time series are much shorter, which is why it is of the utmost importance to continue those measurements on a long-term basis. In addition, it is equally important to extend the length of the time series by digitising historical records from the archives in order to obtain a better regional resolution of sea level changes. This applies in particular to the continuation of sea level measurements using satellite altimetry and to the improvement of data sets existing for the coastal areas.

Where are the measurements taken?

Ensuring the safety of the German coasts requires a system of local tide gauge stations to be in place to monitor regional and local sea level changes. In addition, satellite altimetry observations of the sea level are required and the possibilities for their use for coastal areas need to be improved. Systematic sea level measurements that date back to 1843 come from the tide gauge station at Cuxhaven. While the older time series only contain coarsely resolved data of tidal high and low waters, modern tide gauges with digital recording technology offer high-resolution data at minute intervals. Today, tide gauge measurements are carried out by the German Waterways and Shipping Offices (WSA) and other regional authorities at 165 stations along the German North Sea coast and in the tidally influenced parts of the rivers. Over the years, measurement technology has changed continually, from staff gauges to floating gauges with graphical and digital recording, acoustic gauges through to pressure and radar gauges, all of which are still in use.

▲ *Figure 3.4-2: Locations of the tide gauges along the German coast and in the tidally influenced parts of the rivers (Source: BSH)*

Starting in the early 1990s, satellite altimetry technology has opened-up the possibility of global coverage of sea level observation by means of measurements from space. In the deeper parts of the oceans and areas outside the continental shelves, satellite-based observations allow the determination of sea level and its variability to an accuracy of one centimetre. Work to refine the methods and apply the data also in the context of coastal areas is still ongoing. New satellite altimetry observation technologies, such as the measurement methods applied by the Surface Water and Ocean Topography (SWOT) mission or as part of Synthetic Aperture Radar (SAR) techniques, can help to obtain improved observations of sea level changes especially for coastal areas.

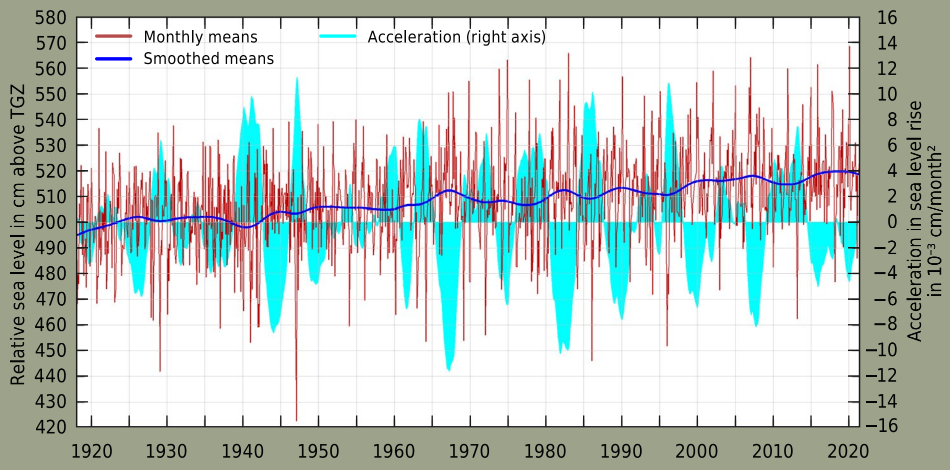
An important aspect of regional sea level analyses for the North Sea is the occurrence of land uplift and subsidence, which sometimes are an after-effect of the last ice age or could also be caused by regional gas and oil extraction. Post glacial large-scale uplift and subsidence of land are superimposed on local water level changes and mostly show linear trends on centennial scales. Vertical motion of land due to extraction, however, is momentary. It is superimposed by compensation movements in the ocean as a result of uplifts near Greenland or Antarctica, which can be felt as far as the North Sea.

To identify such processes, the Federal Institute of Hydrology (BfG) has begun to equip selected tide gauges with additional GPS antennas allowing direct measurements of land uplift and subsidence.

International context and access to data

Sea level measurements by means of tide gauges along the German coast are part of the international network of the Global Sea Level Observing System (GLOSS). GLOSS operates the network under the auspices of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission of UNESCO (IOC). The aim of GLOSS is to provide high-quality global sea level data for use in the fields of climate and coastal research. The core network comprises 290 stations worldwide. Germany contributes station data from the tide gauge at Cuxhaven. Access to the data of all German tide gauge stations (not only Cuxhaven) is possible via the database »Pegelonline«. The data of all 290 stations around the world are available in various modes (real-, near-real or delayed time) from the GLOSS website. Monthly updated trends and analyses of acceleration in sea level rise near Cuxhaven are published on the website of the Federal Maritime and Hydrographic Agency (BSH). Time series of satellite observations of global sea level rise and trend analyses derived therefrom can be found on the websites of Colorado University and of the US American National Oceanic and Atmospheric Administration (NOAA).

Relative mean sea level at Cuxhaven tide gauge (01/1918–07/2021)



▲ *Figure 3.4-3: Monthly means of the relative sea level (above TGZ, red) at Cuxhaven tide gauge from 01/1918 to 07/2021 including smoothed mean (dark blue) and acceleration rate of sea level rise (light blue) (Source: BSH)*

Where do the resources come from?

The monitoring of the marine environment in the North and Baltic Seas is regulated by the Maritime Shipping Responsibilities Act (SeeAufgG). However, a substantial part of the development and service work is still financed through national and international projects within the framework of university research. To secure the sustainability of such services, it is necessary to establish long-term funding. Satellite altimetry missions of the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) are indispensable for coastal protection and therefore need to be continued, including necessary investments in infrastructure. Sustained use of satellite altimetry in this context calls for sufficient funds to finance the further development of required applications.

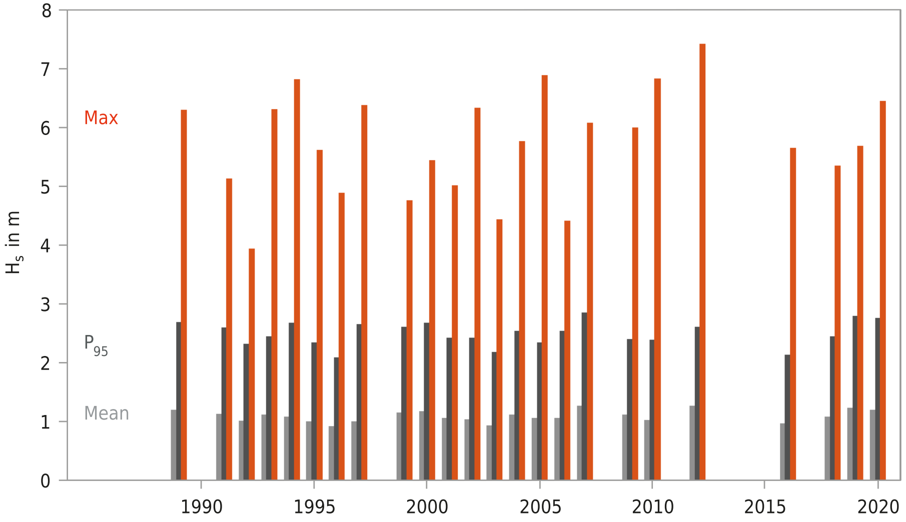
sealevel.colorado.edu/trend-map **star.nesdis.noaa.gov/socd/lsa** **pegelonline.wsv.de** **gloss-sealevel.org**

https://www.bsh.de/DE/THEMEN/Klima/Relativer_Meeresspiegel/relativer-meeresspiegel_node.html

3.5 Sea state

Sea state is the term used for the height of wind-generated waves on the sea surface. Changes in wind conditions and storm intensity have a direct impact on the sea state. It is thus not a primary indicator of climate change, but does play an important role for adaptation strategies in maritime transport and coastal defence as well as in the offshore industry.

Significant wave heights near Helgoland (1989–2020)



▲ *Figure 3.5-1: Annual averages (light grey), percentile P_{95} (significant) wave height not exceeded during 95 % of the year) (dark grey), maximum annual significant wave height (red). Due to data gaps, the latter figures do not necessarily reflect the annual maximum that has actually occurred. (Source: BSH)*

◀ *Photo 3.5-1: Wave-measuring buoy with flash light and antenna, 90 cm diameter*

Climate signals

Records of sea state observations by seafarers have existed since the middle of the 19th century. The beginning of systematic shipboard observations, however, dates back about 70 years. Many of the statistical analyses so far are based on such visual observations. However, long-term data series with a length comparable to that of atmospheric parameters do not yet exist for wave measurements. Current monitoring stations were established primarily for the benefit of shipping, pilotage services and coastal defence, but the data are also available for any interested stakeholders from research institutions and the industry. The statistical-climatological importance of these data series still lies mainly in the validation of numerical wave models and their results. Models, unlike the few monitoring stations, allow the generation of long, continuous and area-covering time series. However, measurements are required to record extreme events and particularly high, dangerous single waves. Some years of the Helgoland time series shown ■ ■ ■

Where are the measurements taken?

Reliable wave measuring technology did not exist until the 1960s. The longest German time series originate from Helgoland and Sylt stations. Beginning in 1989, they meet the 20-year criterion of GCOS for the minimum length of climatological time series. Other monitoring stations followed later: between 1990 and 2020, ten stations were put into operation in the North Sea, between 1991 and 2014 three more in the Baltic Sea. Almost 50 % of the stations are operated as part of research projects. Additional wave measurements are carried out by various federal-state authorities and by research institutions in the coastal area, mostly in connection with projects and using different instrumentation. In recent years, additional monitoring stations have been established in connection with offshore wind farms. Besides these measurements at the sea surface, remote sensing data from satellite radar altimeter operations have been available since the 1980s. Such global data are available from the European Space Agency (ESA) as part of the GlobWave project.

The monitoring stations shown in the map use elastically moored waverider buoys or wave radars. The measurement data are transmitted ashore by Ethernet and radio, in some cases via satellite. They are processed automatically and made available online in near real time. The data and selected data products can be downloaded from the Sea State Portal offered by the Federal Maritime and Hydrographic Agency (BSH) on their website (see link at the end of this article).

The measurements record the water surface displacement as well as the waves' energy spectrum. Based on these data, important wave parameters, e.g. significant wave height, mean wave period and wave direction, can be calculated by means of standardised procedures. The highest single waves are also recorded. The significant wave height is the mean height computed from the highest third of all single waves measured. Measurements were initially transmitted only every three hours, but data transmission is now possible every 30 minutes due to better data connections. This allows better detection of the sea state and, in particular, of extreme situations.

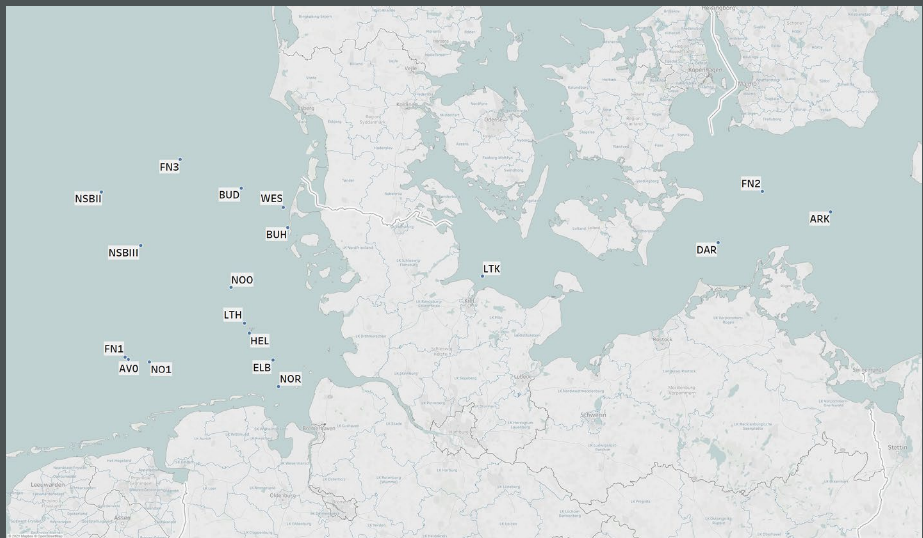


Figure 3.5-2: Positions of permanent wave monitoring stations in the German Bight and the western Baltic Sea. The station WES (Sylt) is run by Schleswig-Holstein's Government-owned Company for Coastal Protection, National Parks and Ocean Protection (LKN.SH), the station BUH (Bunkerhill) by the Helmholtz-Zentrum Hereon and all others by the BSH. (Source: BSH) ▶

■ ■ ■

in Figure 3.5-1 cannot be analysed statistically because of too many data gaps. Over the three decades, there is no clear trend, neither in the mean wave heights nor in the 95th percentile (P_{95}). The trend to higher annual maxima in the last years is probably due to shorter measuring intervals, which allow the exact time of the highest sea state during a storm to be recorded more precisely.

Legal framework

In support of sustainable development of shipping and maritime uses and the protection of the marine environment, the Federal Maritime and Hydrographic Agency (BSH) collects and analyses maritime data and makes them available to the public. The general legal basis for these tasks is the Maritime Shipping Responsibilities Act (SeeAufgG).

International context and access to data

The data from the permanent monitoring stations, together with other oceanographic data, are exchanged within the framework of the European Global Ocean Observing System (EuroGOOS). Both its regional sections, the North West European Shelf Operational Oceanographic System (NOOS) for the North Sea and the Baltic Operational Oceanographic System (BOOS) for the Baltic Sea, are part of the GCOS ocean observing system. However, none of the stations belong to the specifically designed GCOS Surface Network (GSN). Data transmission is automatic on an hourly basis. The data are also transmitted hourly to the Deutscher Wetterdienst (DWD), which distributes them through the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO). Another important element of sea state observations is the Marine Environmental Monitoring Network in the North Sea and Baltic Sea (MARNET). This automated network is operated jointly with the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and the DWD with the aim of recording oceanographic and other physical and chemical parameters. The responsibility for co-ordinating the national and international exchange of data lies with the BSH, which runs the German Oceanographic Data Centre (DOD) for this purpose.

◀ Photo 3.5-2: At half of the measuring stations, redundant measurements are or were carried out using wave buoys or wave radars. In this offshore wind farm, the wave radar is fixed to the substation platform. Redundant measurements serve to compare the different measurement systems and improve data quality control methods.

Where do the resources come from?

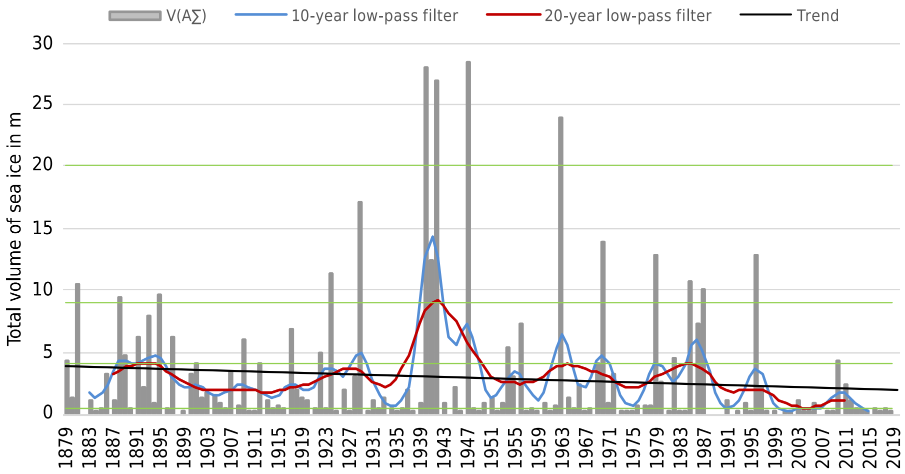
There are good prospects that operation of the existing monitoring stations can be continued in future. Measurements at sea are costly and personnel-intensive, and the risk of equipment failure or loss is high. Maintenance of the systems cannot always be carried out on schedule. This is reflected in gaps in the data series. To keep data loss at a minimum, improved logistics and more personnel will be required. About two thirds of the funds used come from research projects and one third from long-term financing. New developments are particularly the responsibility of research projects.

gloss-sealevel.org **bsh.de/EN/DATA/Climate-and-Sea/Sea_state/sea_state_node.html**

3.6 Sea ice

In polar regions, the ice on the sea has a strong influence on albedo and thus also on the energy budget. Sea ice acts as an insulating layer that reduces heat and nutrient exchange between the ocean and the atmosphere. Ice is relatively inert and reacts only slowly to changes, but since the sea ice cover is relatively well known, it provides a good indicator of variability occurring at seasonal to longer time scales.

Ice winter severity on the Baltic Sea coast since 1879



▲ *Figure 3.6-1: Distribution of total volume of sea ice for the German Baltic Sea coast from 1879 to 2020 (Source: BSH)*

Climate signals

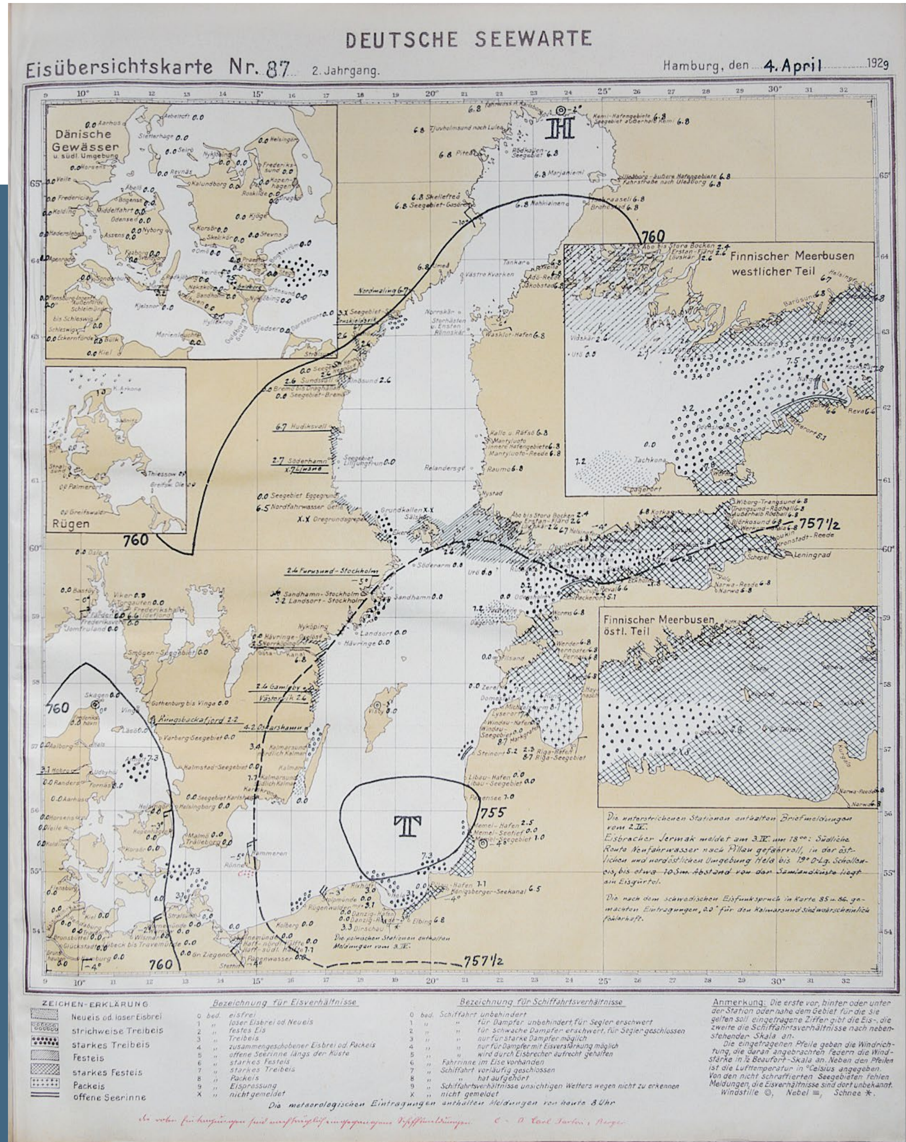
The relatively short time series of satellite-based ice cover data, available since the late 1970s, are widely known to the public for the dramatic decrease they reveal for Arctic sea ice and which is very probably connected with anthropogenic climate warming. Direct observation of ice conditions along the German coast dates back to the end of the 19th century. Estimates of the annual maximum extent of ice cover in the whole of the Baltic Sea date back to the year 1720 and continue to be updated. For the German Baltic Sea coast, the severity of ice winters could be reconstructed with the help of historical documents as far back as 1300. Long time series like these also provide evidence of earlier longer-term climate fluctuations, such as the Medieval Warm Period and the Little Ice Age. Looking back on the past 50 years, ice atlases show a decrease in the frequency of ice occurrence in the entire sea area of Germany.

Legal framework

According to the Maritime Shipping Responsibilities Act (SeeAufgG), responsibility for the provision of ice information services in German sea waters lies with the German Federation. Hosted by the Federal Maritime and Hydrographic Agency (BSH), the German Ice Service provides advice to shipping all over the world. Its history goes back to the late 19th century and to the Deutsche Seewarte (German Maritime Observatory). According to the Act Implementing the Protocol on Environmental Protection (Antarkt-UmwSchProtAG), the BSH is also responsible for issuing Antarctic shipping permits.

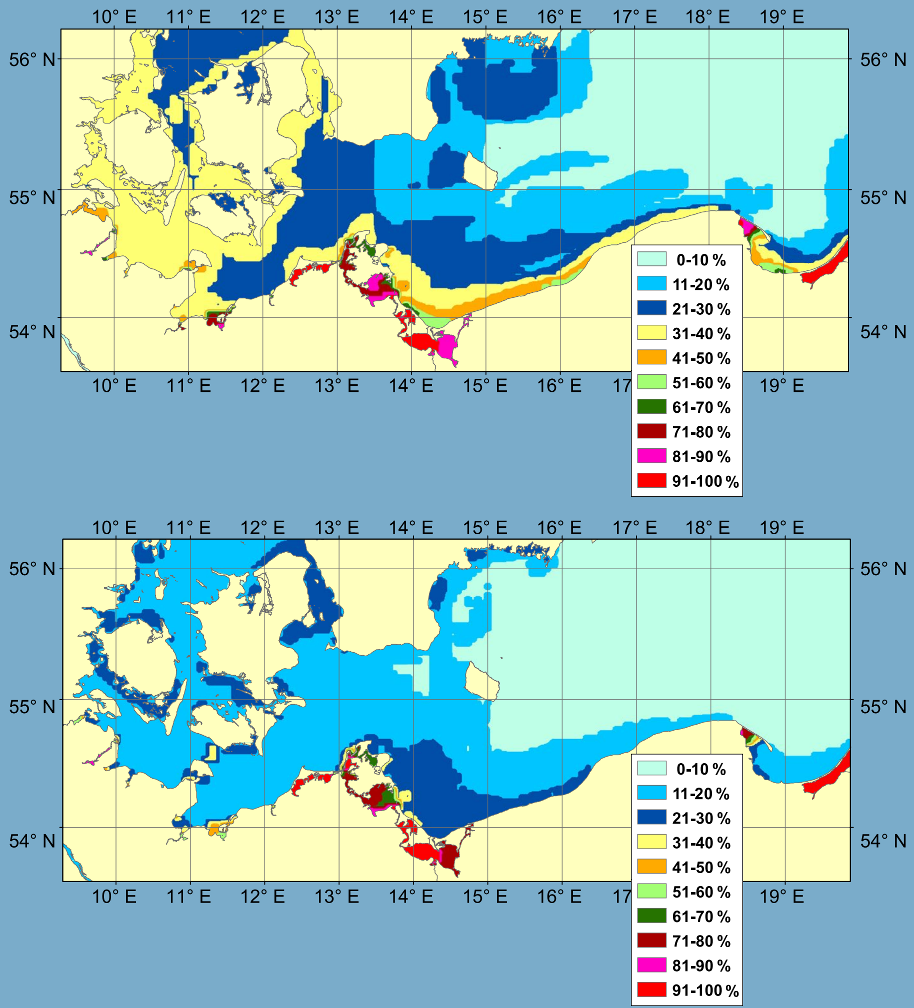
Where are the measurements taken?

Continuous ice observations have been carried out along the German coast since the end of the 19th century. Since the winter of 1927/28, ice maps of the German coast and the whole of the Baltic Sea have been compiled at least once a week. The most important ice parameters measured are coverage and thickness; others include shipping conditions and the form of the ice. The data and maps are archived at the BSH, some of which already in digital form. Information about current ice conditions is available free of charge on the BSH website. For the last few years, global ice coverage has been continuously determined by the universities of Bremen and Hamburg from satellite data. The results of their work are also disseminated free of charge on the Internet. Scientific studies of sea ice are carried out by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven and a number of universities. Many of these investigations are process studies with global coverage, but are not carried out on a continuous basis. Long-term measurements are performed mainly in the Fram Strait and to the north of this region.



▲ *Figure 3.6-2: Overview map of ice in the Baltic Sea, map No. 87, volume 2, dated 4 April 1929 (Source: BSH)*

Decreasing frequency of ice occurrence



▲ *Figure 3.6-3: Frequency of ice occurrence in the western Baltic Sea in the years 1961–1990 (above) and 1981–2010 (below) (Source: BSH)*

International context and access to data

The close co-operation among Baltic Sea ice services reaches back to 1925. Daily exchange of data and reports has carried on for decades, even during the cold war. Today, regular meetings are held and the ice services have a common website. Globally, there is a good level of collaboration among members of the International Ice Charting Working Group (IICWG), which organises international meetings to discuss operational as well as scientific issues. The ice services rely to a great extent on satellite data and work closely with remote sensing agencies, among others the European Space Agency (ESA) and the US American National Oceanic and Atmospheric Administration (NOAA). The international regulation and standardisation of operational ice information services is undertaken by bodies and committees of the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC).

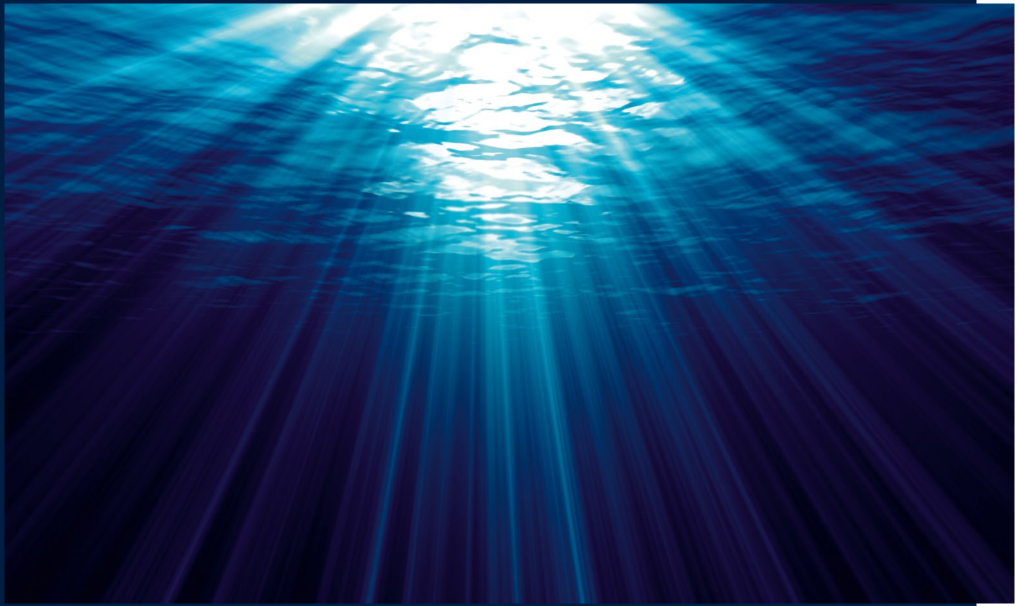
Where do the resources come from?

In accordance with the statutory regulations, funding for the fundamental work of the German Ice Service is relatively secure for the future. Some of the satellite maps used by the Ice Service are compiled by staff and student assistants at universities, who provide these services on a voluntary basis. Other services and scientific studies rely on additional funding, mostly from the federal states, the German Federation and the EU. In most cases, however, the continuity of this funding is not secured. The continuation of the satellite missions is of key importance, especially but not exclusively those carrying Synthetic Aperture Radar (SAR) instruments. Equally important is the continued free availability of satellite data for use by the ice services and scientists working in the field.

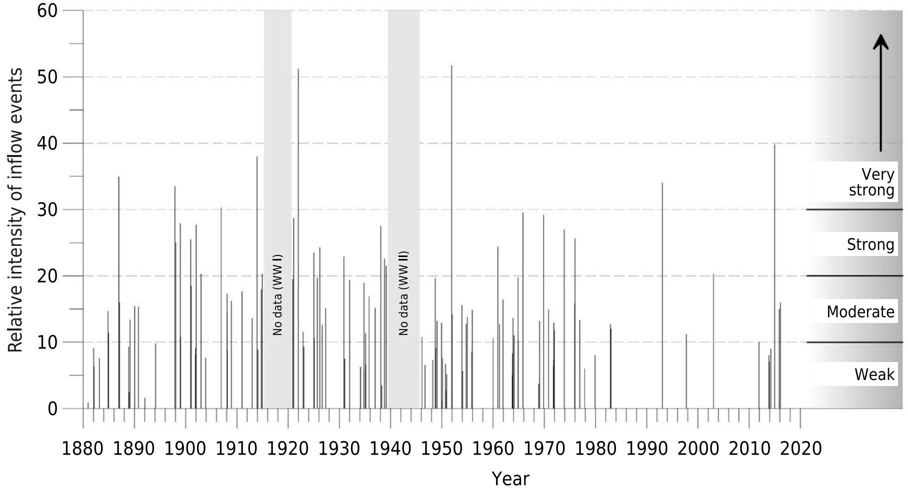
bsh.de/Eis bsis-ice.de nsidc.org/noaa/iicwg

3.7 Ocean currents

In the ocean, currents control the transport of heat, freshwater and mass. Currents are caused by many factors (winds, pressure gradients, tides) and are measured directly (e.g. mechanically, acoustically, based on particle movements) or indirectly (density and pressure measurements). Indirect measurements use further Essential Climate Variables (ECVs), for example Temperature (3.1), Salinity (3.3) or Sea level (3.4). Other ECVs are used to determine fluctuations in the transport of heat, freshwater and mass. At short time scales, currents can show strong variability (e.g. tides), and long time series with a high resolution are needed in order to detect climate signals.

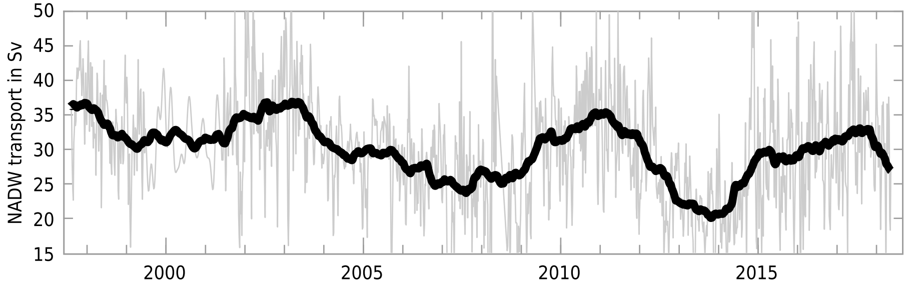


Inflow events in the Baltic Sea (1880–2015)



▲ *Figure 3.7-1: Frequency and intensity of the inflow events in the Baltic Sea between 1880 and 2015 (Source: GEOMAR, modified from Feistel et al. 2016)*

Volume transport of North Atlantic Deep Water at the southern exit of the Labrador Sea



▲ *Figure 3.7-2: Temporal evolution of the volume transport of North Atlantic Deep Water (NADW) at the southern exit of the Labrador Sea for the period from 1997 to 2018. Weekly means are indicated by the grey curve, the running annual mean is shown in black. (Source: GEOMAR)*

Climate signals

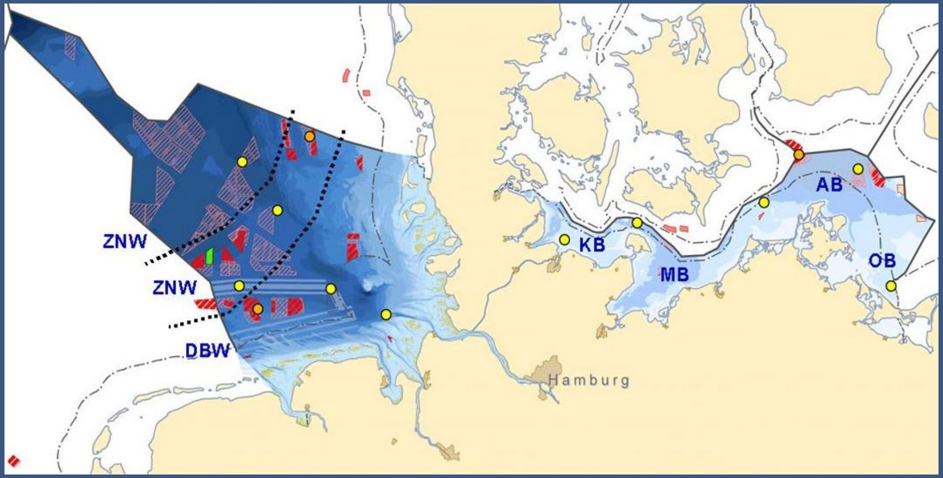
Examples in the German Exclusive Economic Zone (EEZ) are measurements at sites in the North and Baltic Sea, where, locally, there are relatively long time series available that span many decades. In the Baltic Sea, the deep-water ventilation rate is related to inflow events. These inflow events, which result from the combined effects of seabed topography and certain wind conditions, have a major impact on the ecosystem of the Baltic Sea (see also ECV Oxygen). ■ ■ ■

It is possible to determine a transport by scaling the current measurements across a representative area. Oceanic transports can be associated with other climate parameters, for example the meridional heat transport in the ocean with its atmospheric equivalent. Transports are measured in Sverdrup (Sv), with 1 Sv = 10^6 m³/s.

Where are the measurements taken?

Ship-based and stationary observations are carried out within the limits of the German EEZ. Ocean circulation conditions and their long-term changes are described in an annually updated report on the state of the North Sea, published by the Federal Maritime and Hydrographic Agency (BSH). Stationary measurements rely on installations anchored at key locations and monitor the in- and outflows for larger areas. For example, the measurements taken in the Fehmarnbelt, at the Darss Sill and in the Arkona Sea allow for the mapping of the amount of water flowing into and out of the Baltic Sea (MARNET partnership between BSH and the Leibniz Institute for Baltic Sea Research Warnemünde (IOW)).

Measurements of currents in the open ocean are also mainly taken within the scope of large international partnerships (such as GOOS). Germany is responsible for taking direct measurements at key locations in polar regions of the Arctic (Fram Strait) and Antarctic (Weddell Sea), in boundary current regions (Labrador Sea, coasts of Brazil and Angola), and at the equator. Measurements at key locations are collected as part of international co-operations focussing on basin-wide transports. These are associated with, for example, the climate-controlling Atlantic Meridional Overturning Circulation. Also recorded routinely are indirect current and transport measurements in the open ocean. This includes measurements of the ECVs Temperature and Salinity, taken either as part of the global Argo programme (contributions via the BSH) or by ships in co-operation with the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP).



◀ *Figure 3.7-3: Map of the German EEZ (area shown in blue) indicating the positions of MARNET stations (yellow dots). In addition, the different water masses in the North Sea are marked (ZNW= Central North Sea Water, DBW=German Bight Water) as well as the topographical boundaries in the Baltic Sea (KB=Kiel Bay, MB=Mecklenburg Bay, AB=Arkona Basin, OB=Oder Bay). (Source: BSH)*

International context

The long-term measurements in the open ocean are carried out as part of international initiatives. Only the co-ordination in international programmes allows for the translation of regional observations into basin-wide observations of the Atlantic system. International activities, such as the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), the Climate Variability and Predictability (CLIVAR) project of the World Climate Research Programme (WCRP) or the All-Atlantic Ocean Observing System (AtlantOS) programme, support the alignment of the observation activities with the needs of a wide range of stakeholders. The co-ordination of the measurement systems is ensured by international observation networks, such as Argo, OceanSITES, GO-SHIP and the various satellite programmes. For long-term measurements, the definition of standards, quality assurance and the exchangeability of measurement data are particularly important and require international networking through programmes such as OceanSITES.

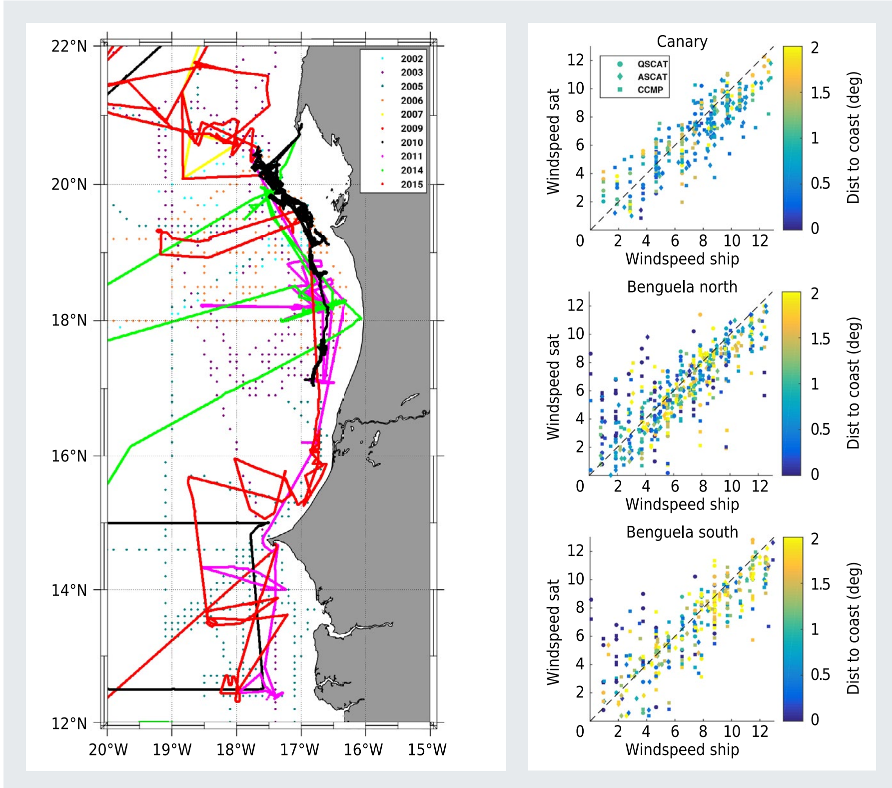
Where do the resources come from?

The monitoring activities in the EEZ are covered by the BSH. In addition, substantial contributions come from university and non-university research projects. For the Deep Argo Mission, the German contributions to open ocean current observations are funded via the BSH. Deployment of moorings and ship-borne measurements are financed by national and European research projects and by programme-oriented funding provided by the Helmholtz centres. For obvious reasons, project-related funding always bears the risk that long-term measurements must be terminated with the end of funding.

3.8 Wind stress

Wind exerts a drag stress on the sea surface, which acts as an elementary drive for movement processes in the sea. The wind-induced stress is rarely measured directly. It is derived using the drag coefficient and the Essential Climate Variable (ECV) Wind, taking into account the ECV Surface currents. Wind stress can be calculated from historical ship observations for periods of more than 100 years and serves to diagnose the causes of climate variability. Improving the parametrisation of wind stress is also very important for climate studies.

Comparison of ship- and satellite-based measurements



▲ *Figure 3.8-1: Comparison of ship measurements (points in left-hand chart) with spatially and temporally congruent satellite-based measurements (right-hand chart) (Source: Schlundt/GEOMAR)*

◀ *Photo 3.8-1: Effects of wind input over the sea*

Climate signals

Due to their close connection with oceanic circulation, variability and trends in wind stress are drivers of climate variability. If influenced by wind stress, slow shifts in wind systems, for instance, can lead to systematic changes in the systems of currents.

Wind stress is also closely associated with the intensity of coastal upwelling, which in turn is related to ocean productivity, and consequently fisheries. The parametrisation of wind stress and in particular the calculation of the drag coefficient are extremely import- ▪▪▪

ant for climate predictions. Studies on this topic are a good example of how process studies can make a valuable contribution to climate research. Another area of research looks at the consistency of data sets that result from different sources, such as ship data and satellite measurements (Figure 3.8-1). The focus here is on systematic deviations, their cause and their correction.

International context

Wind measurements on ships are part of the Voluntary Observing Ships (VOS) scheme, an observation network of the Ship Observations Team (SOT) that co-ordinates its activities with the Global Ocean Observing System (GOOS), this in turn being linked to GCOS.

The Deutscher Wetterdienst (DWD) as the national meteorological service of the Federal Republic of Germany operates a marine meteorological network in order to fulfil the tasks laid down in the Deutscher Wetterdienst Act (DWDG). As part of this network, the DWD operates its own VOS fleet, with currently (as of 06/2021) approx. 600 shipboard weather stations (of which around 120 are automatic) on various ships that participate in the VOS programme for voluntary weather observation at sea. In total, about 670,000 observations from the DWD's VOS stations were fed into the Global Telecommunications System (GTS) in 2020 and made available for weather and climate analyses. Globally, about 2,700 VOS stations have delivered some 2.6 million observations. Co-ordination also takes place at European level under the E-Surfmar programme of the Network of European Meteorological Services (EUMETNET) and globally through the SOT's VOS Panel. The DWD represents the interests of the Federal Republic of Germany in both these bodies. Within the scope of the Marine Climate Data System (WMO/IOC MCDS), the DWD operates a Voluntary Observing Ship Global Data Assembly Centre (VOS-GDAC, see link at the end) for the archiving and exchange of international marine weather reports.

Where are the measurements taken?

Measurements are taken from ships, fixed platforms, and moored and free-drifting surface buoys. Wind stress with high spatial and temporal resolution can be derived from satellite data. One good reason for the in-situ monitoring network are the reference measurements (e.g. at time series stations), which are also used to validate reanalyses and satellite data. The ECVs required for parametrisation are recorded by both research and container ships participating in the VOS programme and are available at high temporal resolution along shipping routes. Measurement platforms in the North and Baltic Seas are used for process studies to improve parametrisation.

Where do the resources come from?

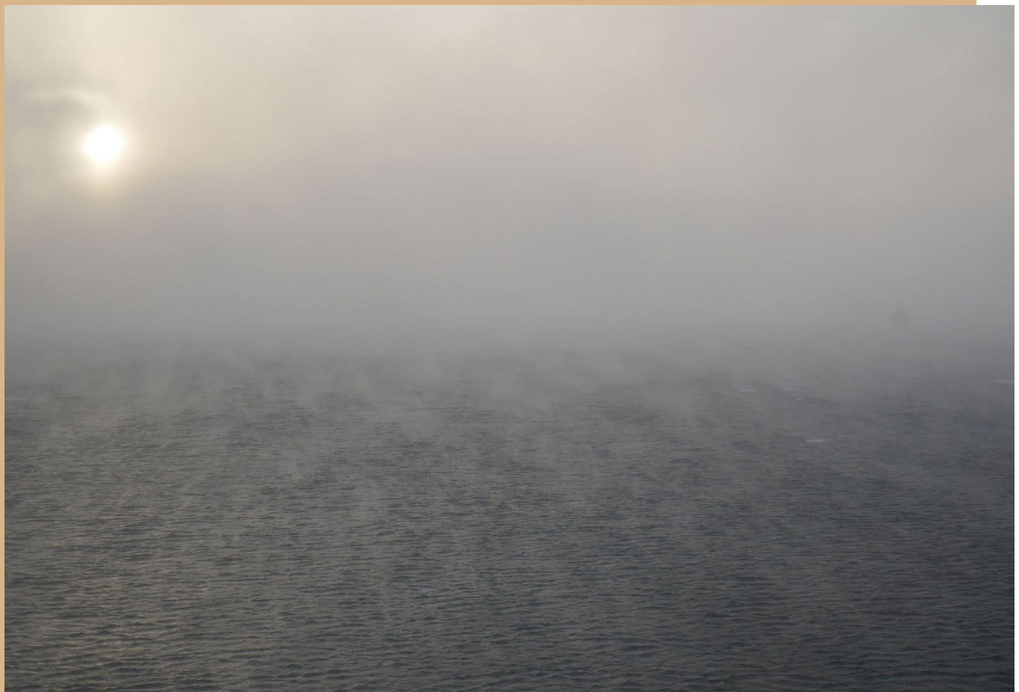
The DWD's marine meteorological network is a fully operational monitoring network operated within the DWD's Business Area Technical Infrastructure and Operations. The VOS activities of Germany are consequently included in the budget of the DWD. E-Surfmar is an optional programme run under the responsibility of the EUMETNET Observations Capability Area. Management of this programme has been contracted out to Météo-France for the current five-year programme period until the end of 2023 and is financed by EUMETNET funds. The VOS programme enables global co-ordination and has only a small budget provided by members on a voluntary basis.

With its pilot project »Underway« Research Data started in 2019, the German Marine Research Alliance (DAM) has begun developing an infrastructure aimed to ensure the provision of relevant ECVs from their initial recording through to quality control and data archiving. Other measurements stem from research projects, which are typically of short duration (3–5 years).

dwd.de/vos-gdac

3.9 Ocean surface heat flux

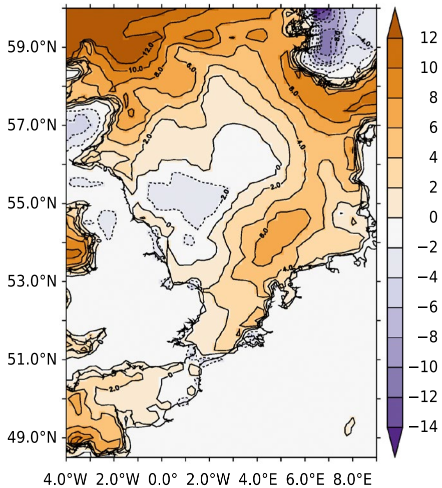
Ocean surface heat flux refers to the exchange of heat between the ocean and atmosphere and is closely linked to the ocean's role in the climate system. About 90 % of the additional heat released into the air since industrialisation have been absorbed by the ocean. The heat flux is divided into four components: solar and terrestrial radiation-based heat fluxes as well as turbulent heat fluxes from evaporation and thermal conduction. The heat fluxes can be determined from historical ship-board observations going back far beyond the last 100 years.



◀ *Photo 3.9-1: Sea smoke, photographed from the research ship FS POLARSTERN in March 2020*

Climate signals

The variability of ocean surface heat fluxes is closely linked to climate factors such as regional and global patterns of ocean warming, changes in the stratification of ocean waters and the solubility of gases, which in turn are related to other ECVs (for example Temperature in the water column, see Item 3.2).



▲ *Figure 3.9-1: Climatological annual mean changes in net heat flux (W/m²) of the RCA4-NEMO RCP8.5 ensemble mean between the simulated periods 1970–1999 and 2070–2099. Blue colours indicate increased heat loss or decreased heat gain of the North Sea. (Source: GEOMAR, modified from Dieterich et al. 2019, licensed under CC0 1.0)*

International context and access to data

The Voluntary Observing Ships (VOS) scheme is an observation network of the Ship Observations Team (SOT), which is organised as part of the Global Ocean Observing System (GOOS), itself a programme co-financed by the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

As the national meteorological service of the Federal Republic of Germany, the Deutscher Wetterdienst (DWD) operates a marine meteorological network in order to fulfil the tasks laid down in the Deutscher Wetterdienst Act (DWDG). As part of this network, the DWD operates its own VOS fleet, with currently (as of 06/2021) approx. 600 shipboard weather stations (of which around 120 are automatic) on various ships that participate in the VOS programme for voluntary weather observation at sea. In total, about 670,000 observations from the DWD's VOS stations were fed into the Global Telecommunications System (GTS) in 2020. Globally, about 2,700 VOS stations have delivered some 2.6 million observations.

At European level, co-ordination of the various national fleets takes place under the E-Surfmar programme of the Network of European Meteorological Services (EUMETNET), at global level through the SOT's VOS Panel. The DWD represents the interests of the Federal Republic of Germany in both these bodies.

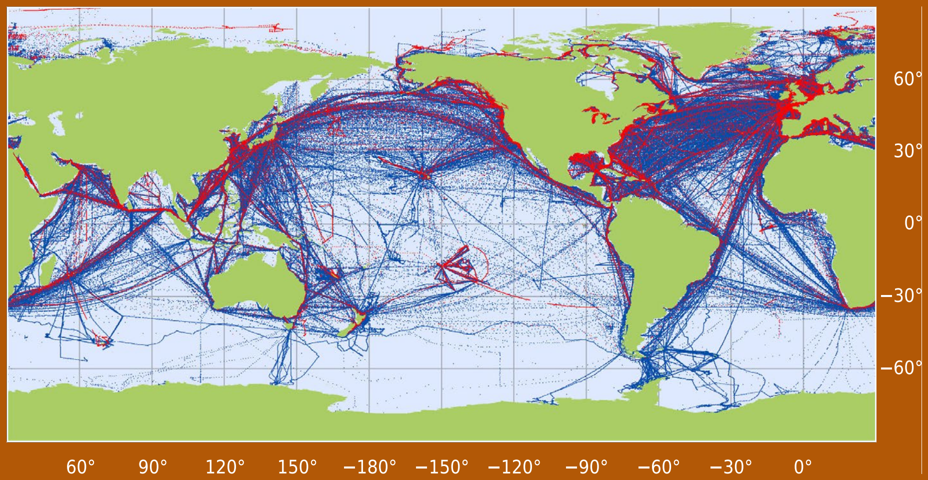
The DWD disseminates its VOS data via the GTS. The data from the measuring platforms in the North and Baltic Seas are available for retrieval on ■ ■ ■

the associated data portals. Access to the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite (HOAPS) data record is possible on the data portal of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Within the scope of the WMO/IOC-led Marine Climate Data System (MCDS), the DWD operates a Voluntary Observing Ship Global Data Assembly Centre (VOS-GDAC, see link at the end) for the archiving and exchange of international marine weather reports.

Where are the measurements taken?

For climate studies, there is an interest in having all four surface heat flux components available at the same time to be able to determine the net heat flux. The turbulent fluxes are derived through parametrisation of oceanic and meteorological parameters, such as wind, air and water temperature, humidity, surface currents. As to radiation, direct measurements (pyranometer, pyrgeometer) are required; approximations are possible based on information about the local atmospheric structure (including cloud cover and structure, temperature, water vapour and aerosol content).

The measurements required are carried out from ships and at fixed platforms as well as by moored and drifting surface buoys. Heat fluxes can also be determined from satellite data (for example the HOAPS data record). One good reason for the in-situ monitoring network are the reference measurements, which are also used to validate reanalyses and satellite data. Presently, around 600 ships are contributing to the DWD's VOS activities, supplying data to calculate the ECVs required for determining turbulent heat fluxes. German research vessels typically carry out measurements allowing the calculation of all four components. The FINO research platforms in the North and Baltic Seas are suited for extensive process studies on parametrisation.



▲ *Figure 3.9-2: Example of the routes covered by the ocean-going vessels participating in the VOS scheme in September 2018 (red) and throughout 2017 (blue) (Source: GEOMAR, modified from Smith et al. 2019)*

Where do the resources come from?

The DWD's marine meteorological network is a fully operational monitoring network operated within the DWD's Business Area Technical Infrastructure and Operations. Accordingly, the VOS activities of Germany are firmly included in the budget of the DWD.

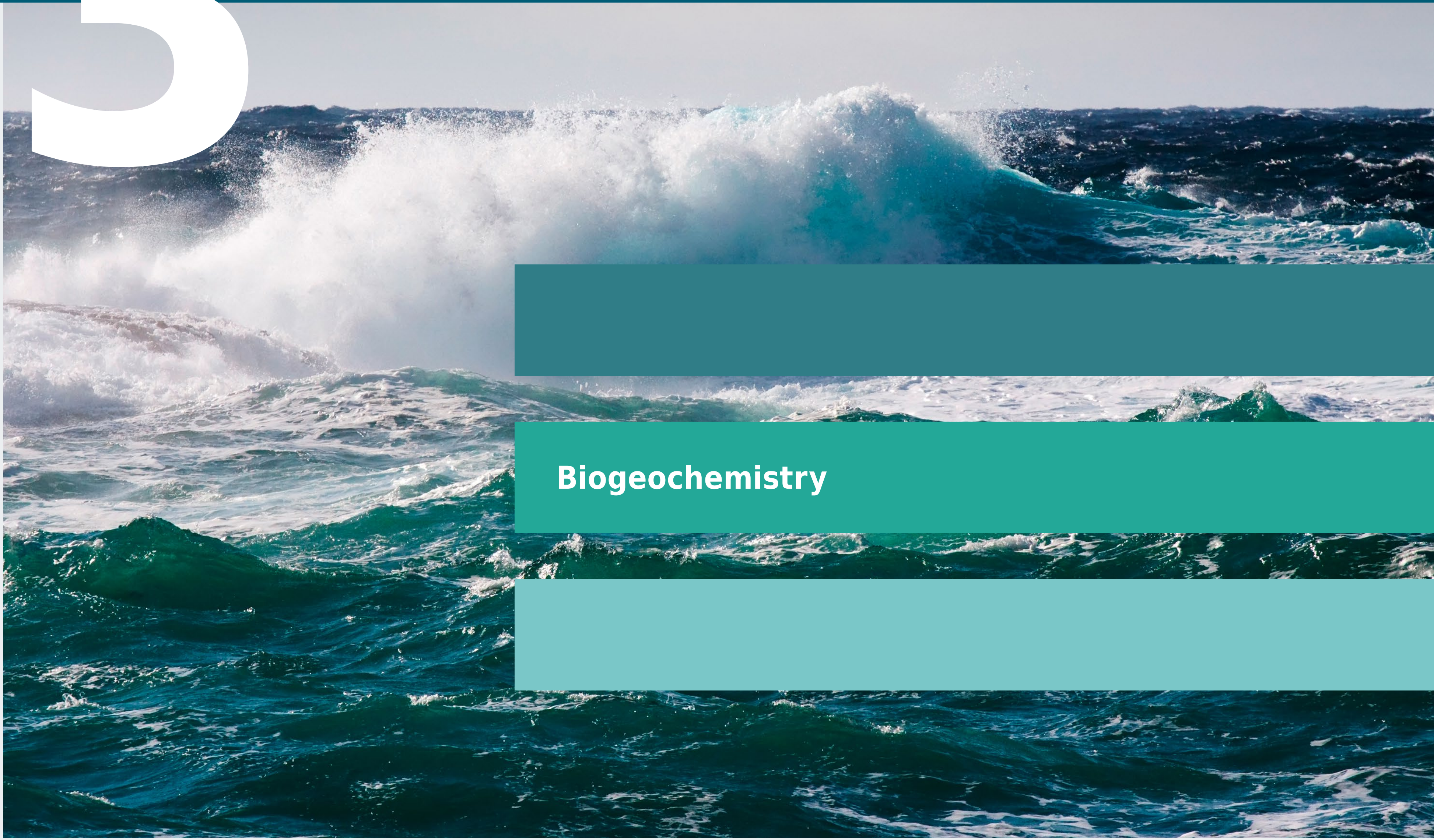
E-Surfmar is an optional programme run under the responsibility of the EUMETNET Observations Capability Area. Management of it has been contracted out to Météo-France as the »responsible member« until the end of 2023 and is financed by EUMETNET funds. The programmes of EUMETNET are planned for 5-year periods and are awarded to a Member State following a call for tenders. The next programme phase from 2023 onwards is already being planned.

The global programmes VOS and SOT are purely organisational initiatives and have only small budgets at their disposal (for example for travel costs), which are funded by the members on a voluntary basis.

With its pilot project »Underway« Research Data started in 2019, the German Marine Research Alliance (DAM) has begun developing an infrastructure aimed to ensure the provision of relevant ECVs from their initial recording through to quality control and data archiving – including for GCOS-related climate applications. Other measurements stem from research projects, which are typically of short duration (3–5 years).

dwd.de/vos-gdac **oaflux.whoi.edu** **cds.climate.copernicus.eu**

3 Ocean observations

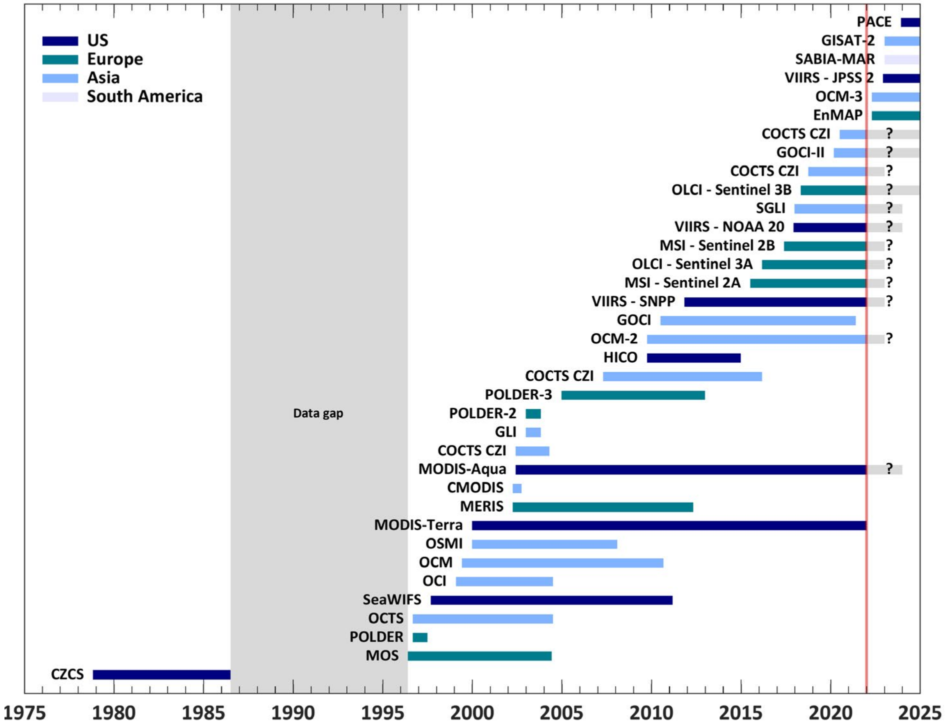


Biogeochemistry

3.10 Biomass/Ocean colour

»Ocean colour« (OC) is a collective term for a number of physical and biological parameters that are derived from multispectral optical remote sensing data. Among the key parameters for ocean monitoring are the concentrations of chlorophyll, suspended matter and yellow substance (also known as gelbstoff) as well as turbidity and depth of visibility. Regular availability of information about the variability of these parameters over space and time is of great significance for ocean monitoring as this allows identification and assessment of anthropogenic and climate-related changes in the oceans and the resulting ecological changes.

Global ocean colour satellite missions

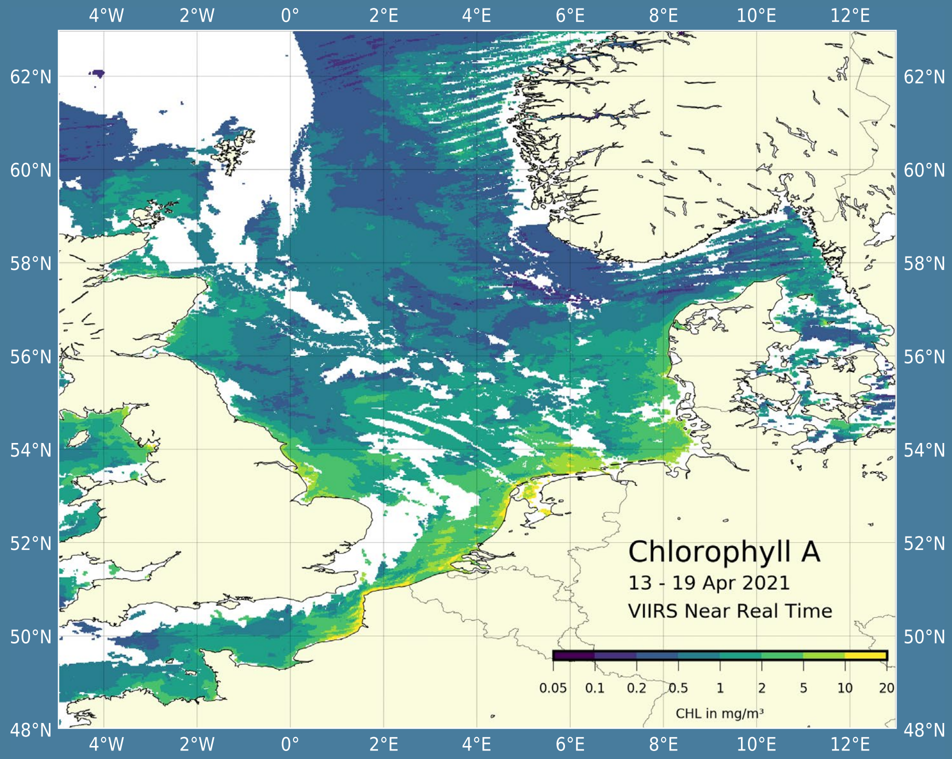


▲ *Figure 3.10-1: Timeline illustrating past, current and future global ocean colour satellite missions (Source: BSH, modified from IOCCG)*

◀ *Photo 3.10-1: Algal bloom in the North Sea*

Climate signals

Since satellite-borne optical remote sensing began in the late 1970s, a greater variety of optical sensors has become available over the last 20 to 25 years, in particular in connection with the Copernicus Services of the European Union (see Figure 3.10-1). This allows the synthesis of consistent time series with data from different satellites. It is an indispensable requirement for analysing climate-related changes in the marine environment because a sufficiently long period of time must be covered to be able to identify climate signals. However, as ocean colour measurements – in particular for local studies – only take records of the near-surface range, it is often very difficult to differentiate between climate trends and natural, sometimes multidecadal variability.



▲ *Figure 3.10-2: Distribution of chlorophyll A in the North Sea, weekly mean for 13 to 19 April 2021 (Source: BSH)*

Where are the measurements taken?

In general, ocean colour products are available worldwide for the open ocean and for the coastal areas. The various satellite sensors feature different spatial resolutions. Because of the satellites' orbits and the area coverage of geostationary satellites, large-scale products for entire parts of the ocean rely on combinations of data from multiple satellites. An example for the North Sea area is shown in Figure 3.10-2.

International context and access to data

A large part of the ocean colour products have been developed in the framework of international projects (e.g. ESA, EUMETSAT) and are provided directly or via local service providers, such as the German Aerospace Center (DLR), research institutes and private companies. The European Ocean Colour Thematic Assembly Center (OC TAC), for instance, which is operated as part of the Copernicus Marine Service (CMEMS), operationally provides high-level products at global and pan-European as well as regional (Atlantic, Arctic, North and Baltic Seas, Black Sea) scales. The data can be accessed via the links listed below.

To facilitate and harmonise access to the data, the European Commission is financing the establishment of five cloud-based platforms, all designed to give central access to the Copernicus data and information services as well as to processing tools.

Legal framework

Under the Maritime Shipping Responsibilities Act (SeeAufgG), the Federal Republic of Germany has a statutory task to conduct oceanographic investigations, including the monitoring of changes in the marine environment. This includes the participation in inspections made by the European Union or other international organisations of which Germany is a member insofar as German participation is necessary to implement legal instruments of the European Union or fulfil Germany's international commitments.

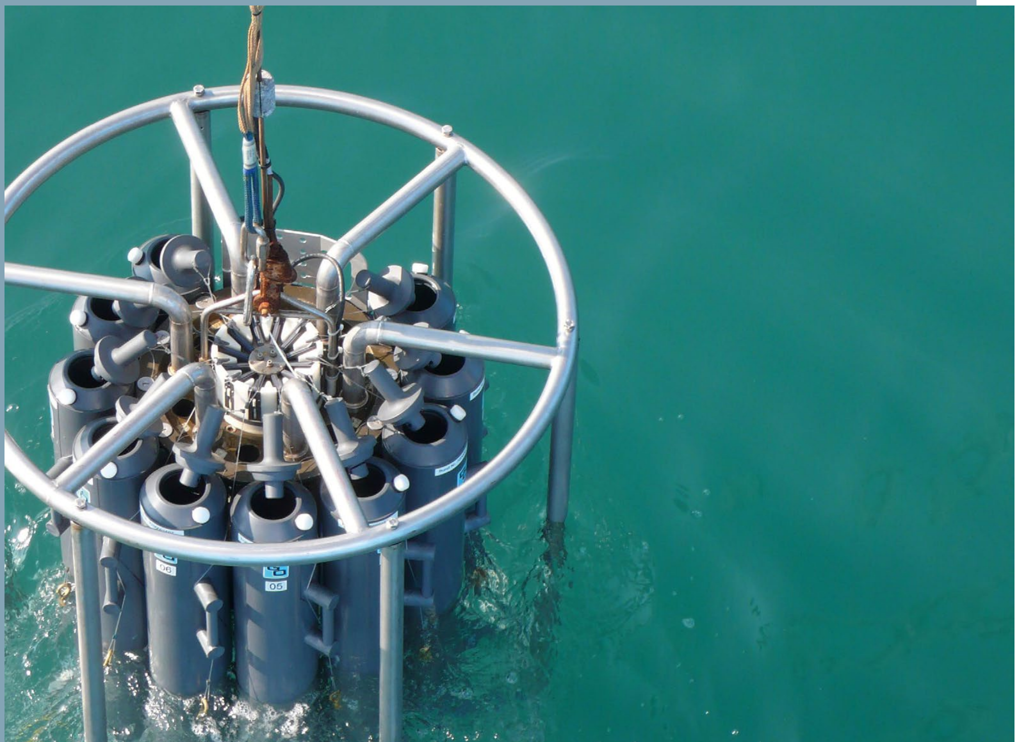
Where do the resources come from?

In Germany, national activities for monitoring the marine environment are secured under the Maritime Shipping Responsibilities Act (SeeAufgG). Fulfilment of the national obligations is furthermore governed by the German Marine Monitoring Programme (BLMP) and the Marine Strategy Framework Directive (MSFD). International commitments are regulated by the OSPAR Convention as well as by the Helsinki Commission (HELCOM). The funds for centralised provision of ocean colour products in Europe via CMEMS come from the European Union.

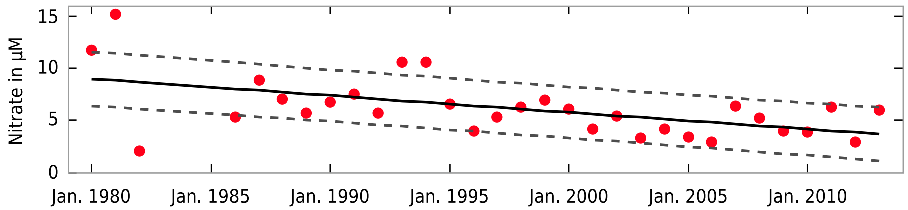
marine.copernicus.eu/about/producers/oc-tac **www.globcolour.info**

3.11 Nutrients

The availability of nutrients is an essential prerequisite for plant growth in the sea. Nutrients are an integral part of substance cycles and thus dependent on biological, biogeochemical and physical processes. Consequently, climate fluctuations can disrupt nutrients and their substance cycles in diverse ways. Other anthropogenic disturbances (e.g. eutrophication) can also have a lasting impact on nutrients. The measuring network for nutrients includes both large-scale and regional observations.



Long-term trend of nitrate concentrations at Boknis Eck time series station



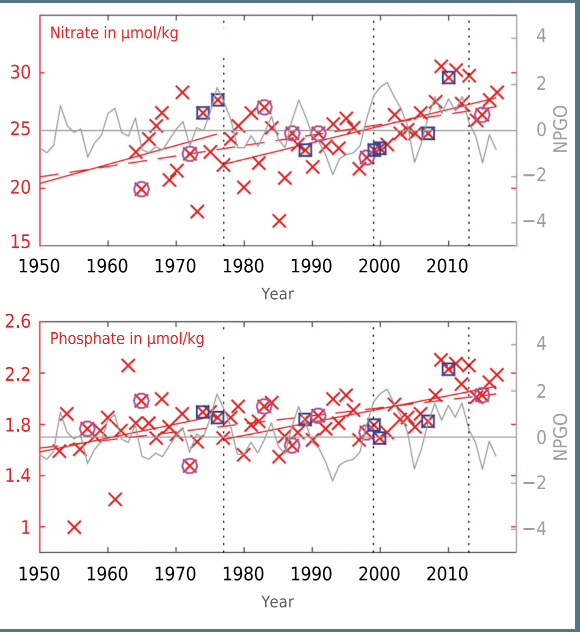
▲ *Figure 3.11-1: Mean winter concentrations of nitrate at Boknis Eck time series station (dots). The graph also shows the calculated long-term trend (solid line) and its uncertainty (dashed line). (Source: GEOMAR, modified from Lennartz et al. 2014)*

Climate signals

In order to better understand the processes and to improve predictive capacities, data collection including biological and physical Essential Climate Variables (ECVs) is strongly recommended. In addition to monitoring nutrient levels in the sea, river observations are also important.

In coastal areas, the huge seasonal fluctuations in nutrient concentrations require regular monitoring over long periods of time in order to identify trends. At Boknis Eck time series station in the Baltic Sea, where nutrients have been measured continuously since 1986, a downward trend in nutrient concentrations in winter can be observed (Figure 3.11-1). Similar trends have also been found in the German Bight and are mainly due to a decrease in nutrient input from rivers. However, increasing stratification (difference in density between deep and shallow water) caused by global warming cannot be ruled out as an influencing factor.

Since there are often only low concentrations in the open ocean, trends here are more difficult to detect and it is of key importance to ensure the comparability of measurements by using suitable reference material (RM). For many nutrients, reference material was developed at an early stage although only on a local level. Globally accepted standards did not become available until recent years. The same applies to methodology documents. Intercalibration makes it possible to identify systematic deviations in nutrient data and possibly also to correct them.



◀ *Figure 3.11-2: Trends of nitrate (top) and phosphate (bottom) in the Oyashio region in the North Pacific. The trend lines were correlated for specific phases of the Pacific Decadal Oscillation (PDO) and the position of the North Pacific Gyre Oscillation (NPGO) as large-scale shifts in these ocean currents are considered to be contributors to the trends. (Source: GEOMAR, modified from Stramma et al. 2020)*

Where are the measurements taken?

In the German Exclusive Economic Zone (EEZ), long-term nutrient measurements are carried out by the Federal Maritime and Hydrographic Agency (BSH) as part of the regular monitoring of the German Bight. Further long-term measurements are conducted by university and research institutes, in the coastal area of the Baltic Sea by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and the GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR) and in the North Sea by the University of Oldenburg and the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). Nutrient inputs into the coastal regions from rivers are measured regularly by the federal-state offices.

In the world's open oceans, various institutions and universities carry out nutrient measurements, mostly ship-based and within the scope of research projects. Long-term trends can be derived by combining data from a number of countries (Figure 3.11-2).

International context and access to data

Co-operation on nutrient monitoring in the Baltic Sea region is co-ordinated by the Helsinki Commission (HELCOM), and in the North Sea by the OSPAR Commission. This mainly involves the use of ships. New sensor technology also makes it possible to measure some nutrients with high data rates on autonomous measuring platforms (underwater gliders, Argo deep floats, moorings). The highest quality standard is achieved by laboratory measurements on research ships, for example in the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), in which Germany is also a regular participating country. GO-SHIP data serve as a reference for climate trends, also using the related data synthesis files from GLODAP. International working groups (e.g. SCOR COMPONUT) are working on the homogenisation of techniques and reference materials.

Most of the nutrient data from observations in the German EEZ can be found on the Chemistry portal of the European Marine Observation and Data Network (EMODnet). Various institutes make other data publicly accessible, for example the measurement series of Boknis Eck station, which has been in operation in the Baltic Sea since the mid-1950s and is now run by GEOMAR. Additional data for the open ocean can also be found at the PANGAEA® data centre (see collection of links below).

Where do the resources come from?

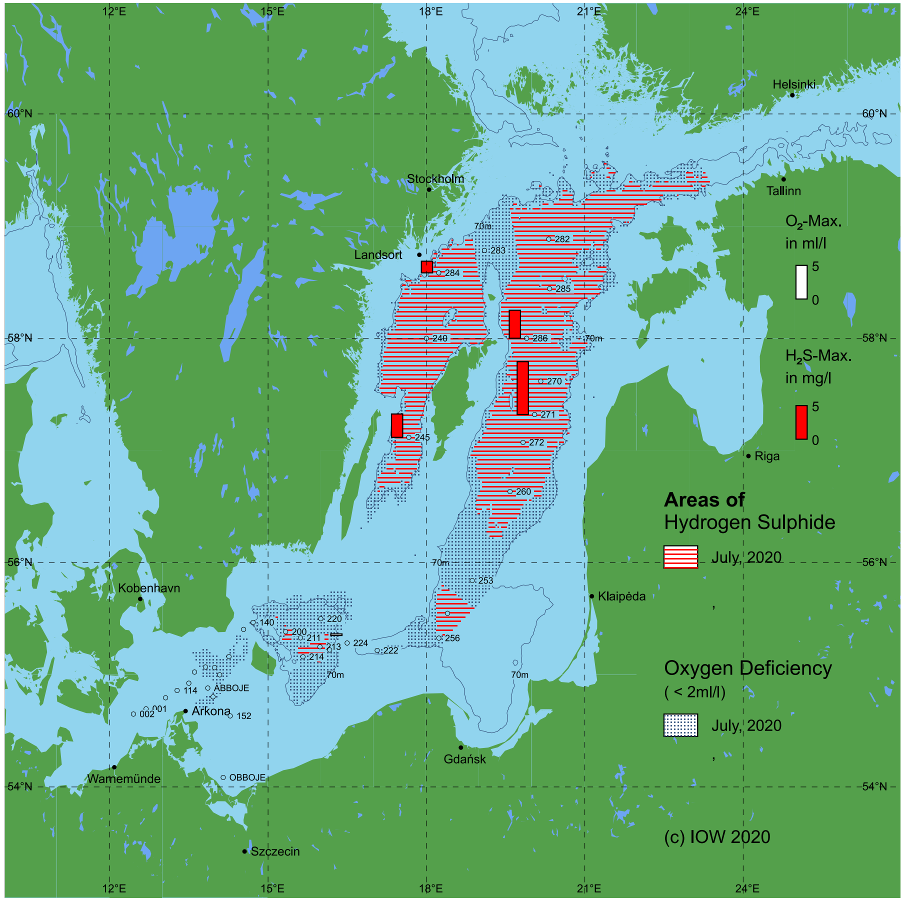
Monitoring of the marine environment is secured under the Maritime Shipping Responsibilities Act (SeeAufgG). Fulfilment of national obligations is furthermore governed by the German Marine Monitoring Programme (BLMP) whereas international agreements are ruled by the OSPAR Convention. The Marine Strategy Framework Directive (MSFD) includes a co-ordinated programme of measures for the European Union. Nutrient observations in international waters are mainly funded by short-term research grants.

emodnet-chemistry.eu **bokniseck.de** **pangaea.de** **glodap.info** **ncei.noaa.gov/products/world-ocean-atlas**

3.12 Oxygen

All higher life in the ocean depends on oxygen dissolved in water. The amount of dissolved oxygen is much smaller in water than in air. One litre of water contains only about one twentieth of the amount of oxygen in the same volume of air. Surface water is usually well supplied with oxygen. Supersaturation with oxygen is a regular occurrence during the algal growth period in spring. In the deep and near-bottom ocean layers, oxygen deficiencies can occur in the second half of the year as a result of oxygen-consuming organic decomposition processes.

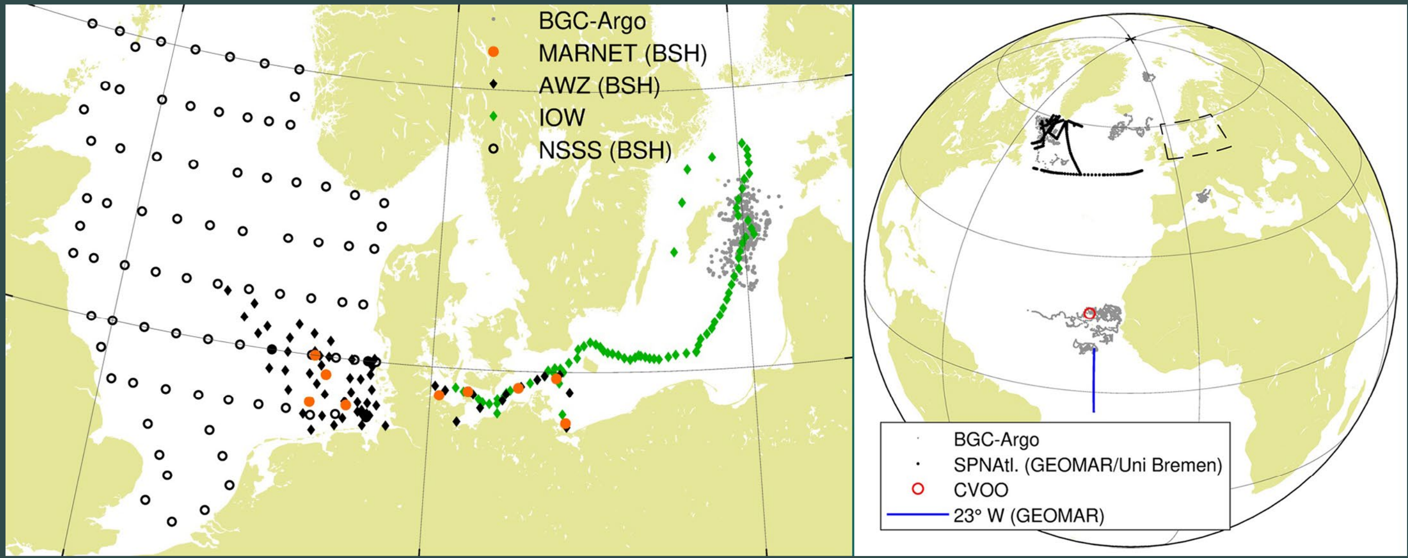
Areas of oxygen deficiency or anoxia in the near-bottom waters of the Baltic Sea in July 2020



▲ *Figure 3.12-1: Areas of oxygen deficiency (black dots) and high levels of H_2S and thus anoxic conditions (hatched in red) in the near-bottom waters of the Baltic Sea in July 2020 (Source: Naumann/IOW)*

Climate signals

Oxygen dynamics in the ocean are determined by physical, biogeochemical and biological processes. Photosynthesis and the exchange of gas between undersaturated surface water and the atmosphere cause the oxygen levels in the ocean to increase. They decrease again due to respiration and the oxidation of chemical compounds in the water column or in the sediment. While the well-mixed surface layer is usually well supplied with oxygen, a physical ■ ■ ■



▲ *Figure 3.12-2: Overview of the German oxygen monitoring network comprising (a) continuous measurements (full dots), (b) seasonal measurements (full diamonds) and (c) annual and multiannual measurements (circles). The colours indicate the measuring programme or responsible institution. (Source: Bittig/IOW)*

Where are the measurements taken?

At certain key locations in the German Exclusive Economic Zone (EEZ) in the North and Baltic Seas, coverage of measurements is assured all year round by automated stations of the MARNET network. In addition, the Federal Maritime and Hydrographic Agency (BSH) organises five monitoring cruises per year, carried out in the North Sea by itself and in the Baltic Sea on its behalf by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW). Within the framework of the IOW's long-term research programme, the cruises are extended into the central Baltic Sea and thus help to obtain a comprehensive picture of the seasonal behaviour of oxygen and of the ecological state of the entire western and central Baltic Sea. The larger scale contexts of the North Sea are subject to the North Sea Summer Survey (NSSS), conducted by the BSH. In addition, long-term research interests that drive, for example, the GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR) or the University of Bremen have resulted in time series of oxygen levels in the subpolar North Atlantic and Labrador Sea, in the equatorial Atlantic and in the subtropical North-East Atlantic. An important component of this is the Cape Verde Ocean Observatory (CVOO) time series station, jointly operated with several partners on the Cape Verde islands. In all above-mentioned areas except the North Sea, further oxygen measurements are carried out using German biogeochemical Argo floats (BGC-Argo).

transport mechanism, known as ocean ventilation, is needed for the layers below the sunlit surface to renew the oxygen consumed. The distribution of oxygen inside the ocean thus provides information on physical and biogeochemical mechanisms in the ocean and on the ecological state of the oceans.

The climate change not only causes the ocean to warm, it also affects ocean circulation. Through reduced oxygen solubility and reduced ocean ventilation, both these factors lead to a decline in the oxygen inventory of the global ocean. This is already a measurable fact: since 1960, the ocean oxygen inventory has decreased worldwide by more than 2 %. In addition, increasing warming and the associated stronger stratification of the water column, together with the growing eutrophication of coastal waters in particular, lead to hypoxia, i.e. decreased oxygen in the ocean.

A situation like this also exists in the Baltic Sea, which is almost completely surrounded by land with only narrow straits that link it to the world ocean and with little exchange of water as a consequence. The area affected by hypoxia currently covers around 70,000 km² in the deep waters of the central basins. In coastal, shallow areas, there is an increasing oxygen deficiency in late summer. Despite a considerable decline of nutrient loads since the beginning of the 1980s, current computations of the ozone depletion rate still give considerably higher values than in previous decades. However, some few coastal areas with strongly reduced nutrient loads ■ ■ ■

■■■

and minor accumulation of organic material are showing improvement. The continuing warming also drives further deoxygenation in marginal seas, for example the Baltic Sea. The future development of the area affected by oxygen deficiency is strongly connected with the nutrient input scenario. Simulations assuming perfect implementation of the Baltic Sea Action Plan (BSAP) even suggest that the state of ecosystems can improve if further reductions are achieved.

Legal framework

In accordance with Sections 1 (9, 11) and 5 (1) (4,5) of the Maritime Shipping Responsibilities Act (SeeAufgG) in the version of 26 July 2002 (Federal Law Gazette I 2876), the marine environment of the North and Baltic Seas is to be monitored by the German Federation and the federal states of the Federal Republic of Germany. Pursuant to this, responsibility for the German EEZ lies with the Federation, with the BSH as subsidiary of the Federal Ministry for Digital and Transport (BMDV) being responsible for the chemical and physical monitoring as required for assessing the implementation of the Marine Strategy Framework Directive (MSFD). Monitoring the Baltic Sea area and the Atlantic is part of the ecological state assessment under both the Helsinki Convention (managed by HELCOM) and the OSPAR Convention.

International context and access to data

All data collected under the various programmes and during the monitoring cruises are freely available in corresponding databases (in some cases only after a certain period of embargo). Environmental monitoring data are usually forwarded to the International Council for the Exploration of the Sea (ICES). BGC-Argo data are freely available from the Argo data centre. Other data (e.g. from monitoring cruises) are archived in different places depending on their origin (e.g. PANGAEA®). An overview can be found using the cruise inventory and data search function offered by the Oceanographic Data Centre (DOD) of the BSH. To facilitate searchability and access to the data, international efforts are currently under way to set up a comprehensive Global Ocean Oxygen Database and ATlas (GO_2DAT) and establish a consistent flow from data collection to national data centres and other data providers through to a uniform data product.

Where do the resources come from?

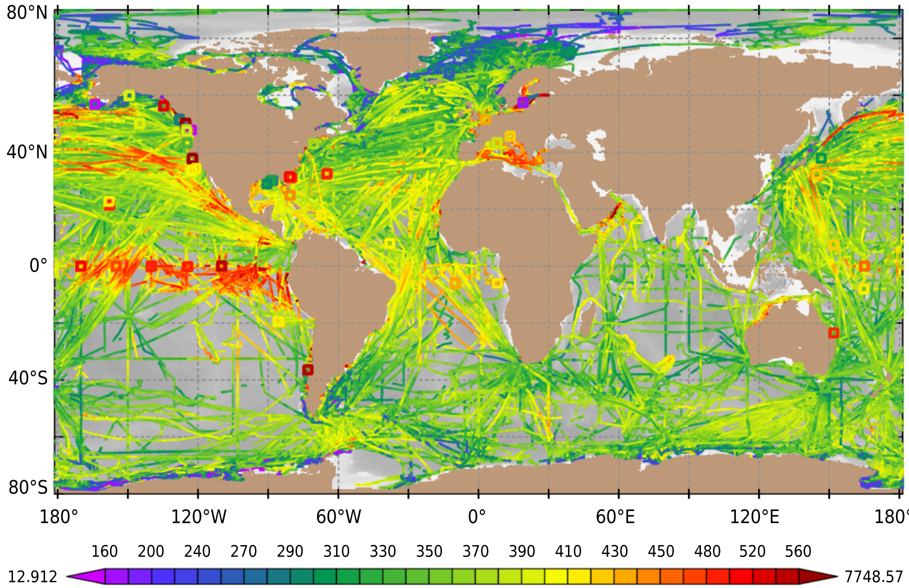
Monitoring of the oxygen situation in the marine environment is secured under the Maritime Shipping Responsibilities Act (SeeAufgG). National obligations are specified in the German Marine Monitoring Programme (BLMP) and will in future be integrated into an internationally co-ordinated monitoring programme under the MSFD. Additional measurements are financed from the budgets of the participating research institutes (e.g. IOW) or from research projects (e.g. GEOMAR, University of Bremen). The funds for the German Argo programme come from the BMDV, the extension to include oxygen and other biogeochemical parameters is currently funded by the BMBF.

bsh.de **https://www.io-warnemuende.de/environmental-monitoring.html** **cvoo.de** **pangaea.de**

3.13 Inorganic carbon in the ocean

Observation of marine carbon circulation is one of the main tasks of marine research. The focus of attention is on the uptake and storage of anthropogenic carbon dioxide (CO_2), on changes in the natural carbon cycle caused by climate change and other anthropogenic influences and on the effects of CO_2 uptake on the marine ecosystem.

Measurements of CO_2 partial pressure in the ocean



▲ *Figure 3.13-1: Map of the 33.7 million quality-controlled measurements of CO_2 partial pressure in the surface ocean contained in SOCATv2022 for the period 1957 to 2021 (Source: DWD, modified from Bakker et al. 2016)*

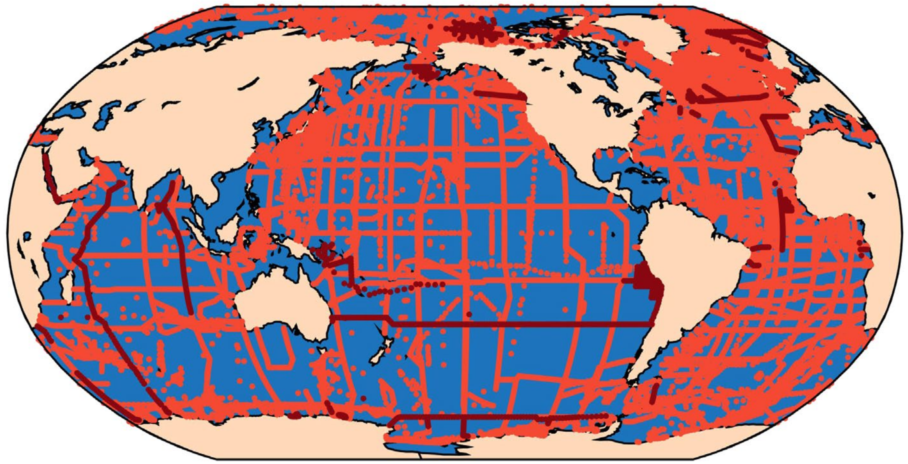
◀ *Photo 3.13-1: An autonomous Saildrone robot boat equipped with state-of-the-art sensor technology encounters the German research vessel METEOR in the tropical North Atlantic as part of a co-ordinated initiative during the METEOR Expedition M160 to study the role of ocean eddies in the marine carbon cycle.*

Anthropogenically disrupted carbon cycle

The ocean plays a central role in the global carbon cycle. In the period 2010–2019, for example, the ocean absorbed around 26 % of the CO_2 emitted globally from the combustion of fossil fuels in the same period. Cumulatively since 1750, the share of emissions is as high as 38 %. At the same time, this additional CO_2 uptake causes changes in the chemistry of the inorganic carbon system that have a variety of potentially negative impacts on marine life. These changes are generally known under the heading of »ocean acidification«. Systematic monitoring of the marine CO_2 system is therefore of great scientific importance and imperatively called for because of Germany’s commitments to international agreements (UNFCCC, OSPAR, MSFD).

Data products

Data on inorganic carbon in the ocean have been collected systematically for over two decades under strict, internationally agreed protocols to ensure high quality. A number of international data products have emerged from this that are publicly available and can be found and cited. German research groups contribute both on the conceptual level and through the regular provision of data. Outstanding examples are the Surface Ocean CO_2 Atlas (SOCAT, see Figure 3.13-1 and link at the end) and the Global Ocean Data Analysis Project (GLODAP, see Figure 3.13-2 and link at the end). SOCAT version 2022 contains 33.7 million quality-controlled measurements of CO_2 partial pressure in the surface ocean from the period 1957–2021. GLODAP version 2.2021 includes quality-controlled and internally consistent data on CO_2 parameters from 1.3 million water samples collected on 989 expeditions between 1972 and 2020. Both data products are routinely used to produce the important annual Global Carbon Budget.



▲ *Figure 3.13-2: Map of hydrographic stations with quality-controlled and internally consistent measurements of biogeochemical parameters (including carbon concentrations) on more than 1.3 million water samples from 989 research expeditions between 1972 and 2020 (Source: Lauvset et al. 2016 and 2021, Key et al. 2015)*

Where are the measurements taken?

Due to the diverse scientific requirements, systematic observations of inorganic carbon in the ocean are carried out in various networks. The three most important are:

Ship-of-Opportunity (SOOP) network

The global observatory for CO_2 observations in the surface ocean is predominantly based on commercial shipping vessels (container ships, ferries) and forms the basis for quantifying the oceanic CO_2 sink. The German contribution (ICOS) comprises three such SOOP lines in the Baltic Sea (IOW), the North Atlantic (GEOMAR) and the polar regions (AWI), where automatic measurements of CO_2 partial pressure and other variables are continuously carried out. The data are routinely entered into the international SOCAT database after quality control.

Network of ocean time series stations

Ocean time series stations provide insights into the natural variability of the marine CO_2 system and allow a definitive identification of temporal trends, as has been shown for the BATS, ESTOC and HOT stations (OceanSITES). The German contribution (ICOS) includes two such stations in the Fram Strait (Hausgarten, AWI) and in the tropical north-eastern Atlantic (Cape Verde Ocean Observatory, GEOMAR). A systematic international data product of the ocean time series stations is currently being developed under the direction of the GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR).

Global Argo float observatory

The highly successful global observatory of profiling deep floats is being expanded to include a biogeochemical component (BGC-Argo). The new pH sensor technology now makes it possible for the first time to take autonomous profiling measurements of the marine CO_2 system in the upper 2,000 metres of the ocean. The German contribution includes methodological work as well as regional pilot studies in the subpolar North Atlantic (BSH, GEOMAR) and in the Baltic Sea (BSH, IOW).

◀ *Photo 3.13-3: A water sampling rosette with 24 closed water samplers returns to the surface from a water depth of over 4,000 metres.*

International context

The participating German research groups are involved in international initiatives, such as SOCAT, GLODAP and IOCCP, where they also take on leadership responsibilities. Of particular importance are the contributions to the European research infrastructure Integrated Carbon Observation System (ICOS) for quantifying Europe's greenhouse gas balance. In this context, Germany contributes five components to the Ocean Network.

Where do the resources come from?

The German ICOS contribution was developed between 2012 and 2016 with funding from the Federal Ministry of Education and Research (BMBF). In the operational phase, which has been running since 2017, the atmosphere programme is financed by the Federal Ministry for Digital and Transport (BMDV) while the funds for the ocean programme currently come from the partner institutions GEOMAR, AWI and IOW out of their own resources. Operations in the German Argo programme are financed by the BMDV. BMBF project funds, however, continue to play a key role for further expansion, methodological innovations and accompanying research. In the medium term, observation tasks in the area of inorganic carbon in the ocean must be more strongly integrated into the sovereign budget in order to guarantee the structures and expertise that have been built up on a sustainable basis.

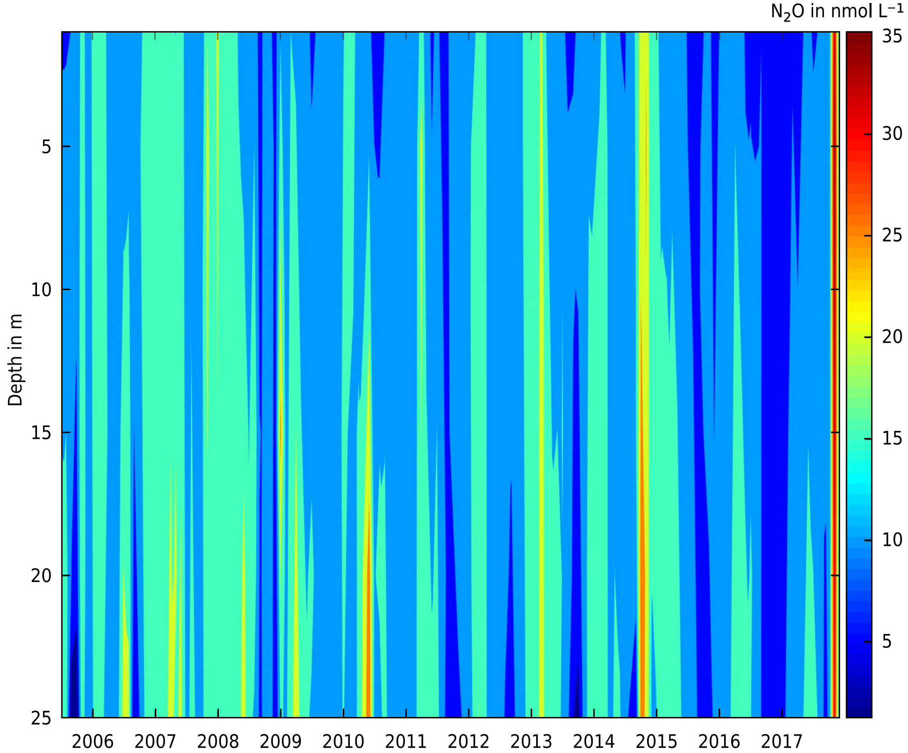
◀ *Photo 3.13-2: Dr Björn Fiedler from GEOMAR prepares Argo deep floats with various biogeochemical sensors for deployment in the tropical Atlantic.*

socat.info **glodap.info**

3.14 Nitrous oxide in the ocean

Nitrous oxide (N_2O) is a long-lived trace gas that is the third largest contributor to the greenhouse effect and plays a critical role in the depletion of stratospheric ozone. Currently, about 60 % of global N_2O emissions are from natural sources, with the ocean contributing one third. Due to the scarcity of observations and only partial recordings of natural variability, there are still huge uncertainties surrounding estimates of marine N_2O emissions. In this connection, long-term measurements are a key component of international measurement networks to identify Essential Climate Variables (ECVs).

Measurements of N_2O in the water column at Boknis Eck time series station (2005–2017)



▲ *Figure 3.14-1: Monthly measurements of N_2O in the water column (5–25 m deep) at Boknis Eck time series station between 2005 and 2017. Yellow-reddish tones represent high concentrations of N_2O and blue tones low concentrations. (Source: GEOMAR, modified from Ma et al. 2019)*

◀ *Photo 3.14-1: The German research cutter LITTORINA on its way to Boknis Eck in Eckernförde Bay (Schleswig-Holstein)*

Climate signals

Atmospheric N_2O levels have increased more or less continuously by about 0.8 ppb per year in recent years. This reflects the increasing N_2O emissions from anthropogenic sources.

Nitrous oxide is produced as an intermediate or by-product during conversion processes in the nitrogen cycle. On the one hand, increased N_2O emissions can often be attributed to eutrophication processes while on the other hand there is a close link between N_2O production and the oxygen content of the environment. Various studies on the oxygen dependence of N_2O production show that the most N_2O is produced at very low oxygen levels, but N_2O decompos- ■ ■ ■

ition occurs when there is no oxygen at all. Changes in the oxygen levels in bodies of water thus have a direct impact on N_2O distribution. However, the development of N_2O emissions depends largely on the physical exchange processes between water and the atmosphere.

Results of time series measurements at Boknis Eck show that eutrophication has decreased in the coastal waters of the southern Baltic Sea over recent decades. At the same time, however, changes in the stratification of the water column have led to an increase in the number of years with severe oxygen deficiency in deep water. The measurements of N_2O taken to date are not yet sufficient to assess whether global warming, ocean acidification and eutrophication together lead to an increase or decrease in natural N_2O emissions.

Where are the measurements taken?

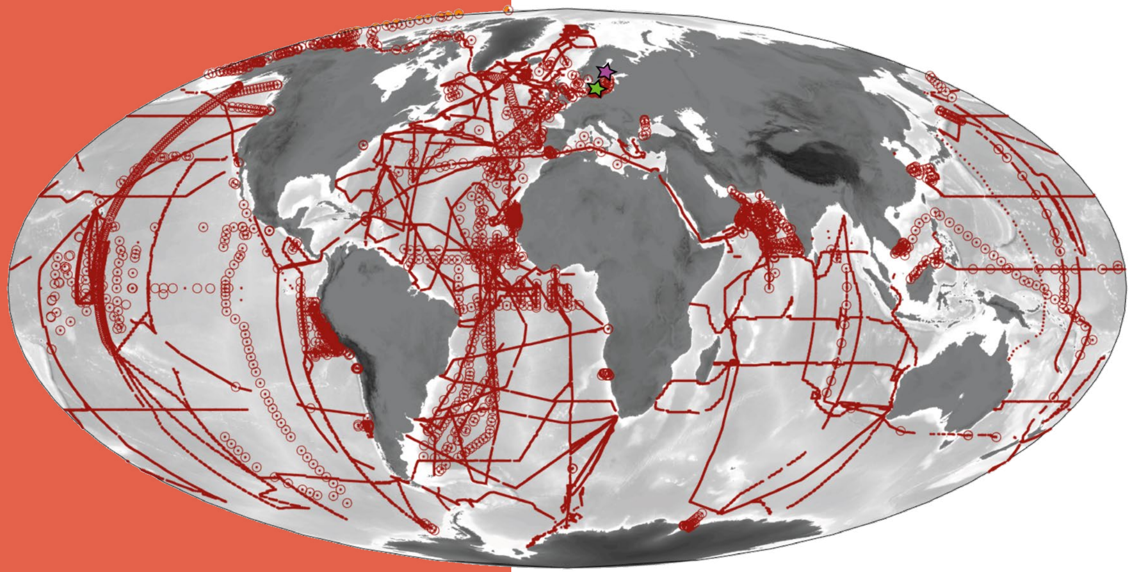
Observations of N_2O in the atmosphere are currently carried out by the Federal Environment Agency (UBA) as part of the Global Atmosphere Watch programme (GAW) and as the German component of the Integrated Carbon Observation System (ICOS). The measurement networks include several stations throughout Germany where N_2O is measured continuously. At the same time, other trace gases and relevant atmospheric variables are measured in order to be able to determine the climate gas fluxes in Germany. Regular observations of N_2O in the German Exclusive Economic Zone (EEZ) come from ship-based monitoring cruises to fixed time series stations and autonomous measurements on board merchant ships (»Ships of Opportunity«, SOOP). Monthly measurements of N_2O in the water column (1–25 m deep) at Boknis Eck time series station (Eckernförde Bay, 54° 31′ N, 10° 02′ E) began in 2005. The measurements are taken by scientists from the GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR). Continuous measurements of N_2O in surface water have been taken since winter 2020 on board a ferry (M/V FINNMAID) that crosses the main basins of the Baltic Sea every two days between Travemünde and Helsinki (Finland). These observations are operated by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) as part of ICOS. On international waters, N_2O measurements with German participation are mostly taken during ship-based research expeditions.

International context

Atmospheric N_2O measurements from GAW stations operated by Germany are supplied to the public through the World Data Centre for Greenhouse Gases (WDCGG). Oceanic measurements of N_2O from national measurement campaigns are usually archived together with other data gathered during these campaigns in national or international geospatial databases (e.g. PANGAEA®, BCO-DMO). In 2009, the MEMENTO database (MarinE MethanE and NiTrous Oxide) for global oceanic methane and N_2O measurements was set up and is operated by GEOMAR. In this database, existing measurements of N_2O from national and international campaigns are collected, transferred into a unified data format and published to create a comprehensive, unified data set of N_2O in the ocean and to enable global estimates of oceanic N_2O emissions. Figure 3.14-2 shows the positions of the N_2O surface and depth profile data contained in MEMENTO (as of December 2020).

...

The atmospheric observations listed are a valuable contribution to international measurement programmes (GAW, ICOS, Total Carbon Column Observing Network (TCCON), Network for the Detection of Atmospheric Composition Change (NDACC)) and the Global Carbon Project (GCP). In addition, the data provided are highly relevant for the extension of temporal data coverage for N_2O as an ECV of the Global Ocean Observing System (GOOS). Archiving in global data centres, for example WDCGG and PANGAEA®, guarantees public access to the data. The data collected in MEMENTO also serve as a basis for estimating global oceanic N_2O emissions, which in turn play a key role in estimating the greenhouse gas balance of the open oceans and coastal waters collected as part of the GCP.



◀ *Figure 3.14-2: Positions of surface (dots) and depth (circles) profile data of N_2O in MEMENTO. The green star shows the location of Boknis Eck time series station, the pink star the transit area of the M/V FINNMAID. (Source: GEOMAR)*

Where do the resources come from?

Most oceanic and atmospheric observations at national and European level are financed through institutional funds as well as funds acquired as part of third-party projects. In Germany, the UBA is responsible for implementing quality assurance measures for atmospheric N_2O measurements. One of the world calibration centres established under GAW is operated by the Karlsruhe Institute of Technology (KIT) and funded by UBA. With the exception of the N_2O measurements in the Baltic Sea (aboard an SOOP) as part of ICOS Germany, there is no continuous funding for time series of oceanic N_2O measurements in Germany.

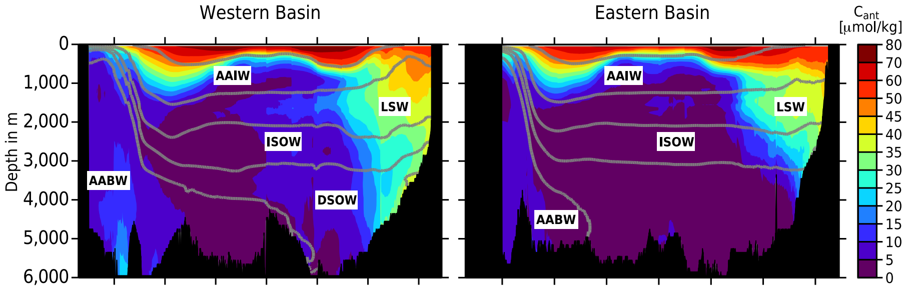
gaw.kishou.go.jp **public.wmo.int/en/programmes/global-atmosphere-watch-programme**

umweltbundesamt.de/daten/klima/atmosphaerische-treibhausgas-konzentrationen **icos-infrastruktur.de** **memento.geomar.de**

3.15 Anthropogenic trace gases in the ocean

Anthropogenic trace gases, such as chlorofluorocarbon (CFC) and sulphur hexafluoride (SF_6), enter the ocean from the atmosphere. At first, they are transferred into the surface waters through air-sea gas exchange. Vertical mixing and convection (deep water formation) then cause the gases to reach the abyss, where the large-scale circulation spreads them further. As the trace gases are chemically and biologically inert, their concentrations only depend on the year in which the water mass left the surface and on how quickly they mix with the waters.

Anthropogenic carbon in the Atlantic

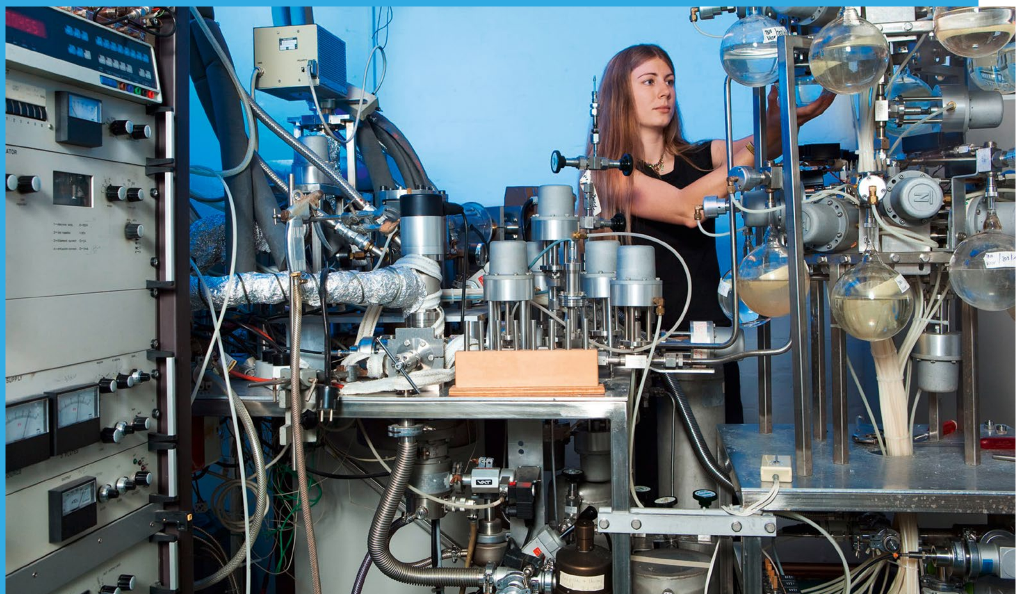


▲ *Figure 3.15-1: Distribution of anthropogenic carbon (C_{ant}) in the Western (left) and Eastern Basin (right) of the Atlantic in 2010. The most important water masses are also shown: Antarctic Intermediate Water (AAIW), Labrador Sea Water (LSW), Iceland–Scotland Overflow Water (ISOW), Denmark Strait Overflow Water (DSOW) and Antarctic Bottom Water (AABW). (Source: IUP)*

Climate signals

The monitoring of anomalies in the concentration of anthropogenic trace gases enables estimates to be made about how quickly climate signals are spreading in the ocean. Climate models predict a weakening of water formation rates and associated overturning forces. This would lead to changes in the transport of heat and fresh water in the ocean – with considerable consequences for the climate and the sea level in western Europe. It would also affect the storage rates of anthropogenic carbon.

The key ocean regions react very sensitively to changes in the atmospheric forcing. This high sensitivity is also the reason why the ocean responds to natural variability in the atmospheric forcing with large natural fluctuations. This response, however, hampers the detection of fluctuations of anthropogenic origin so that long data series are needed to distinguish between natural variability and long-term trends.



◀ *Photo 3.15-1: Laboratory for the analysis of trace gases at the Institute of Environmental Physics, University of Bremen (IUP)*

Where are the measurements taken?

The trace gases (CFCs, SF_6) are extracted from water samples and are then analysed by gas chromatography. This can either be done directly on the research vessel or the water samples are flame-sealed in glass ampoules, transported to the laboratory at home and analysed there. Per research cruise, around 1,000 to 3,000 samples are collected. Without the infrastructure of German research vessels, such as FS POLARSTERN, FS METEOR and FS M. S. MERIAN, sampling campaigns of this extent would not be possible.

The main focus of German measurements is on the Atlantic (see Figure 3.15-2). Trace gas measurements in the Atlantic sector of the Southern Ocean (Weddell Sea and Circumpolar Current) began in 1986 and have since been repeated every 2 to 3 years. This is only possible thanks to the research icebreaker FS POLARSTERN. The measurements collected along the prime meridian constitute one of the longest trace gas time series in the world. Other regions where German trace gas measurements take place are located in the tropical Atlantic and Pacific (upwelling regions), in the Mediterranean, in the subpolar North Atlantic (deep water formation region) and, to an increasing extent since recent years, in the Arctic (e.g. as part of the MOSAiC expedition).

In the Atlantic, Germany is technologically and scientifically leading in the analysis and interpretation of trace gas data, as well as in the number of measurements undertaken.

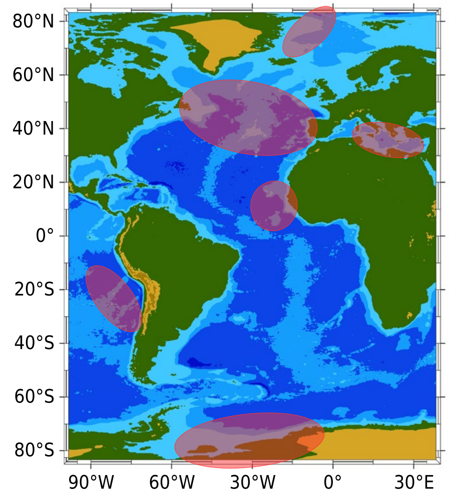
Since the trace gas measurements take place within the framework of third-party projects, they focus on specific scientific topics, including changes in the formation and spreading of deep water, ventilation and variability of air masses, upwelling, mixing and vertical heat fluxes.

Another area of application of large-scale trace gas measurements is the calculation of anthropogenic CO_2 (C_{ant}) stored in the ocean. Like other trace gases, C_{ant} enters the ocean via air-sea gas exchange, bound up, however, in chemical and biological processes that are difficult to assess. Therefore, an internationally proven method to calculate the amount of C_{ant} in the ocean relies on the distribution of trace gases.

As a result of the Montreal Protocol, designed to ensure the protection of the ozone layer, atmospheric concentrations of CFCs have been declining slightly for around 20 years. This has also caused the CFC content in the ocean convection region to remain static, which makes it very difficult or even impossible to determine the spreading times of waters. Hence, SF_6 is preferably used as tracer as its atmospheric concentrations still continue to increase.

International context and access to data

The national measurement of trace gases is incorporated in international research activities such as the CLIVAR project of the World Climate Research Programme (WCRP), which focuses on climate variability and predictability with a special focus on ocean–atmosphere interaction. The measurements also contribute to European research projects, such as CARBOOCEAN, CARBOCHANGE, AtlantOS and COMFORT. The German oceanic trace gas data are stored in European and international data archives as well as in the national PANGAEA® database. Moreover, they are a component of the Global Ocean Data Analysis Project (GLODAP). The aim of this project is to collect trace gas data as well as data about other carbon-related parameters from around the world and, after running quality checks, publish these in a uniform format. This enables easy access to the data, for example to create a basin- or worldwide inventory for oceanic C_{ant}.



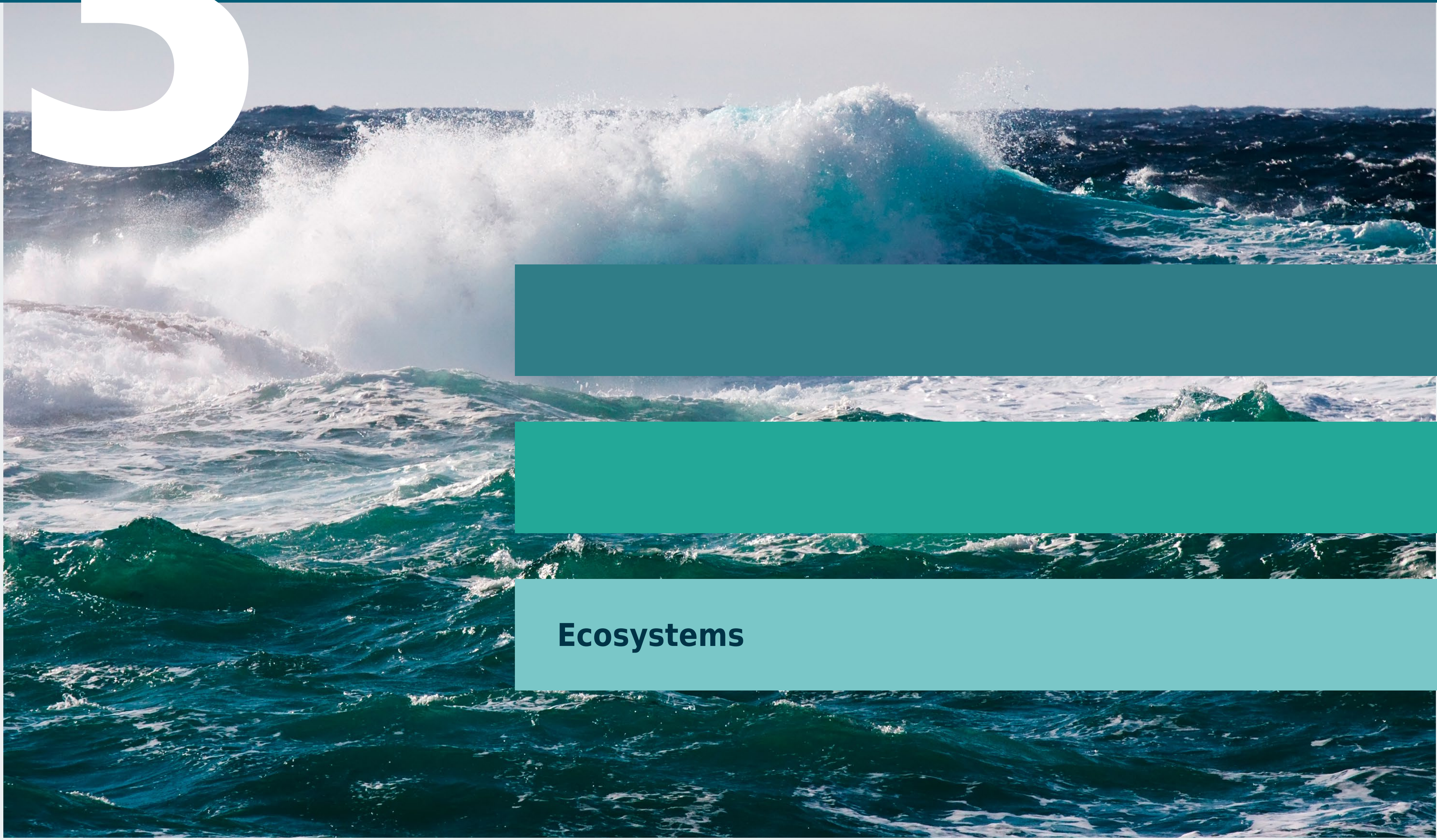
▲ *Figure 3.15-2: Areas where German institutions (GEOMAR, University of Bremen) take regular measurements of trace gases, see red oval markings (Source: IUP)*

Where do the resources come from?

The measuring of oceanic trace gases – including some of the required technical personnel and further technological development of analysis systems – are funded through temporary research projects; continuity is therefore not secured. In addition, the measurements can only be carried out if ship time on suitable research vessels (FS M. S. MERIAN, FS METEOR, FS POLARSTERN) is granted.

geomar.de   www.ocean.uni-bremen.de   glodap.info

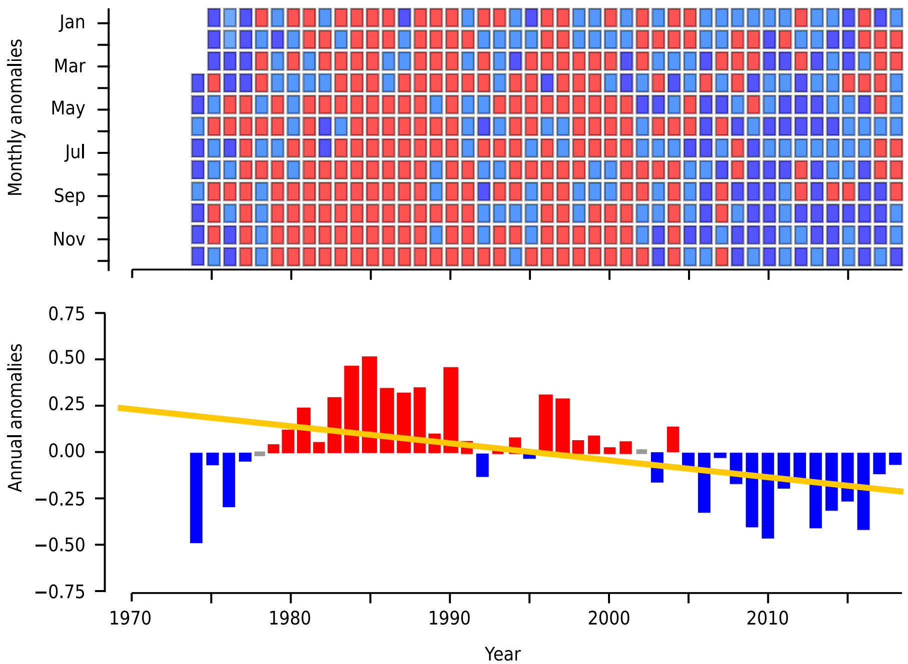
3 Ocean observations



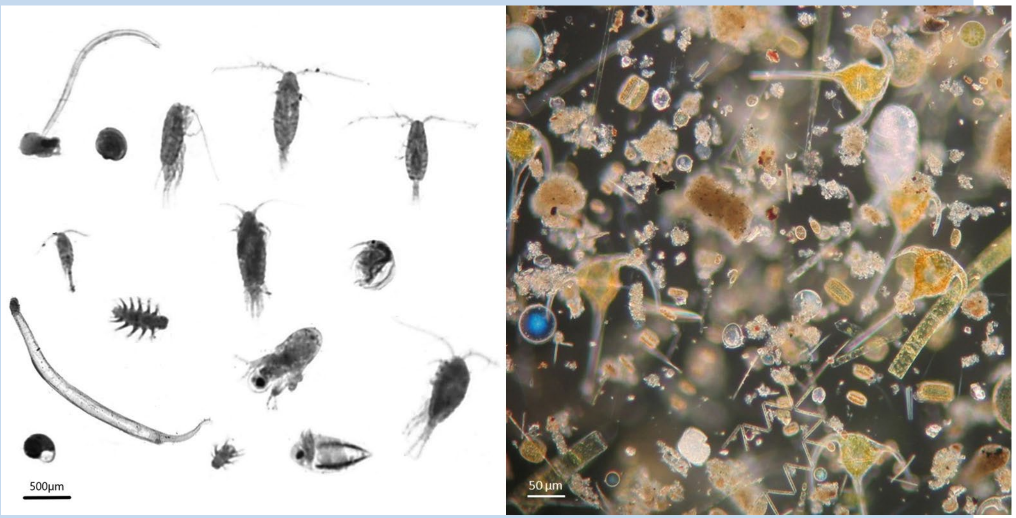
Ecosystems

3.16 Plankton

Plankton are organisms floating in open water that are unable to swim independently against ocean currents. A distinction is made between phytoplankton (which include unicellular bacteria and microalgae and, through photosynthesis, form the base of the marine food web) and zooplankton (which comprise a variety of animals from unicellular ciliates and copepods to very large jellyfish). Zooplankton are the most important link between primary production and higher trophic levels (such as fish) and are thus extremely important for marine and oceanic ecosystems. Phytoplankton and zooplankton serve as indicators of water body status and are therefore also parameters of the EU's Water Framework Directive and Marine Strategy Framework Directive.



▲ *Figure 3.16-1: Seasonal and interannual anomalies in the abundance of small copepods at Helgoland Roads time series station (Source: GEOMAR, modified from NMFS)*



Climate signals

Quantitative observations of plankton based on standardised plankton net catches have been made since the end of the 19th century. There are currently no long measurement series for plankton comparable to those for atmospheric and hydrographic parameters. The available data from the last century show that there have been shifts in distribution, especially in the temperate latitudes. As a result, in the North and Baltic Seas, there is an increasing number of species that are favoured by warmer temperatures while others have been pushed back to the polar regions. There has also been a shift in phenology similar to the changes in the vegetation periods on land, i.e. in the temporal sequence of the growth periods of primary pro-

◀ *Photo 3.16-1: Zooscan images of various mesozooplankton organisms from the Baltic Sea (left) and microscopic image (dark field) of a living plankton sample from the Baltic Sea containing mainly diatoms and dinoflagellates (right). The image is magnified by a factor of approximately 10 (see scale).*

Where are the measurements taken?

The longest continuous measurement series in Germany is the Helgoland Roads time series (54° 11′ 18″ N, 7° 54′ E). It started in 1962 for phytoplankton (every working day) and in 1975 for zooplankton (every Monday, Wednesday and Friday). In addition to Helgoland Roads, three transects starting from Helgoland and extending into the Weser, Elbe and Eider estuaries are also sampled once a month. This long-term series is known as the Helgoland Transects and has also been running for over 30 years. As at Helgoland Roads, temperature, salinity and inorganic nutrients are also measured here. Phytoplankton diversity has also been surveyed for several years. The Baltic Sea time series, operated by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and set up in 1979 within the framework of the Helsinki Commission (HELCOM), records long-term changes in plankton abundance and diversity in relation to climatic and anthropogenic influences. The relevant samples are taken at 10 (phytoplankton) and 9 (zooplankton) stations on five cruises per year in February, March, May, August and November.

Monitored sites extend from the Western Belt Sea and the Arkona Sea to the Bornholm and the Eastern Gotland Basins along a pronounced salinity depth gradient that exerts a strong influence on the local plankton. The respective federal-state authorities of Schleswig Holstein, Mecklenburg-Western Pomerania and Lower Saxony (State Agency for Agriculture, Environment and Rural Areas (LLUR), State Agency for Environment, Nature Conservation and Geology (LUNG) and State Enterprise for Water Management, Coastal and Nature Conservation (NLWKN)), co-ordinated by the BLANO expert working group on eutrophication, nutrients and plankton (Fach-AG EuNäP), are working on an increasingly harmonised measurement programme in the North and Baltic Seas.

In addition, an increasing number of real-time measurements have been carried out in recent years that are largely independent of research vessels and allow continuous observations. The three underwater nodes of the Coastal Observing System for Northern and Arctic Seas (COSYNA) in the North Sea (Helgoland), Baltic Sea (Boknis Eck) and Arctic Ocean (79° N off Spitsbergen) are of particular importance. Alongside hydrographic parameters, acoustic and optical plankton data are also collected. The time series of Cape Verde Ocean Observatory (CVOO) contains continuous measurements of oceanographic moorings as well as ship-based point observations of zooplankton down to a depth of 1,000 metres. In the long term, monthly measurements are planned.

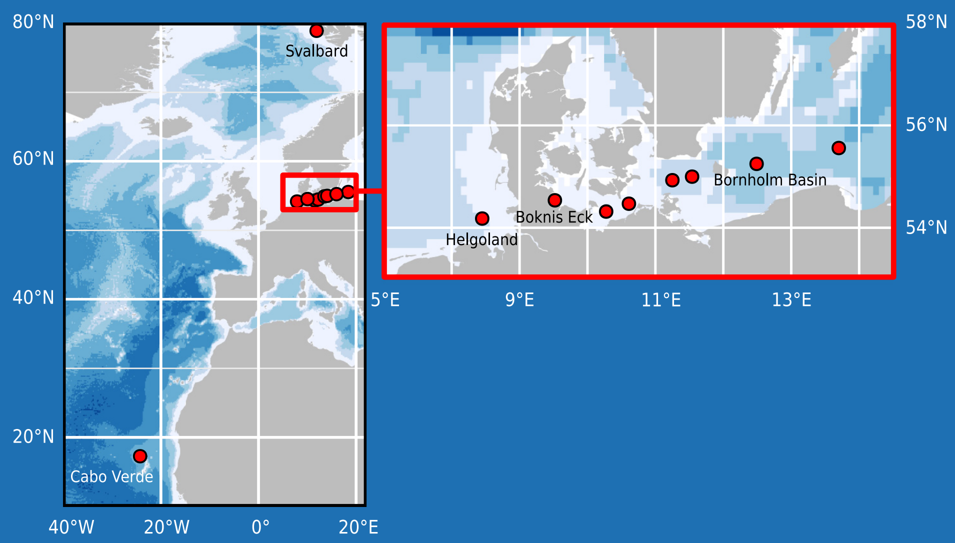


Figure 3.16-2: Maps of the plankton time series stations operated by German scientists (Source: GEOMAR) ►

ducers (phytoplankton) and the consumers (zooplankton) that depend on them. Since the presence of suitable zooplankton in spring is particularly important for fry (match/mismatch), there is a direct connection to commercially exploited fish stocks.

International context and access to data

The Working Groups of the International Council for the Exploration of the Sea (ICES) on Phytoplankton and Microbial Ecology (WGPME) and on Zooplankton Ecology (WGZE) are international expert groups that discuss and co-ordinate methods and analyses for time series. The collaboration of these ICES working groups with the WG125 of the Scientific Committee on Oceanic Research (SCOR) has laid the foundation for the integrated Coastal & Oceanic Plankton Ecology, Production, & Observation Database (COPEPOD) hosted by NOAA. The HELCOM Phytoplankton Expert Group (HELCOM PEG) co-ordinates monitoring activities in the Baltic Sea, which are carried out by the various riparian states in proportion to their coastlines. The International Long Term Ecological Research (ILTER) is an international network for long-term ecological observations, covering terrestrial as well as limnic and marine systems. The data collected by the federal-state authorities are delivered to the national Marine Environmental Database (MUDAB).

A lot of data (both from time series stations and individual sampling) are compiled in the COPEPOD database, thus opening up access to information on, among other things, abundance and biomass of major taxonomic groups (e.g. diatoms or copepods). More detailed observations at genus or species level are usually published by the individual institutions, for example on PANGAEA®, and are freely available. The COSYNA data are available to the general public on a dedicated data portal.

Where do the resources come from?

Most existing time series samples are still counted manually under the microscope and the resources needed come out of the budgets of the research institutes preforming the work, federal-state budgets or from acquired third-party funding projects. In contrast to parameters that can be measured directly by calibrated sensors, the main resource required in plankton monitoring is the time needed by well-trained personnel to perform the taxonomic evaluations. The use of image analysis (both in-situ observations and digitisation of samples) offers an increasingly attractive alternative as machine learning makes the sorting work easier and more consistent (although the results still need to be validated by experts). It also offers the possibility of a digital archive so that personnel costs can be minimised over time.

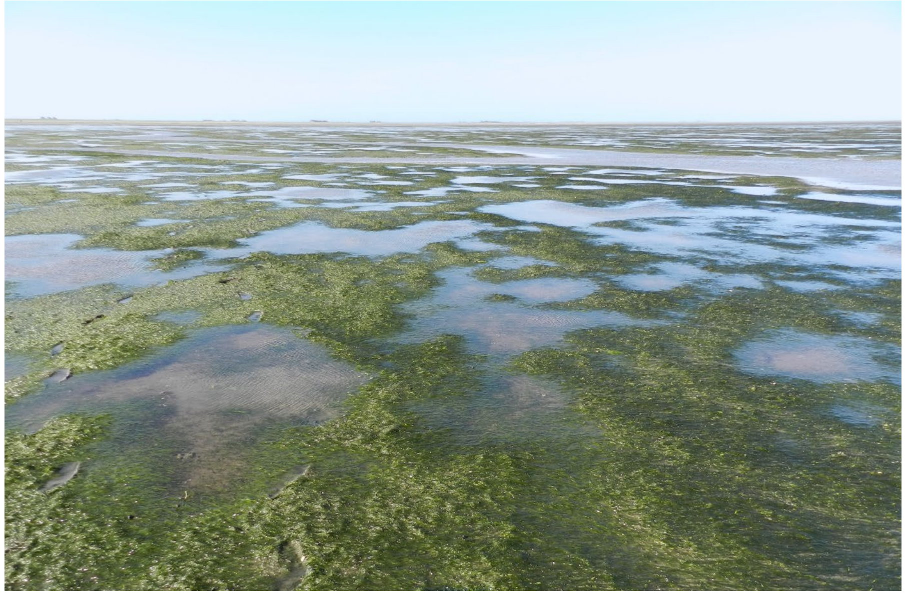
◀ *Photo 3.16-2: Quantitative plankton net catches remain an integral part of long-term plankton observations. Depending on the target group, plankton nets with different diameters and mesh sizes are used. The picture shows a bongo net (combined with baby bongo).*

ufz.de/lter-d **https://codm.hzg.de/codm/** **geoportal.bafg.de/MUDABAnwendung**

mhb.meeresschutz.info/de/kennblaetter/neue-kennblaetter/details/pid/7

3.17 Marine habitats

Germany is rich in marine habitats (not considering the pelagic realm). These include seagrass meadows, which occur both in the North Sea (e.g. near the island of Sylt) and in the Baltic Sea, as well as soft bottom benthos. Hard substrata (rocky shores) are largely confined to the area around the island of Helgoland (except for artificial substrata). Apart from scientific interests, the main motivation for marine habitat monitoring in Germany is to fulfil national and international reporting duties. Monitoring of soft bottom habitats in the German Exclusive Economic Zone (EEZ) in the North Sea takes place on the basis of European guidelines, such as the Habitats Directive and the Marine Strategy Framework Directive, and is aimed to evaluate management measures for the regulation of fisheries.



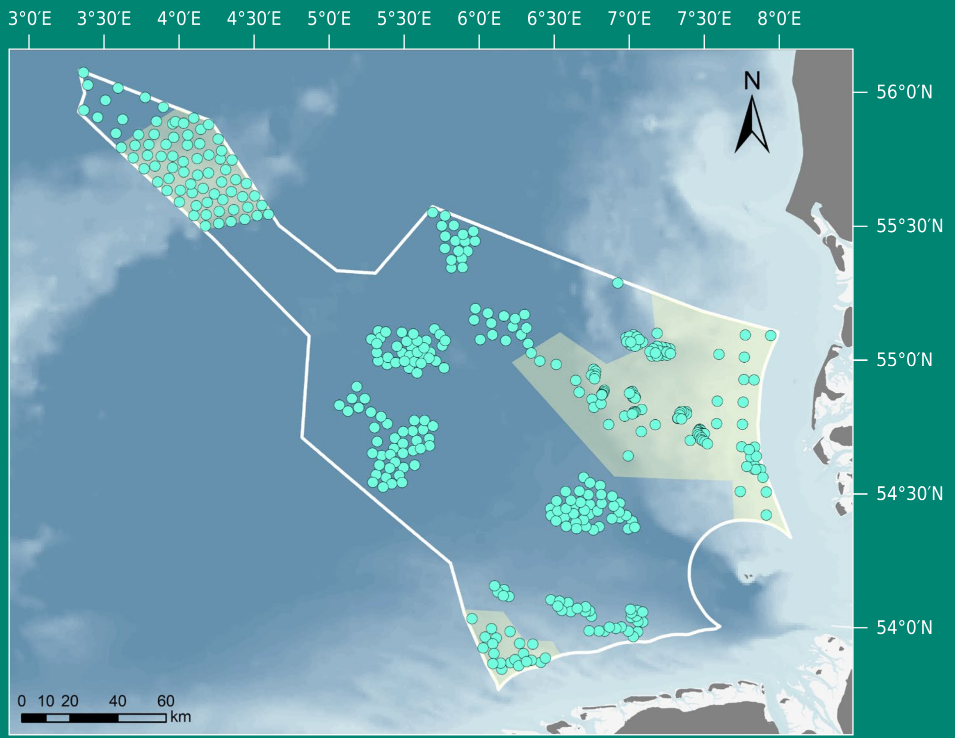
▲ *Photo 3.17-2: Seagrass occurs in groups, often growing to large meadows, such as in the North Frisian Wadden Sea near the island of Föhr.*

Climate signals

For soft bottom benthos, the monitoring activities described here have not yet led to the identification of clear climate signals.

The monitoring of macroalgal and macrobenthic species has revealed that, in recent years, more and more invasive species have migrated to the areas around Helgoland and that species that were previously only known from neighbouring coastal areas have settled there. Most of these species appear to be warm-temperate inhabitants. At the same time, the brown seaweed vegetation of the low- to mid-rocky shore level has increased, which may be the result of milder winters or springs. However, further long-term monitoring will be necessary before any firm conclusions can be drawn in this respect.

◀ *Photo 3.17-1: Seagrass meadow near Dranske, Baltic Sea*



◄ Figure 3.17-1: Overview of the stations with continuous sampling for monitoring purposes since 2011. The monitoring takes place as part of the project »Label« in the German EEZ in the North Sea and is funded by the BfN. (Source: Beermann/ AWI)

Where are the measurements taken?

Soft bottom benthos:
Macrobenthos monitoring has been carried out regularly in the German EEZ in the North Sea since 2011. Further soft bottom benthos monitoring as well as observations of fish diversity and abundance are performed by the Thünen Institute in the North and Celtic Seas as well as by the Senckenberg Institute in Wilhelmshaven for several sites in the German Bight and at Dogger Bank.

Rocky substrata:

1. Since 2004, monitoring of marine macroalgae and associated macrozoobenthos (mussels, snails) has been carried out in the area off the island of Helgoland twice a year (summer/winter). A regular georeferenced monitoring network of about 100 fixed measuring points was established in the tidal area of the abrasion platform. At each point, the percentage cover of visible species is recorded quantitatively. In addition, an overall survey is conducted once a year in summer to evaluate the macroalgal biodiversity of the intertidal area using classical morphological identification methods and georeference the spread of the stock-forming main brown alga Fucus serratus.
2. For the sublittoral, the depth distribution of character species, especially of the biomass-dominant brown seaweed Laminaria hyperborea (palm kelp), has been quantitatively recorded at least three times in six years since 2008 along three parallel depth transects.
3. In addition to macrophyte monitoring, the zoobenthos is recorded annually by the LLUR by examining replicated samples from the »Tiefe Rinne« to the south of Helgoland and from Laminaria hyperborea holdfasts.

International context and access to data

Soft bottom benthos monitoring is embedded in activities of the International Council for the Exploration of the Sea (ICES) and in the work of the expert groups of the OSPAR Commission. Relevant open data repositories are offered by the Federal Agency for Nature Conservation (BfN), ICES, OSPAR and, with CRITTERBASE, by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). The raw data are submitted to the Schleswig-Holstein State Agency for Agriculture, Environment and Rural Areas (LLUR) as the funding institution, who processes them into a standardised format for integration in its biodatabase. The AWI has also access to this database.

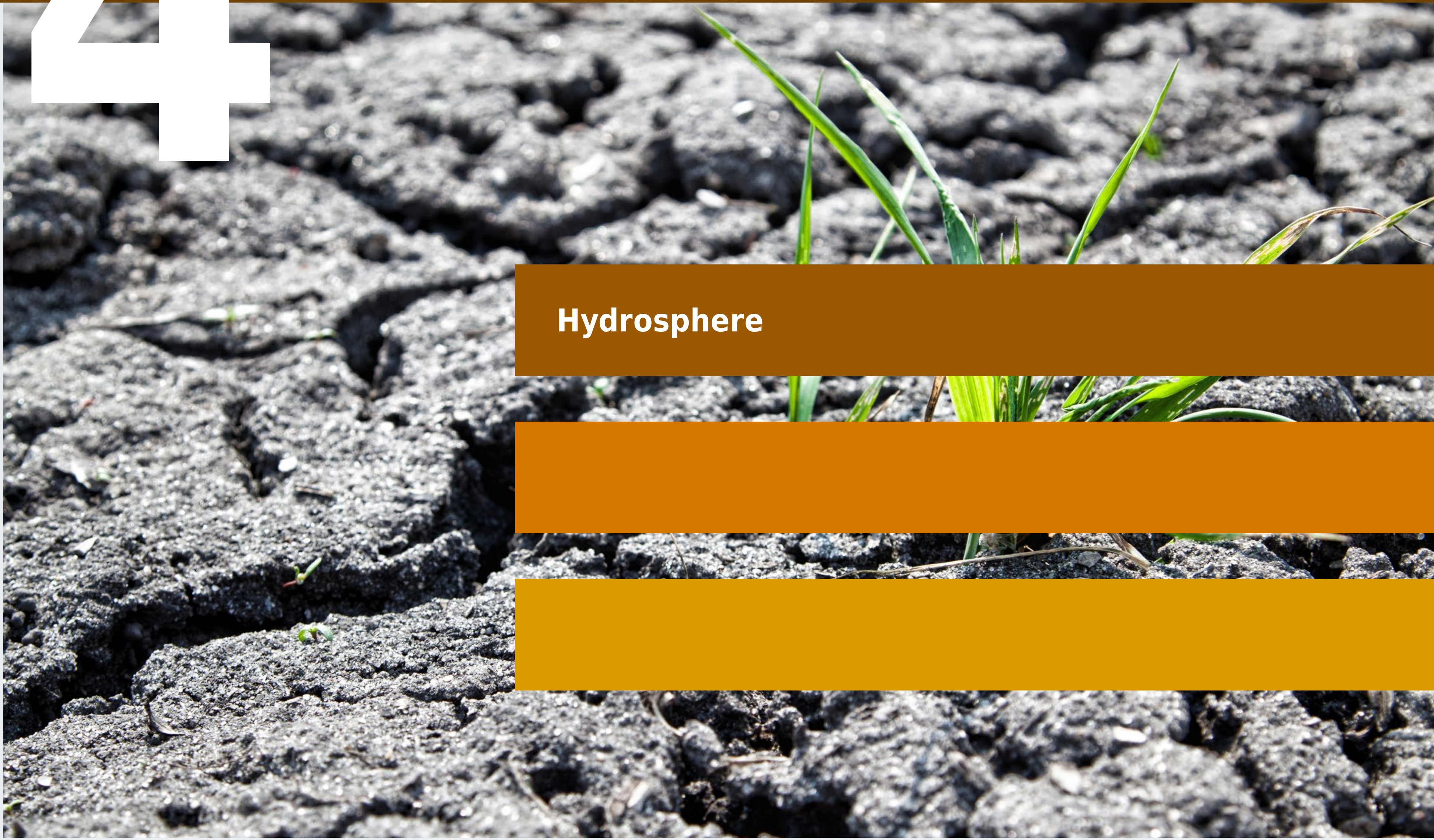
Where do the resources come from?

Monitoring activities for the soft bottom benthos in the German EEZ (the part managed by the AWI) are financed by the BfN project »LABEL« and by basic funding of AWI. The monitoring of the rocky substrata is mainly funded by the LLUR.

https://www.awi.de/forschung/besondere-gruppen/nordseebuero **ices.dk/data/Pages/default.aspx**

4 Terrestrial observations

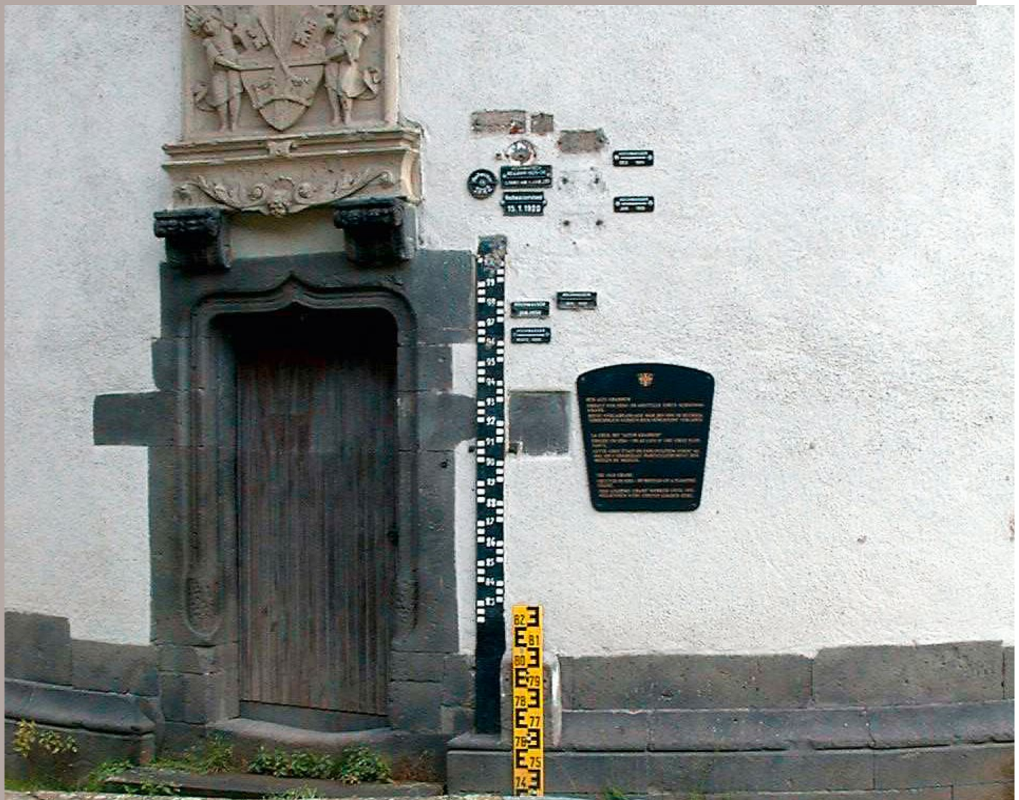
4 Terrestrial observations



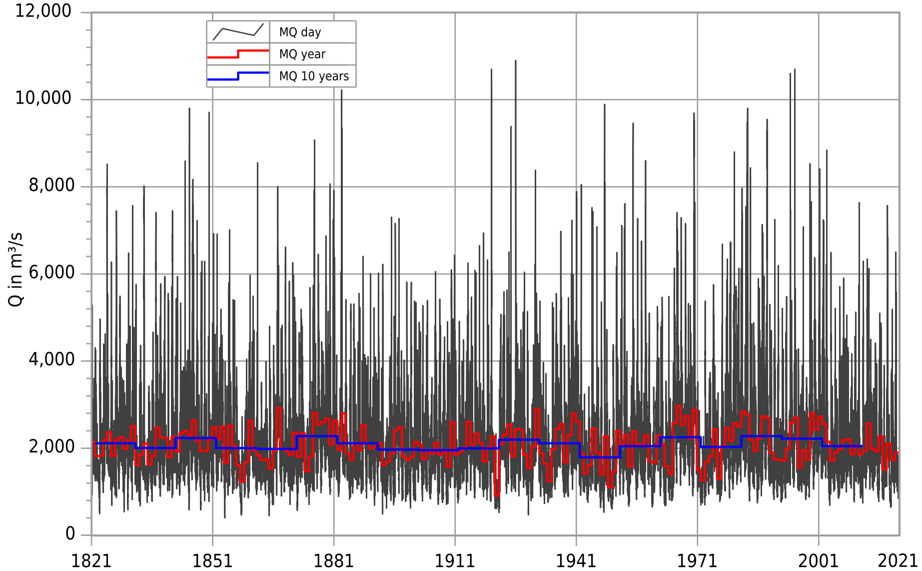
Hydrosphere

4.1 Runoff

The most comprehensive data possible on water resources, in addition to their importance today for climate studies and climate-impact research, have long been essential in the context of a wide range of socio-economic and ecological concerns. The validity of any statements to be made depends on the quality of the data material from which they are derived: outputs cannot be better than the data on which they are based.



Mean runoff at Cologne Rhine river gauge since 1821

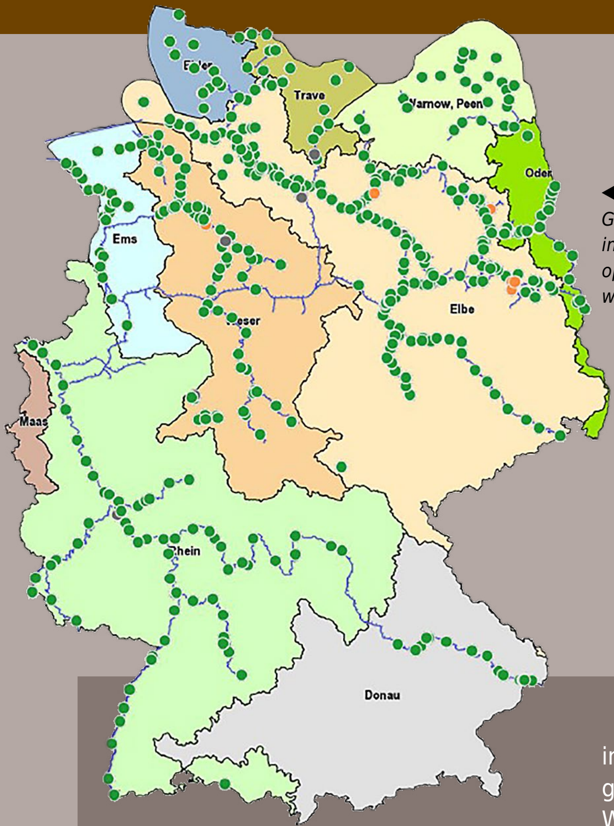


▲ *Figure 4.1-1: Daily, annual and decadal mean runoff (Q in m³/s) since 1821 (part of the time series recorded at Cologne Rhine river gauge and going back to 1816 (MQ = mean runoff)) (Souce: BfG, modified from BfG and WSV)*

◀ *Photo 4.1-1: Staff gauge with historic flood marks at Andernach Rhine river gauge*

Climate signals

Ancient civilisations already constructed water gauges and documented the observations made from them. This was often a prerequisite for the existence of communities who depended on the organised and efficient use of water as the basis of life. For example, there exists a comprehensive, around 500-year long continuous time series of annual Nile flood data from the third millennium BC. In Germany, water level measurements have been made since the 18th century. The oldest and longest time series of water levels are from Magdeburg on the Elbe (since 1727) and Düsseldorf on the Rhine (since 1766). Apart from some periodic variations, the runoff data from Cologne Rhine river gauge (see Figure 4.1-1) do not reveal any systematic long-term trend. However, this does not apply in the same way to other German watercourses. Especially the water flows of rivers in catchment areas with strong anthropogenic influence often show trend-like changes.



◀ *Figure 4.1-2: Map of river gauges in Germany: up-to-date water level data of important hydrological measuring sites operated by the WSV along federal waterways (Source: WSV)*

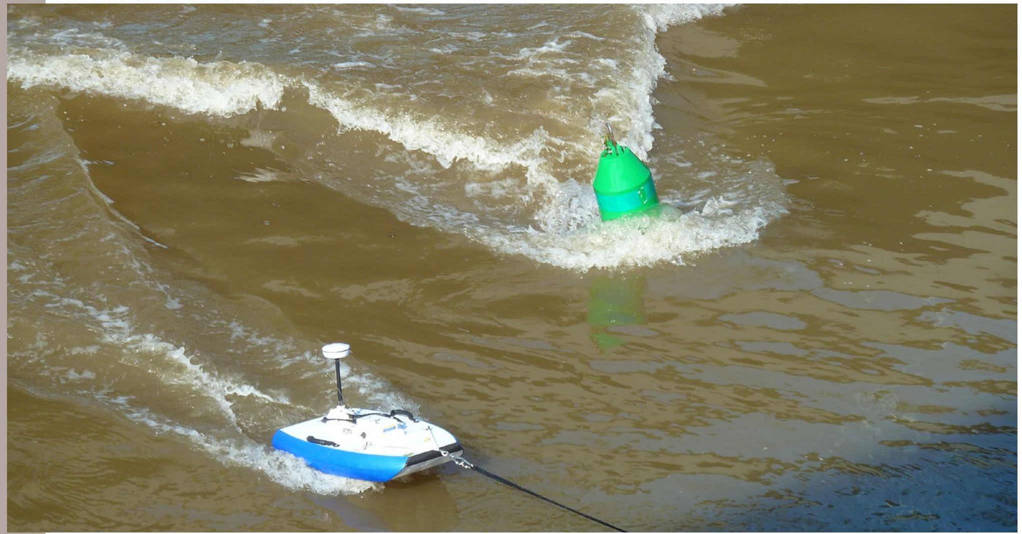


Photo 4.1-2: Runoff measurement by means of an acoustic Doppler current profiler (ADCP, in the foreground) during the Elbe flooding in 2013 ▶

Measurements in Germany

Long runoff time series are also essential for today's technological society. They enable spatial and temporal variations in runoff to be analysed, usable water resources and high- and low-water risks to be calculated, and the impacts of anthropogenic activities (climate change, changes in land use) to be investigated. Runoff data also provide the basis for the development and deployment of water management strategies, concepts and decisions.

The hydrological measuring network in Germany comprises the nationwide gauging network of the German Federal Waterways and Shipping Administration (WSV) as well as the measuring stations operated by the 16 federal states or by local authorities and third parties (e.g. water utility companies). The network consists of about 4,250 hydrological gauges, of which about 3,000 also provide throughflow measurements. This network monitors and keeps records on the entire inland waterways system (down to the level of ditches), in total around 500,000 km of waterways. The WSV is responsible for the large shipping waterways in the basins of the rivers Rhine, Danube, Elbe, Oder, Weser and Ems. In these areas, it operates numerous gauging stations for shipping and navigation operations as well as approximately 620 hydrological gauges, of which 163 also measure runoff or throughflow.

The German Hydrological Yearbook (DGJ) alone includes daily and monthly maximum runoff data from around 1,170 gauges, as well as corresponding long-term, primary hydrological statistical values, exceedance probability data and extreme values, all made available online (see link at the end). The printed version of the DGJ additionally contains historic data from numerous other measuring stations (including data series for tides, water temperature and suspended matter). The average length of runoff time series in the DGJ is 55 years. However, as standard practice, the time series are truncated at 1931 even when older data are available (in almost all basins, in particular the Rhine (20 stations), Danube (8), Weser (10), Oder (2) and Elbe (20) basins, there exist gauging sites with observational records going back more than 100 years). In addition to the DGJ, there are other important archives and distribution centres for data from gauging stations on the federal waterways. This includes the databases of the regional WSV offices and, at federal level, the data archives held by the Federal Institute of Hydrology (BfG). The federal states maintain their own databases for stations operated by them. A comprehensive overview is given by the web-based, trans-federal data portal »Pegelportal« (see link at the end).

◀ *Photo 4.1-3: Radar-based level gauge at Borkum/Südstrand with four measurement sensors*

Legal framework

As a federal country and member of the European Union (EU), Germany is subject to the EU's water regulations, such as the Water Framework Directive (WFD) and Floods Directive (FD), and has to respond to federal concerns as well as to those of the individual German federal states. This is implemented by the Federal Water Act (WHG), which sets out opening clauses for many of the regulations adopted in the German federal states. Federal navigable waterways, as well as their water level and high water information services, are regulated by the Federal Waterways Act (WaStrG). The use of collected data is regulated by the Environmental Information Act (UIG).

International context

The Global Runoff Data Centre (GRDC, see 5.2), based in Germany, receives runoff data from federal and federal-state side for more than 336 stations to feed the GRDC database (which now also includes the stations of the former European Water Archive of the UNESCO EURO-FRIEND-Water research group). The GRDC is the conduit for contributions to the Global Terrestrial Network for River Discharge (GTN-R), jointly funded by GCOS, the Global Terrestrial Observing System (GTOS) and the World Meteorological Organization's (WMO) programme for Hydrology and Water Resources (HWRP). Selected real-time data on water levels and runoff are used for medium- and long-term flood warnings by the European Flood Awareness System (EFAS), based at the EU's Joint Research Centre in Ispra, Italy.

Required resources

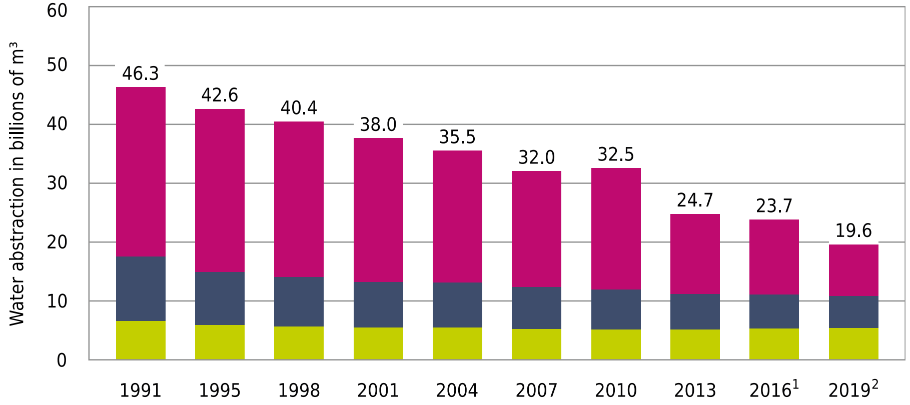
The requirements for hydrological statistics is growing due to the ever-increasing socio-political demands regarding the informational value and political relevance of hydrological information. To this end, there is not only an urgent need for having an adequate base of data available. It is also necessary to develop and implement modern methods for statistical analysis of hydrological data. At the same time, adequate resources must be guaranteed.

bafg.de **dgj.de** **pegelportal.de** **pegelonline.wsv.de**

4.2 Water use

Demographic and technological developments as well as changes in the climate will have a great impact on water demand and water availability in Germany. For this reason, knowledge about trends in water requirements by the main user groups, i.e. industries, private households and agriculture, is gaining in importance.

Water abstraction for public water supply, industries and thermal power plants



Public water supply
Mining and processing industries
Thermal power plants

[1] Saarland: Figures from the 2013 Inventory Report as no new data were available until the reporting date of the present inventory

[2] Saarland: Figures from the 2016 Inventory Report as no new data were available until the reporting date of the present inventory

▲ *Figure 4.2-1: Time series of water abstraction for public water supply (green), mining and processing industries (dark blue) and thermal power plants in billions of cubic metres (Source: Destatis)*

Trends

Over the past 30 years, the volumes of water used by thermal power stations, mining and processing industries as well as for public water supply have decreased by nearly 60 %. This is because of technological progress, use of systems of multiple use and recycling of water as well as orientational political decision-making (»energy turnaround«).

Public water supply services provide about 99 % of the private households and small businesses with drinking water, most of which is withdrawn from groundwater. In 2019, the daily demand in drinking water in private households was around 128 litres per inhabitant and day, which corresponds to a reduction of 19 litres per person in the years 1990 to 2019. However, this development was not continuous. After a decrease to 122 litres until 2007 and stagnating figures until 2013, water consumption has been increasing again. This is primarily due to changed consumer behaviour towards water saving and to the growing spread of domestic water-saving technology. The temporary stagnation of the per capita demand shows that the influence of the long-term trend is decreasing. A comparison between the federal states for 2019 has revealed consumption figures varying between 139 litres per inhabitant and day in Hamburg and 93 litres per inhabitant and day in Thuringia.

Measurements in Germany

Data on water abstraction by municipal water companies for supplies to private households and small businesses and by all types of processing and manufacturing industries, power utilities and agricultural businesses are collected at federal-state level by the corresponding statistical offices. Processing and evaluation of the data at the federal level is done by the Federal Statistical Office (Destatis). Demographic and technological progress as well as changes in the political decision-making in the field of climate and energy will heavily influence the demand for water and water availability in Germany. For this reason, knowledge about trends in water consumption by the main user groups, i.e. industries, private households and agriculture, is gaining in importance. The droughts of recent years with temporary regional water scarcity started a public debate on the prioritisation of user groups. In order to secure water resources sustainably, the Federal Government presented a national water strategy in 2021.

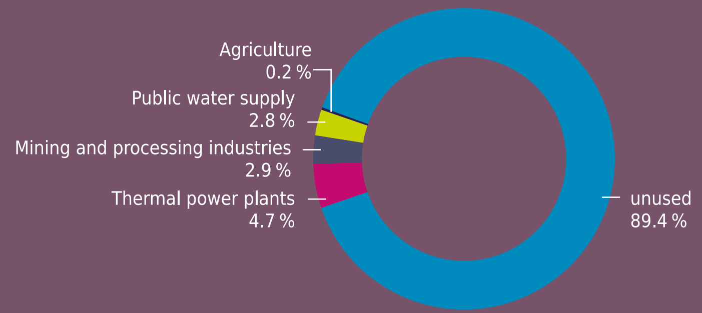
Surveys are conducted every three years. The current legal basis is the Environmental Statistics Act (UStatG) of 22 September 2021. The data are evaluated for different administrative and non-administrative territorial units and are used for public information and as an aid to political decision-making in matters of water conservation. The main users of these data are national and international authorities, institutions and associations as well as interested private persons.

The water user groups industry (including power utilities), private households and agricultural businesses withdraw different volumes of water from aquifers and surface water bodies. Industrial and agricultural businesses often operate their own water-tapping facilities to meet their demands while private households are usually supplied by municipal waterworks.

The largest water users are thermal power plants, which abstract water for cooling purposes and return nearly the whole amount after use back into the natural water cycle. The second rank among water users is now held by private households, followed by mining and processing industries.

In 2019, the total volume of water abstraction amounted to 20.7 billion m³, which was around 11 % of the potential water resources of 188 billion m³ (reference period: 1961–1990). This means that close to 90 % of the available water (long-term average) remains unused. The situation may differ greatly from year to year depending on the region.

Water resources and water use in Germany in 2019



▲ *Figure 4.2-2: Potentially available water resources of 188 billion m³ = 100 % (reference period: 1961–1990). The figures for the Saarland are those from the 2013 Inventory Report as no new data were available until the reporting date of the present inventory. (Source: Destatis 2022, UBA 2017)*

Legal framework

Water use in Germany is ruled at an overall federal level by the Federal Water Act (WHG) of July 2009 (last amended in July 2022), which implements the EU's Water Framework Directive (WFD) and – along with subsidiary national directives – regulates the protection and management of groundwater and surface water resources. The aim of sustainable water management in accordance with the WHG is the preservation of the ecological functions of water for the benefit of the general public and in the interest of individuals. Any use of water bodies, including abstraction for different purposes, requires an official permit. The WHG defines which nationwide requirements apply; reponsibility for their enforcement lies with the authorities of the federal states.

International context

Scientific assessments of water scarcity and water shortage investigate the ratio between available water resources and water demand. International institutions, such as the Organisation for Economic Co-operation and Development (OECD), the European Commission (EC) and the European Environment Agency (EEA), evaluate the national data from certain angles in order to highlight problems in the water sector and to derive recommendations for action. At the same time, they pool the data provided by the individual states in international databases and make this information available to all interested users worldwide. The German data on water quantities are transmitted to these organisations every other year as part of the joint questionnaire initiative of the EU's statistical office Eurostat and the OECD (Questionnaire on the state of the environment in the EU's Member States). The results are also made available to the EEA and the United Nations Environment Programme (UNEP).

Required resources

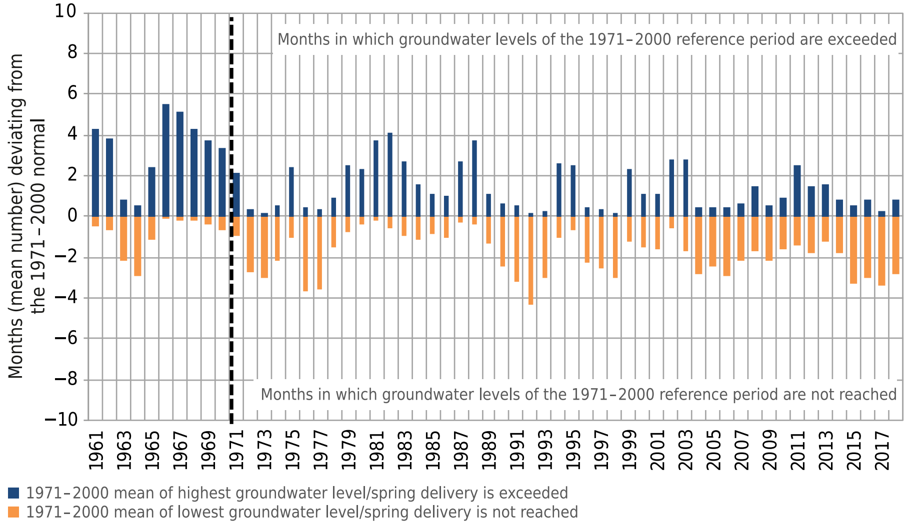
It would be desirable to adapt the frequency of national data polls to the European demand for annual data.

destatis.de **umweltbundesamt.de**

4.3 Groundwater

Groundwater meets about 74 % and thus the most important part of drinking water supplies in Germany. Groundwater is also used for irrigation and commercial purposes. In nature, it is the basis for groundwater-dependent terrestrial eco-systems and feeds surface water sources. Groundwater recharge is dependent on the weather, which makes precipitation supply a key indicator for climate-related changes.
In Germany, groundwater is subject to intensive quantitative monitoring by the federal states.

Deviation of groundwater levels at 136 gauge sites in Germany from the 1971–2000 normal



Extended range of monitoring sites as from 1971 Data source: Groundwater monitoring networks of the federal states

▲ *Figure 4.3-1: Number of months (1961–2018) in which highest and lowest mean groundwater levels have exceeded or remained below the 1971–2000 normal (Source: UBA 2019)*

Climate signals

In order to detect and record climate-related changes in groundwater levels in as spatially differentiated a manner as possible, long-running time series of comparable and representative groundwater level data are required.
In 2019, as a contribution to the monitoring report for the German Strategy for Adaptation to Climate Change (DAS) prepared under an R&D project of the German Federal Environment Agency (UBA), a small team tasked by the German Working Group on water issues of the Federal States and the Federal Government (LAWA) analysed the data of 136 groundwater gauges across Germany. The stations were chosen for being affected as little as possible by anthropogenic influences and for being representative of the upper aquifer and unconfined from the effects of atmospheric pressure. The time series available on monthly data go back to 1971 at least and are widely continuous.

For each data series, first the long-term means of highest and lowest groundwater levels were calculated, then the deviation of the monthly means (above or below the long-term highest or lowest mean groundwater level, respectively). Figure 4.3-1 shows an increase in the number of months with below-normal mean groundwater levels as opposed to no obvious trend for the months with mean levels above the long-term mean.

Legal framework

The European Water Framework Directive 2000/60/EC (WFD) and its daughter, the Groundwater Directive 2006/118/EC (GWD), constitute the principal legal foundation for groundwater protection in Germany. At national level, the protection of the groundwater is enshrined in the Federal Water Act (WHG) and in the federal states' water acts. The practical implementation of quantitative and qualitative monitoring and the evaluation of the groundwater situation is ruled by the Groundwater Ordinance (GrwV). In addition, regulations on the use of plant protection products and fertilisers have been adapted in response to evidence about nitrate, pesticides and metabolites of pesticides in groundwater.

International context

The Federal Institute for Geosciences and Natural Resources (BGR) is a partner in the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP), an initiative of UNESCO and the World Meteorological Organization (WMO). The aim of WHYMAP, which is run in co-operation with the International Groundwater Resources Assessment Centre (IGRAC), is the global mapping of groundwater resources for use in a geographic information system where all groundwater-relevant data are made available in digital form. At the European level, the information network EUROWATERNET, established by the European Environment Agency (EEA) in collaboration with the European states, has been in operation since 1998.

Measurements in Germany

Networks for monitoring groundwater levels and groundwater quality have been in place in Germany for several decades, operated by the federal states. When the two EU directives WFD and GWD came into force, this marked the introduction of the first European-wide principles for the management of groundwater bodies and for the recording and assessment of their quantitative and chemical status. Following the requirements of the Groundwater Ordinance, a dense, nationwide network of monitoring sites has been established and now records the quantity and quality of groundwater. According to investigations carried out on relevant websites and publications, the hydrological services of the federal states operate around 21,500 gauges for recording groundwater levels. In addition, there are a large number of wells belonging to private or public institutions; they serve, for example, as upstream measuring sites for water suppliers or to monitor dewatering sites. North Rhine-Westphalia alone counts more than 35,000 gauge sites.

For the assessment of the quantitative and chemical status of groundwater bodies as prescribed by the EU's WFD, the management plans for the second management cycle (2016–2021) took account of altogether 12,804 measuring sites (Bundesanstalt für Gewässerkunde 2021), of which 5,319 exclusively gauge groundwater levels and 4,100 are exclusively for water quality. Both components were measured at a total of 3,385 measuring sites.

The monitoring data are increasingly transmitted by means of automated procedures and are tested, evaluated and provided as official data using state-of-the-art methods. The majority of the federal states offer internet-based user-friendly interfaces for access either to (unchecked) near real-time water levels or to (verified) time series for groundwater levels. Through this channel, most of the federal states also offer access to the digital Water Registers, which, apart from any other water permits and authorisations, also contain permits for groundwater extraction. There is no publicly available information on the quantities actually collected.

In order to exploit groundwater measurements across the federal-state borders, standardised data services for groundwater levels would be required, such as those already available for river water levels and accessible via the app »Meine Pegel«, for example. The selection of representative gauging stations would of course have to be carried out by the experts in the federal states.

Required resources

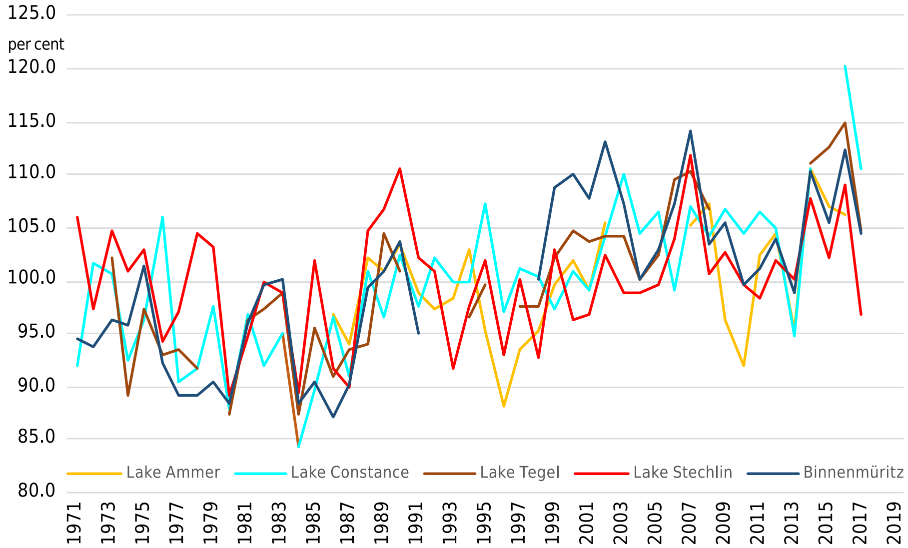
The technical prerequisite for providing up-to-date data from representative groundwater gauges already exists in the form of the data portal »Pegelportal« operated by the federal states. Integration could be done with reasonable effort via the administration interface of the respective federal-state portals. The data in question are unchecked raw data from the last two or four weeks. However, for use as an Essential Climate Variable (ECV), verified time series are required, issued by the hydrological services. It would be necessary to ascertain for each federal state the input in terms of expense and time as well as the framework conditions required to enable an electronic retrieval of these data.

bafg.de **geoportal.bafg.de/ggina-portal** **pegelportal.de** **un-igrac.org/regions/europe**

4.4 Lakes

According to the Federal Environment Agency (UBA), there are more than 12,000 lakes in Germany. They serve as water reservoirs and recreational spaces, and constitute important habitats for plants and animals. For this reason, lakes were already monitored before the EU Water Framework Directive (WFD) came into force. Due to their ecological and physical-chemical characteristics, they provide important climate indicators. Water level, water temperature, lake ice cover as well as biological quality components such as phytoplankton can be used to assess current climate-induced changes.

Evolution of the water temperatures of selected lakes in Germany (1971–2018)

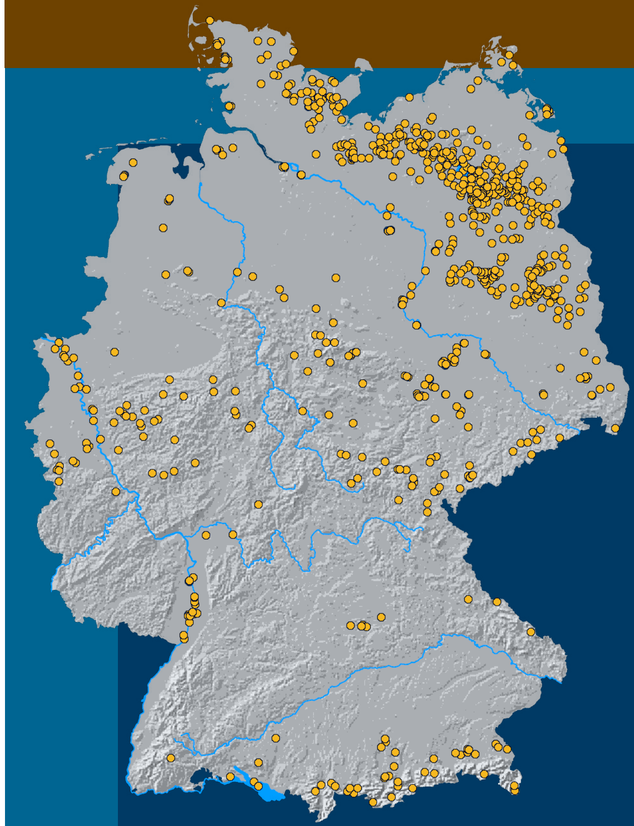


▲ *Figure 4.4-1: Evolution of water temperatures shown as the ratio of annual means (hydrological year) to long-term mean (= 100 %) for the respective lake (Source: DWD, modified from the respective hydrological services of the federal states)*

◀ *Photo 4.4-1: Western shore of the nature reserve Krakower Obersee at the southern end of Lake Krakow, Mecklenburg-Western Pomerania*

Climate signals

Given the lack of an explicit statutory mandate, long-term measurement series are only available for a small number of lakes in Germany. In addition, some years are missing in the existing series due to a lack of interest, funds or staff, or for administrative or technical reasons. The data gap at the Müritz (1992–1997) results from the reorganisation of water management structures in the east German federal states following the political changes of the German reunification. Figure 4.4-1 shows the annual means of water temperature over the hydrological year (1.11.–31.10.) for selected lakes in Germany. They have not been calculated as absolute value but in relation to the long-term mean (1971–2018) (= 100 %). Therefore, values above 100 indicate that the temperature mean of the respective year exceeds the long-term mean. Figure 4.4-1 demonstrates that, although each lake must be considered individually, developments over the years are largely parallel. All time series since the middle of the 1990s show an increasing trend.



◀ *Figure 4.4-2: Overview map of Germany with all 947 measuring sites in lake water bodies with a water surface of more than 50 ha and therefore subject to WFD reporting obligation. The samples are usually taken at the deepest point of the lake. (Source: BfG)*

Measurements in Germany

According to the history of both the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB) and the Institute for Lake Research (ISF), the beginnings of any lake research in Germany go back to the late 19th or early 20th century, respectively. The coming into force of the WFD for the first time created an obligation to carry out physical-chemical and biological tests regularly and systematically. In total, the WFD reporting obligation applies to 730 water bodies of the approximately 12,000 lakes in Germany with around 950 measuring sites. The scope of the examinations is described in detail at https://gewaesser-bewertung.de. However, the frequency (six times per year) and the period (April–October) of sampling do not fulfil all the requirements described by GCOS for the ECV Lakes. According to the subgroup on Climate Indicators instigated by the German Working Group on water issues of the Federal States and the Federal Government (LAWA), the best level of data coverage regarding water level and water temperature is only available for a small number of lakes in Germany. Older data series, in particular, contain some gaps and are based on one daily or monthly sample. Currently, there are no comprehensive and systematic measurements of parameters such as water extent and lake ice cover.

Since the introduction of automated measurement devices and given the progress in remote data transmission in recent years, measurements of lake water levels or temperatures have been available with a higher temporal resolution. They are recorded and made available in real time by the hydrological services of the federal states in the same way as the measurements taken at flowing waters. The federal states have created a joint nationwide platform, »Pegelportal«, for water level data. However, these data should be treated with reserve and not be included in the definition of this ECV without knowledge of their background. At most observed lakes, water levels are regulated, which can lead to a distortion of the climate signal for water levels. At gauges with pressure probes, the water temperature is used to correct the measurement and is therefore often not calibrated.

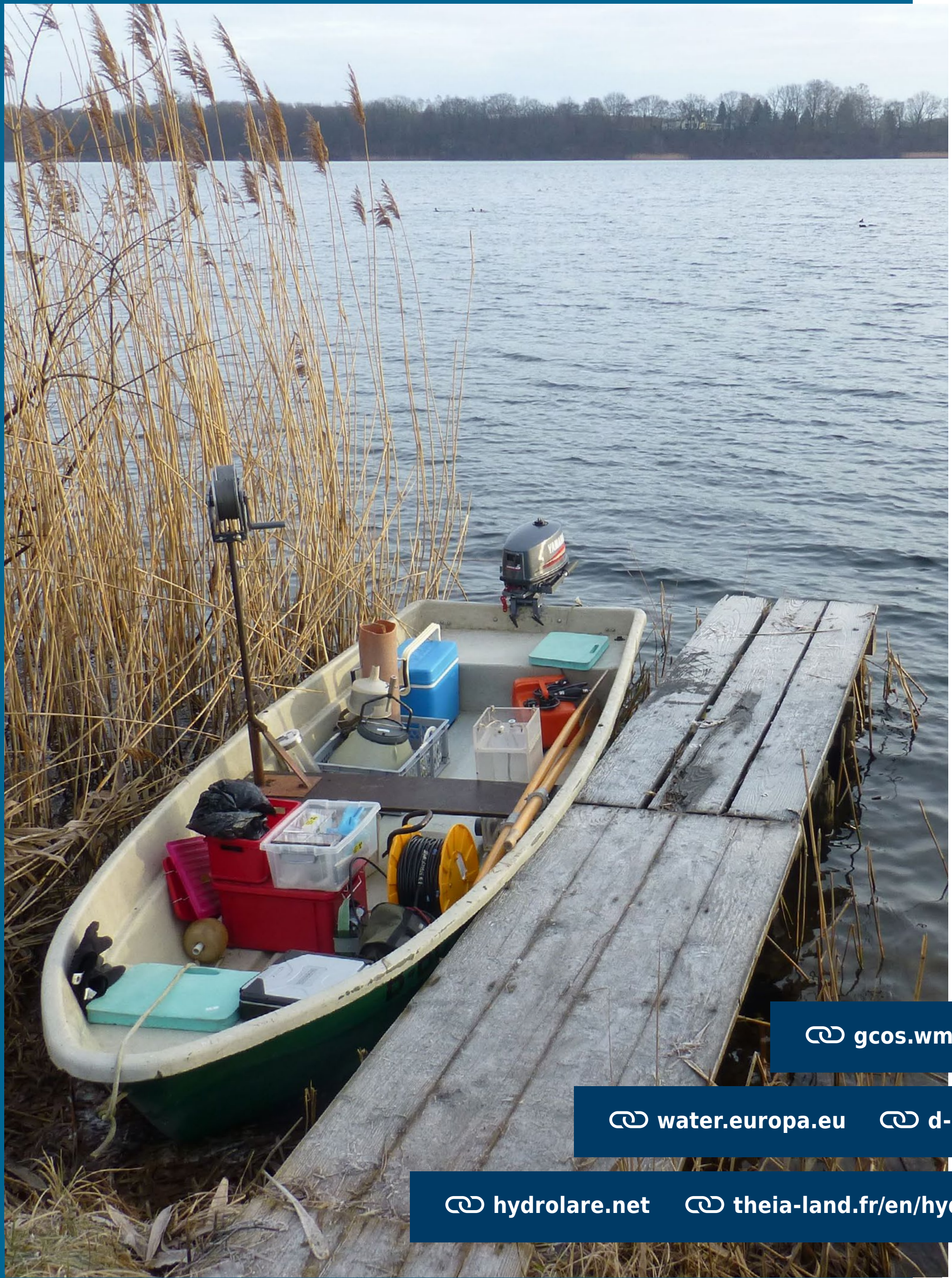
Satellite-based measurements come closest to fulfilling the requirements of the GCOS Implementation Plan 2016, especially the data products of the Sentinel missions (Copernicus). Current research activities deliver promising results for temperature, ice cover, visibility depth and chlorophyll. However, these data can only be consulted for larger lakes. Due to the so-far insufficient coverage of radar data, water levels can only be measured at selected lakes.

Legal framework

The protection of German lakes is enshrined in the Federal Water Act (WHG) and in the federal states' water acts, all of which include the implementation of the EU Water Framework Directive 2000/60/EC into national law. The minimum requirements for recording and assessing the ecological and chemical states of lakes are laid down in the German Surface Waters Regulation (OGewV). However, the recording of the Essential Climate Variable (ECV) Lakes (water level, temperature, ice cover, water extent) is not directly governed by law, which is why long-term and complete data series are not or only rarely available.

International context

At European level, there exists the information network EUROWATERNET, established in 1998 by the European Environment Agency (EEA) in co-operation with the European states. Since 2020, the work of the GCOS Secretariat has been supported by the EU. It has thus been possible to draw on the infrastructure and services of the Copernicus Earth observation programme, especially with regard to remote sensing products. For the WFD monitoring, data on the ecological and chemical states of lakes can be accessed throughout Europe via the Water Information System for Europe ■ ■ ■



(WISE). In addition, the data centre HYDROLARE provides a global database for around 550 lakes throughout the world. HYDROLARE also receives the data from Hydroweb, which contributes satellite-based continuous long-term series of water levels for 80 lakes of more than 100 km² as well as for the 20 largest rivers worldwide.

An international research team led by the Rensselaer Polytechnic Institute, USA (RPI) in co-operation with the IGB analysed a total of more than 45,000 oxygen and temperature profiles of almost 400 lakes throughout the world. The results show that the oxygen content in the lakes monitored has decreased since 1980 by 5.5 % at the surface and by 18.6 % in the deep zones.

◀ *Photo 4.4-2: Boat, laden with sampling equipment, at the Tiefwarensee, Mecklenburg-Western Pomerania*

Required resources

Real-time water levels and temperatures of lakes are already available via the federal states' water level portals and can also be accessed via the app »Meine Pegel«. The app publishes unverified raw data from the previous two (or four) weeks. In order to be used as ECV, longer verified time-series would be needed from the hydrological services. It would be necessary to ascertain for each federal state the input in terms of expense and time as well as the framework conditions required to enable an electronic retrieval of these data.

gcos.wmo.int/en/essential-climate-variables/lakes
https://gewaesser-bewertung.de
water.europa.eu
d-copernicus.de
pegelportal.de
hochwasserzentralen.info/meinepegel
hydrolare.net
theia-land.fr/en/hydroweb
igb-berlin.de/en/news/global-warming-lakes-lose-too-much-oxygen

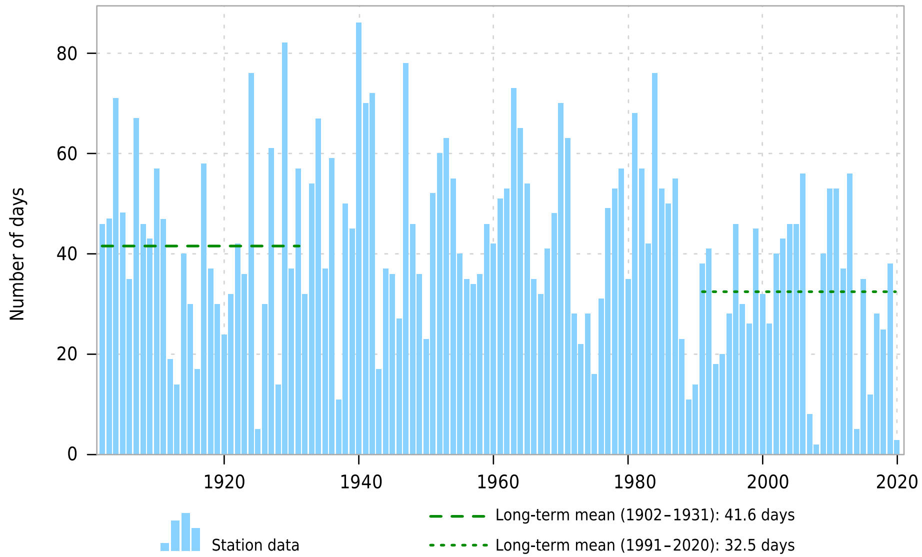
4 Terrestrial observations

Cryosphere

4.5 Snow cover

Snow cover is a major factor influencing the climate. Therefore, the parameters snow depth and new snow depth as well as the related parameters type of snow cover, state of soil and water equivalent are of particular interest and importance in the context of tourism, water management and transport as well as for estimating snow loads in the construction sector.

Snow cover days in Munich (1902–2020)



▲ *Figure 4.5-1: Snow cover days in the meteorological winter (December, January, February) at Munich weather station from 1902 to 2020 (Source: DWD)*

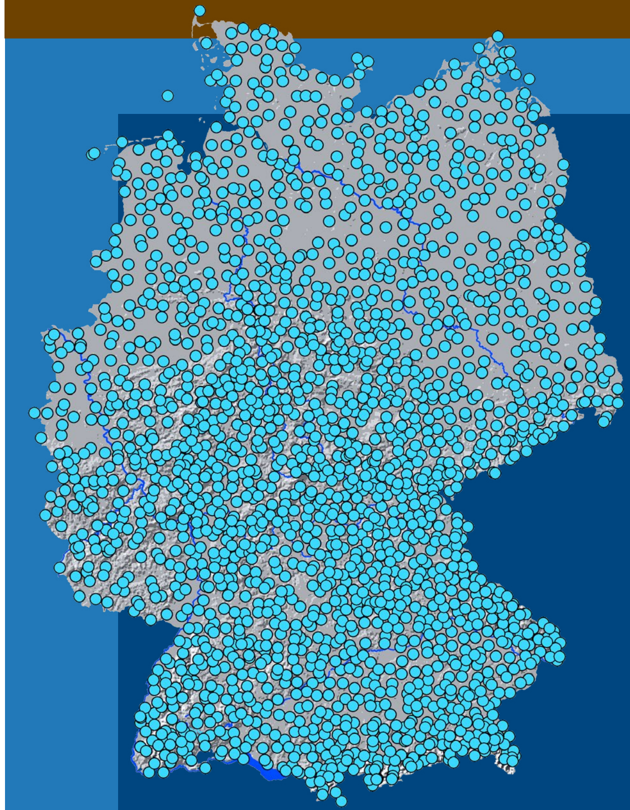
Climate signals

Against the backdrop of global climate warming, most stations have recorded a decrease in the duration of the snow cover season, but with large variations from year to year depending on the total amount of precipitation, which by its nature is also highly variable. The few outliers that may occur have no effect on the general trend towards less snow cover, especially in the last decades.

Legal framework

The Deutscher Wetterdienst Act (DWDG, Section 4) gives the DWD the responsibility for short- and long-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere, as well as for the operation of the required measurement and observation systems.

According to DWDG Section 6 and to the Ordinance Setting the Terms of Use for the Provision of Federal Spatial Data (GeoNutzV), the measurement series recorded at DWD stations are made available as open data.



◄ *Figure 4.5-2: Map of stations where snow depth and other snow parameters are recorded (Source: DWD)*

Measurements in Germany

The Deutscher Wetterdienst (DWD) operates a network of surface weather stations, which are classified into weather stations and precipitation stations. As is the case with precipitation, snow cover observation, due to the high degree of spatial variability, requires a densely distributed network of stations. Currently, there are about 1,800 stations carrying out at least daily measurements of snow depth. For the past, the number of DWD stations where snow measurements were taken varies depending on the time of the measurements or on the monitoring programme. On average, the measurement series for snow parameters date back some 70 years. From before 1950, the data archive contains no more than a couple of time series and there are only very few single digitised snow measurements available from before 1935. Currently, snow measurements of higher temporal resolution are only conducted at around 180 stations, with snow depth readings by sensors taken every 10 minutes.

Human observers used to measure total snow depth manually on a snow measuring board by means of a snow stake or a measuring stick. With the introduction of automatic stations, manual snow measurements were replaced by snow depth sensors working with ultrasonic or laser-based distance-measuring technology. When using the resulting time series, it must be borne in mind that the sensor measurements take place at a fixed point in the terrain of the station whereas manual measurements were taken at different points and then averaged over all values.

In addition to the time series already available digitally, further snow measurement records exist in paper form and are planned for digitisation under different projects. This way, snow depths from several hundred stations have been digitised, in particular during the last few years, with the aim to improve the base of data for estimating snow loads in the construction sector.

Alongside the DWD stations, there are additional snow measurement programmes run by other institutions or individual persons. However, only minor parts of these data series are included in the DWD's database as they often do not meet the high standards of representativeness, measurement methods and continuity of operation.

Satellite data, in combination with the station data, enable the provision of area-covering data sets of snow cover at high temporal resolution. At the DWD, research is under way to explore this.

International context

The synoptic reports from 180 stations are disseminated worldwide on a routine basis. For a selected number of these stations, monthly climatological information is made available in the form of CLIMAT reports. The stations at Frankfurt, Hamburg, Hohenpeissenberg and Lindenberg are part of the GCOS Surface Network (GSN).

Required resources

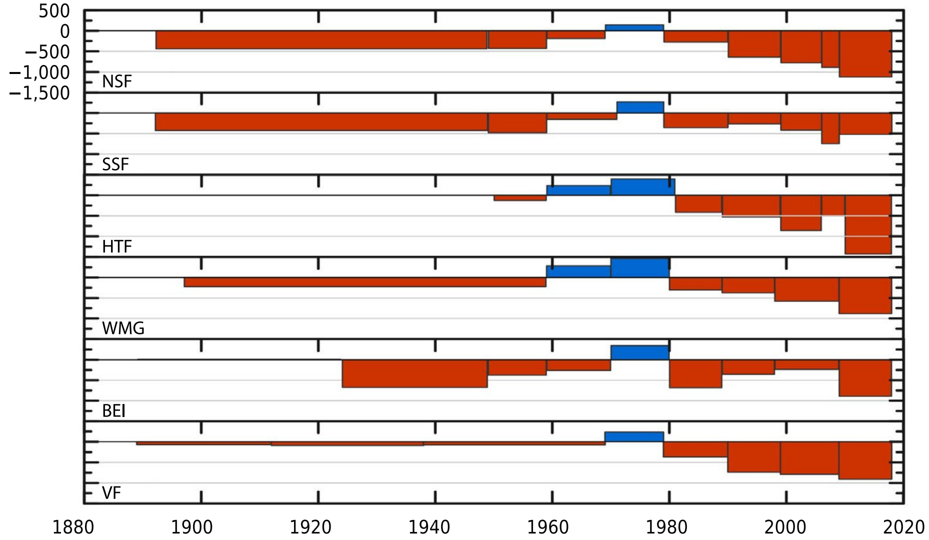
The measuring and observation network of the DWD has by now been changed almost completely to automated observation. The operation of the existing measuring stations can generally be considered as secured.

cdc.dwd.de/portal   opendata.dwd.de/climate_environment/CDC

4.6 Glaciers and permafrost

The results of alpine glacier research show clear evidence of climate change. Whereas the glacier retreat during the first half of the 20th century can be related to non-anthropogenic influences, the rapid decline over the past 40 years proves the influence of humankind on glaciers and climate, with consequences also for permafrost in mountain regions.

Time series of geodetically determined mass balances of the five Bavarian glaciers and Vernagtferner in Austria



NSF = Northern Schneeferner SSF = Southern Schneeferner HTF = Höllentalferner WMG = Watzmann Glacier
BEI = Blaueis (near Berchtesgaden) VF = Vernagtferner (Austria)

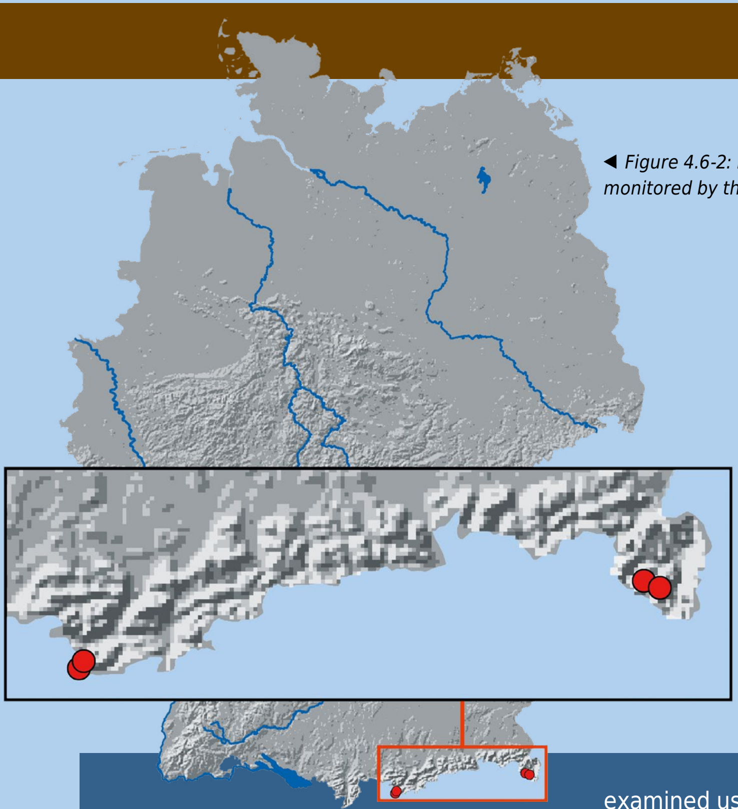
Mass gain Mass loss

▲ *Figure 4.6-1: The bars represent the average mass change per year (unit: mm water equivalent per year) for the given period, calculated from altitudinal variations (m/a) by applying a mean ice density of 900 kg/m³. A period of mass gain (blue bars) is clearly visible in the second half of the 20th century, periods of ice mass loss (red bars) are also recognisable, one after 1889 and a second one after 1980. There is also a close-to-balance period for Blaueis between 1889 and 1924. The bottom line shows the values for Vernagtferner in the Ötztal Valley, Austria (see 6.2). (Source: LfU Bayern)*

◀ *Photo 4.6-1: Zugspitz Plateau with Northern Schneeferner (August 2011)*

Climate signals

The mapping of the Bavarian glaciers, which is needed for determining the geodetic mass balance, started in 1889 for Blaueis, in 1892 for Northern and Southern Schneeferner and in 1897 for the Watzmann Glacier. The shortest period of observations is available for Höllentalferner, starting in 1949. All glaciers are observed using the »geodetic method«, based on the difference between two elevation models from different epochs for quantifying the volume change. While Blaueis is the northernmost glacier, Watzmann Glacier has the lowest mean altitude at 2,060 m a.s.l. (Mayer et al. 2021).



◀ *Figure 4.6-2: Map of Bavarian glaciers monitored by the KEG (Source: LfU Bayern)*

Measurements in Germany

The KEG periodically monitors all Bavarian glaciers – Northern Schneeferner, Southern Schneeferner (until 09/2022) and Höllentalferner on the Zugspitze as well as Watzmann and Blaueis in the Berchtesgadener Land – using the geodetic method. The comparison of geodetic measurements (digital elevation models) for periods of approximately ten years reveals changes in glacier area, surface elevation and, by assuming a mean glacier wide density, mass balance (see Figure 4.6-1). In the case of the Northern Schneeferner, the period 1962/63 to 1968/69 was additionally examined using the glaciological method. This method determines annual mass balance sums for the glaciological year (from 1 October to 30 September of the following year) by calculating the difference between mass gains (mainly due to precipitation in winter) and losses (mainly due to melting in summer). For all Bavarian glaciers, measurements of ice thickness are available that have been carried out between 2006 and 2010 using ground penetrating radar technology.

Permafrost, i.e. continuous underground temperatures below 0 °C, plays only a small role in Bavaria. Its thawing can result in damaging rockfalls and subsidence. In a study within the Alpine Space project PermaNET, Zurich University ran a model which showed that the areas mainly affected by permafrost are the northern exposed rock faces of the region, with a total area of approximately 65 km². The distribution is depicted on a map indicating the probability of permafrost. Since 2007, the Bavarian Environment Agency (LfU Bayern) has been running an observation station at the summit of the Zugspitze, from where long-term documentation of changes in permafrost is supplied.

All glaciers in Bavaria have experienced an extreme mass loss since the end of the 19th century. Since then, the glaciated area has reduced from 2.5 million m² to less than 0.45 million m², a reduction of about 82 %. During the observation period 2009–2018, the mean thickness decreased by about 7.6 m (−46 %), which relates to a mass loss of almost 66 % (Mayer et al. 2021). These changes correlate well with observations at other glaciers of the eastern Alps (see 6.2) and with the observed increase in the mean summer (JJA) temperature at the summit of Zugspitze by about 2 °C during the last 40 years.

A climate indicator (highest value of the daily average temperature measured by the sensor during the meteorological year in 23.65 m distance from the south side) was introduced to document the development of the permafrost. This value has increased by about 0.4 K during the last decade, from −1.14 °C (2011) to −0.73 °C (2020).

Legal framework

The Geodesy and Glaciology group (KEG) of the Bavarian Academy of Sciences and Humanities (BAdW) is the only national institution that studies the evolution of German glaciers over the long term. The legal framework for their work comprises Sections 2 (1 to 3) and 19 (2) of the statute of the BAdW. The observation of permafrost falls within the legal competence of the Bavarian Environment Agency (Law on the Bavarian Environment Agency (LfUG), Section 1).

International context

The results of glacier measurements made by the KEG are regularly presented in the two most important publications for glaciological monitoring data. These are issued by the World Glacier Monitoring Service (WGMS) in Zurich, Switzerland, and by the Institute of Arctic and Alpine Research (INSTAAR) or the National Snow and Ice Data Center (NSIDC) in Boulder, USA. The German results are thus made available to the key international organisations: UNEP, WMO, UNESCO and ISC. Very close co-operation exists with the universities of Innsbruck (Austria), Zurich (Switzerland) and Milan (Italy). Joint research projects are in place together with national and international groups in High Mountain Asia. The areal permafrost surveys were carried out by the LfU Bayern in co-operation with universities, agencies and governmental departments in Austria, Switzerland, Italy and France within the framework of the Bavarian PermaNET-BY. Operation of the permafrost observation station at Zugspitze summit takes place within the consortium of the Environmental Research Station Schneefernerhaus (UFS).

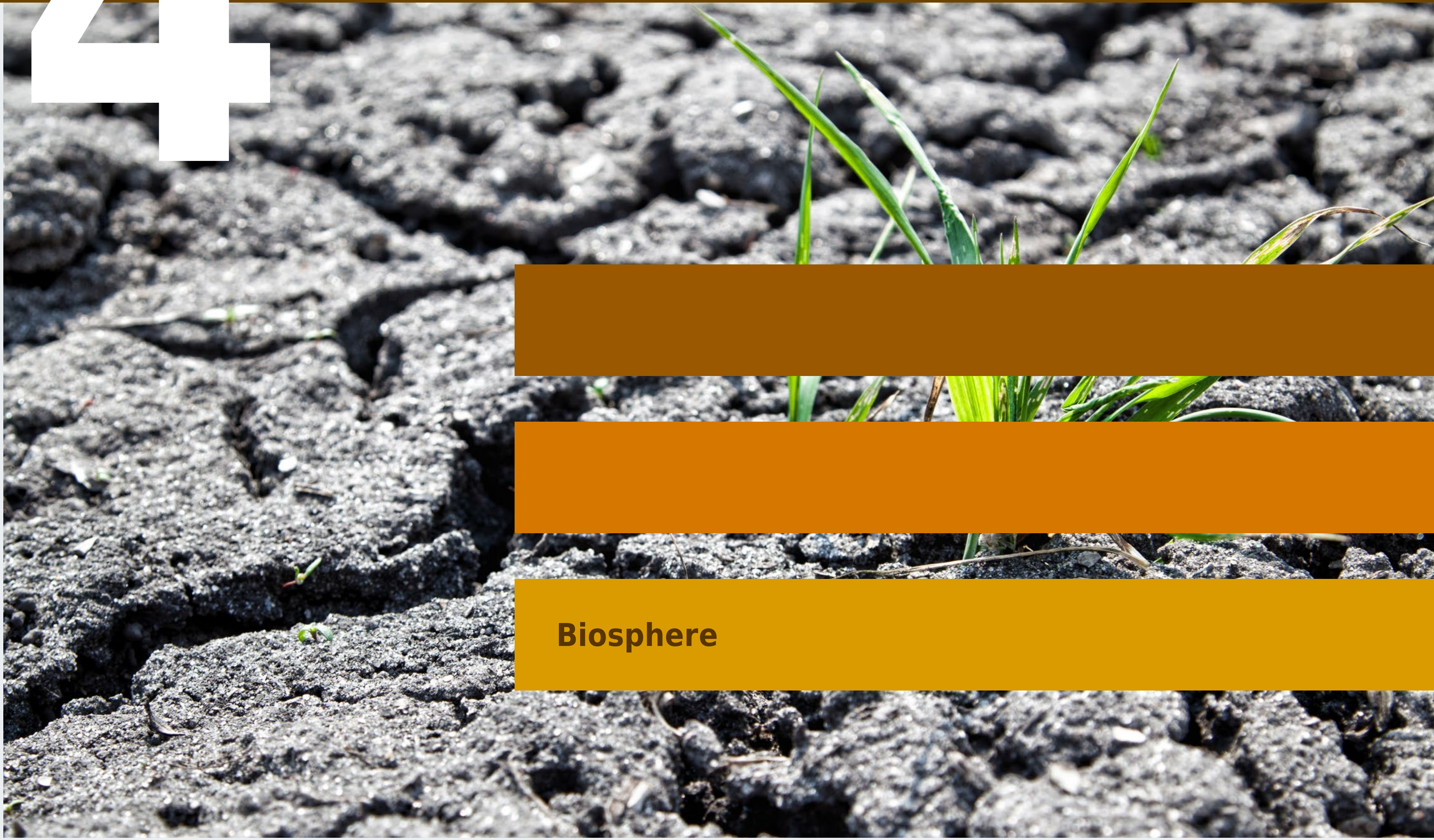
Required resources

The glaciological work at the BAdW is currently financed by the State of Bavaria through institutional funding and in addition by external project funds (e.g. German Research Foundation (DFG), Bavarian State Ministry of Environment and Consumer Protection).

◀ *Photo 4.6-2: Sampling of snow for determination of snow cover density in spring*

permanet-alpinespace.eu lfu.bayern.de/geologie/permafrost/index.htm geo.badw.de/en bayerische-gletscher.de

4 Terrestrial observations

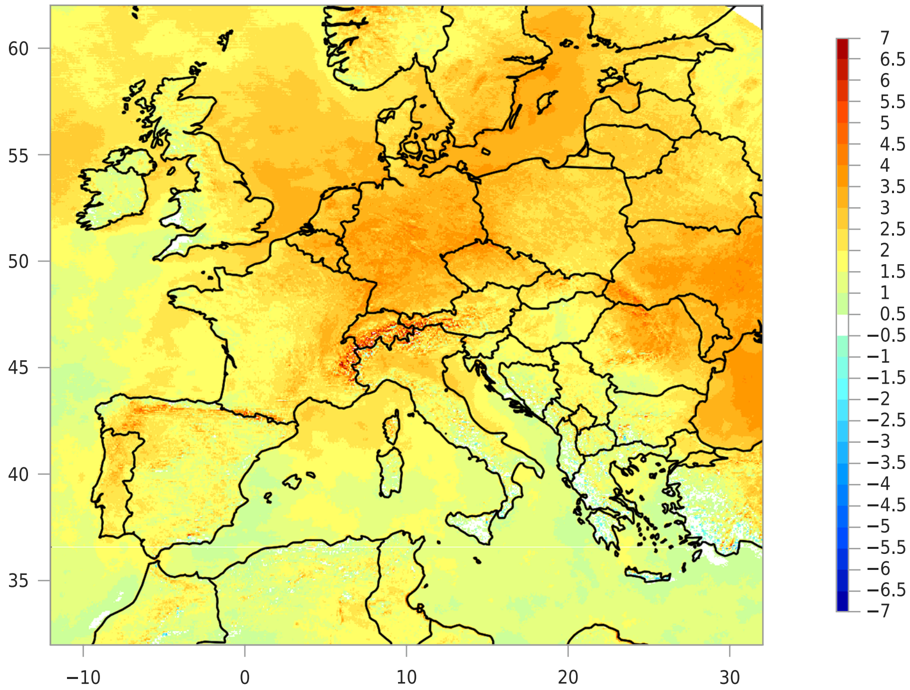


Biosphere

4.7 Albedo

Surface albedo represents an important component of the radiation balance at the Earth's surface. Trends in surface albedo influence radiation from the Earth's surface and thus also the climate system. Effective cloud albedo (Mueller et al. 2011) defines the albedo of clouds relative to cloudless sky. Even a small percentage change in effective cloud albedo would have an effect comparable in magnitude to the anthropogenic greenhouse effect. A long-term change would therefore have huge consequences for the interpretation of temperature measurements.

Trend in solar surface irradiance in W/m²/decade (SARAH-2.1 with ICDR, 1983–2020)



▲ *Figure 4.7-1: Trend in solar surface irradiance over Europe (1983–2020) in W/m²/decade resulting from long-term changes in effective cloud albedo (Source: CM SAF)*

Climate signals

The EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF, see 5.8) currently offers a time series for surface albedo (SAL) and effective cloud albedo (CAL) covering more than three decades. CAL and SAL are also available via the EUropean Reanalysis and Observations for Monitoring (EURO4M) project. Long time series enable trends and extremes of surface albedo to be analysed, which, in Germany, are generally related to variations in winter snow cover. This may be the reason why no clear trend in surface albedo can be discerned. The analysis of seasonal SAL trends is therefore probably more appropriate in central Europe. The three arid summers in 2017, 2018 and 2019 might be a clear indicator for a climate change and a potential increase in arid summers could lead to increasing trends in SAL, which should be considered within the analysis of the climate system. ■ ■ ■

By contrast, the effective cloud albedo shows significant trends. These long-term changes in the effective cloud albedo lead to regional trends in solar surface irradiance of up to several W/m² per decade (see Figure 4.7-1). Until now, however, this parameter has hardly been taken into account by climate monitoring programmes. The main reason for this has been the lack of data. Effective cloud albedo cannot be determined from surface measurements. However, climatological time series for cloud albedo have been available from the CM SAF for several years.

Legal framework

On the one hand, the work of the CM SAF is embedded in the legal framework of the Deutscher Wetterdienst (DWD). On the other hand, it is undertaken in accordance with contractual agreements between the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the DWD. The CM SAF's tasks include the long- and short-term observation and registration, monitoring and evaluation of meteorological processes and of the structure and composition of the atmosphere. It also has responsibility for ensuring the availability, archiving, documentation and release of meteorological and climatological spatial data and services. Both these tasks are in accordance with Section 4 (1) (4 and 9) of the Deutscher Wetterdienst Act (DWDG). Detailed work plans and task specifications are set out in accordance with these aims in a five-year contract between EUMETSAT and the DWD, with the participation of the concerned partner organisations of the CM SAF.

International context

The products and procedures of the CM SAF not only serve the aims of GCOS but are also relevant for other international programmes, such as the World Climate Programme (WCP) and the World Climate Research Programme (WCRP). They are essential for the activities undertaken by the Group on Earth Observations (GEO) and under the Copernicus Earth observation programme. The CM SAF is also involved in European initiatives, for example the European Space Agency's (ESA) Climate Change Initiative, and in several other EU projects (for example EURO4M).

Measurements in Germany and in Europe

Comprehensive data on surface albedo of a sufficiently high quality are only obtainable from satellite or reanalysis data. Present reanalysis data have a very coarse spatial resolution (≥ 30 km², ECMWF Reanalysis v5 (ERA5)). For this reason, comprehensive high-resolution data are currently only available from satellite observations. In Europe, high-quality data on surface albedo at high temporal and spatial resolutions come from the Satellite Application Facilities (SAFs), all financed by the national meteorological services and EUMETSAT. These also include the SAF on Land Surface Analysis (LSA SAF) for near real-time land surface data and the SAF on Ocean and Sea Ice (OSI SAF) for information on ice coverage and, indirectly through this, on surface albedo.

Long time series of surface albedo, the basis for analysis of climatologically relevant trends and extremes, are currently only available from the CM SAF and EUMETSAT (Govaerts 2008).

The creation of comparable quality raster data from surface measurements is not possible due to the low spatial density of measuring stations. In Germany, there is only one adequately equipped measuring station with long-term data on surface albedo, namely the DWD-run station of Falkenberg.

As to effective cloud albedo, comprehensive data of a sufficiently high quality are only obtainable from satellite or reanalysis data. Corresponding climatological time series are available from the CM SAF. Satellite-based cloud albedo data feature higher resolutions and it can be assumed that they yield a higher accuracy than reanalysis data.

Required resources

A general problem consists in the lack of scientific capacity for analysis of the incoming data sets. This is essentially due to a lack of basic funding for university appointments, which makes sustainable research almost impossible. Creating a long time series for albedo from satellite data would require about 48 person months, as well as several terabytes of digital storage capacity. A one-off analysis of the data set would require around a further 48 person months.

cmsaf.eu **landsaf.ipma.pt** **osi-saf.eumetsat.int**

4.8 Soil carbon

Forests play an important role in the global carbon cycle as plants absorb carbon dioxide during photosynthesis, binding it in the biomass in the form of carbon. Around one half of it is released back into the atmosphere by plant respiration. With the decay of plants, the remainder enters the soil, for example in the form of leaf or root litter. Soil is the largest reservoir in the active carbon cycle of terrestrial ecosystems. Estimates of global soil carbon show reservoirs to a depth of 1 m of around 1.5 × 10^{12} tonnes (Jobbágy and Jackson 2000). The largest soil carbon stocks are found in wetland and in peatlands.

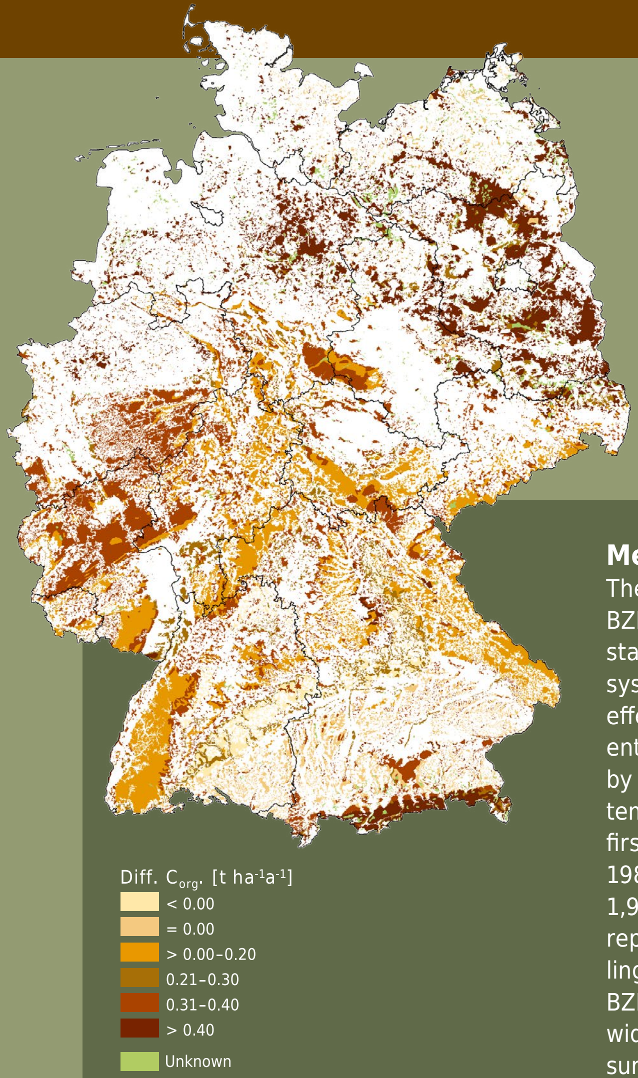
Climate signals

The amount of carbon remaining in the soil in the form of organic matter depends on temperature and water availability. Accordingly, climate and climate change have a great impact on the size and development of carbon stocks. Larger changes in the volume of carbon stored in soil due to release of carbon dioxide or methane into the atmosphere can, in turn, have a significant impact on the climate. In Germany, carbon stocks were extrapolated and annual change rates calculated from data collected for national forest soil surveys (in German referred to as BZE-Wald). Accordingly, the National Inventory Report for the German Greenhouse Gas Inventory relates an annual change in the carbon stocks of 0.41 ± 0.11 tonnes (Grüneberg et al. 2014). Although the data on changes in carbon reservoirs were presented in the national inventory reports, they were not taken into consideration for the stocktakes. Based on current knowledge, it is problematic to ensure continuous updating of the data. The upcoming third national forest soil survey, BZE III-Wald, is expected to provide new insights into changes in soil carbon from 2026 onwards. No trend has yet been identified resulting from the German national survey for agricultural soils, BZE-LW, which so far has been conducted just once.

Legal framework

The national forest soil inventories were established as an outcome of the debate about damaged forests at the end of the 1980s and have since become an integral part of forest monitoring. In accordance with the federal structure of Germany, responsibility for data collection lies with the federal states, which transmit the data to the Thünen Institute of Forest Ecosystems for evaluation at national level. Last amended in 2010, the German Federal Forests Act (BWaldG, Section 41a) provides that, with the consent of the federal states and by way of statutory instrument, the Federal Ministry of Food and Agriculture (BMEL) may collect data on the nutrient supply and pollution of forest soils. The corresponding ordinance authorising the third BZE III-Wald survey was decreed in 2020. There are no legal regulations governing the counterpart for agricultural soils, but it has been agreed with the BMEL to task the Thünen Institute of Climate-Smart Agriculture with the execution of the respective survey. Under the terms of the United Nations Framework Convention on Climate Change (UNFCCC), Germany has committed itself to report on anthropogenic sources and sinks of greenhouse gases as well as on changes in soil and biomass carbon stocks (UNFCCC Articles 3.3 and 4.1). This commitment also applies to soils used for agricultural purposes. The international regulatory framework of the Intergovernmental Panel on Climate Change (IPCC) requires countries to provide data on the main carbon sources. In ■ ■ ■

Germany, this includes data on soils used for agriculture and forestry as well as data on built-up areas and corresponding land use changes. Germany's national forest soil inventories also contribute to the reports under the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) of the United Nations Economic Commission for Europe (UNECE). In addition, it provides information required for implementing the Federal Soil Protection Act (BBodSchG) regarding the prevention of harmful soil changes (in particular Section 9).



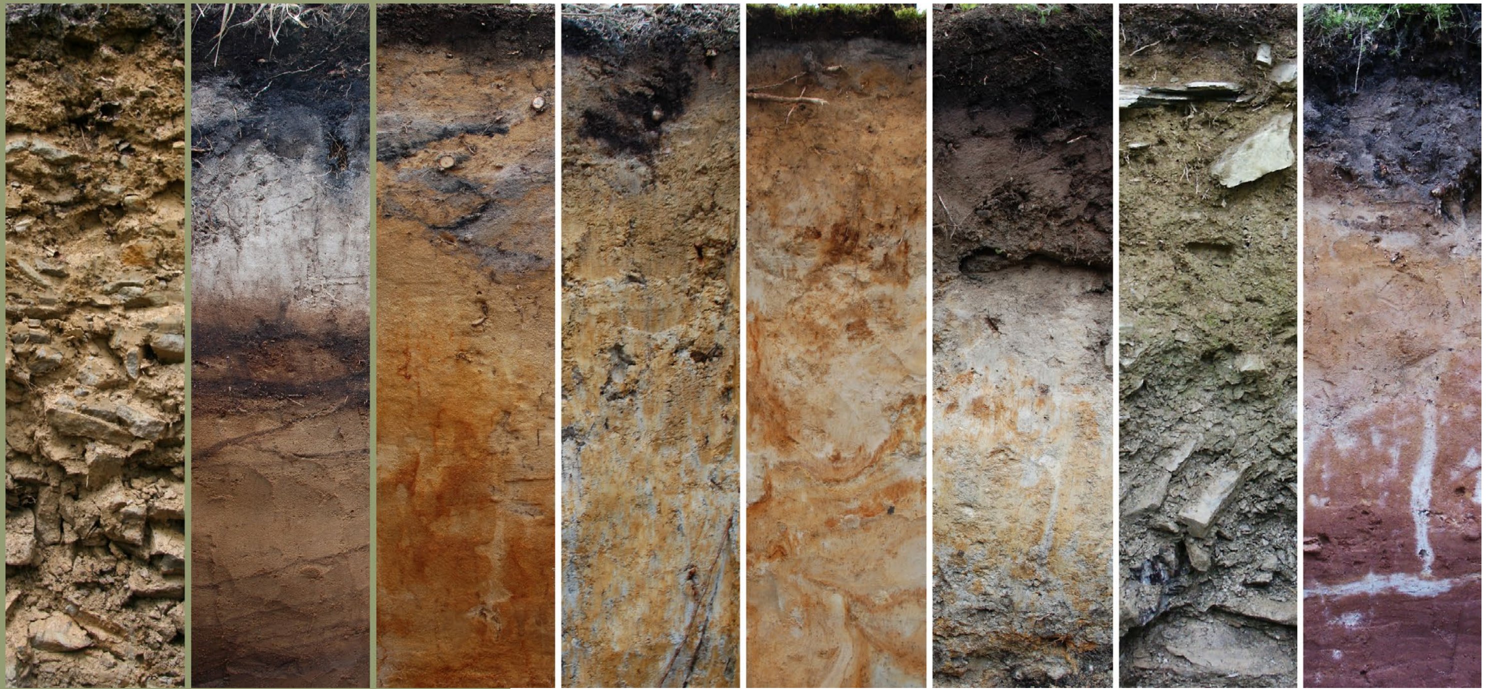
▲ *Figure 4.8-1: Annual change rate of organic carbon stocks in the upper 30 cm of the mineral soil in German forests between 1990 and 2006 (Source: Thünen Institute of Forest Ecosystems)*

Measurements in Germany

The German national forest soil survey, BZE-Wald, is aimed at monitoring the state and development of forest ecosystems and at analysing cause-and-effect relationships. To this end, the entire forest area in Germany is spanned by a nationwide representative and systematic 8 × 8 km sampling grid. The first inventory was conducted between 1987 and 1993, with samples taken at 1,936 sites. In the years 2006 to 2008, a repeat survey took place at 1,859 sampling sites. The agricultural soil survey BZE-LW (2011–2018) was the first nationwide consistent and representative survey of carbon stocks in the upper 100 cm of agricultural soils in Germany. The measurements to determine soil carbon stocks were taken at a total of 3,104 sampling points on arable land, pastures and special crop areas. For this survey, the sites were also chosen based on a representative, systematic 8 × 8 km grid spanning the whole of Germany. The results of the second BZE-Wald survey (Wellbrock et al. 2016) and the first BZE-LW (Jacobs et al. 2018) give an overview of the current state of the major part of soils in Germany. In addition, Germany contributes with an own component to the European Integrated Carbon Observation System (ICOS) and operates altogether 18 monitoring sites on arable land and pasture, in forests and on peatland. Apart from measuring greenhouse gases (Eddy covariance method), these stations also record changes in soil carbon stocks, in some cases with records going back to 2001. Permanent soil observation as carried out by the federal states covers around 780 baseline observation sites and around 100 intensive observation fields in woods and on arable land, pastures and special crop areas, sometimes situated in settled areas. Most permanent soil observation fields have existed since the 1980s and early 1990s, with organic carbon levels in the soil recorded around every five years.

International context

At European level, a subsample of data collected for the national forest soil inventories on a 16 × 16 km grid is examined in a comparative analysis under the ICP Forests programme. The methods to be applied for data collection are set out in a manual (UNECE ICP Forests 2016). Comparability of data is guaranteed by regular participation in international ring tests. The Parties to the UNFCCC are running inventory and monitoring programmes that are partially comparable to this. However, there is no internationally standardised methodology. The Land Use and Coverage Area frame Survey (LUCAS) carried out for Europe also provides uniform baseline data on soil carbon stocks. The aim of this project is to create a harmonised data set on land cover and land use within the European Union. So far, four surveys have been carried out, with several adjustments made to the parameters collected and, in some cases, to the location of the sampling sites and the sampling methods. Comparability of the different data sets as well as cross-border evaluation are therefore only possible with restrictions.



▲ *Figure 4.8-2: The diversity of soils is reflected in the different properties and special functionalities resulting from bedrock, surface of the landscape, climate and vegetation. Soils therefore are a good indicator of our environment as they store and filter substances, protect drinking water and are the ground on which trees, plants and animals grow and live. (Source: Thünen Institute of Forest Ecosystems)*

Required resources

Despite Germany's UNFCCC obligation to report on anthropogenic sources and sinks of greenhouse gases as well as on changes in soil or biomass carbon stocks, and also despite the IPCC's request to provide national data on the main carbon source groups (such as agricultural and forestry soils), there is still no uniform legal basis for recording soil carbon. In 2021, the Peatland Monitoring Program for Climate Protection (MoMoK) was launched, a BMEL-funded pilot project aimed to improve the base of data on organic soils. Responsibility for organic soils in non-forest landscapes lies with the Thünen Institute for Climate-Smart Agriculture; the study of forest sites is the task of the Thünen Institute of Forest Ecosystems. First results are expected for 2025. The sample size of BZE III-Wald, which was started in 2022, is similar to those of the previous forest soil inventories. The first repeat survey for the agricultural soil survey BZE-LW will start in 2023. This marks the beginning of regular monitoring of soil carbon stocks in Germany. However, there is currently no legal provision for ensuring continuous stocktaking.

umweltbundesamt.de/publikationen/bodendaten-in-deutschland-0

thuenen.de/de/fachinstitute/agrarklimaschutz/projekte/bodenzustandserhebung-landwirtschaft-bze-lw

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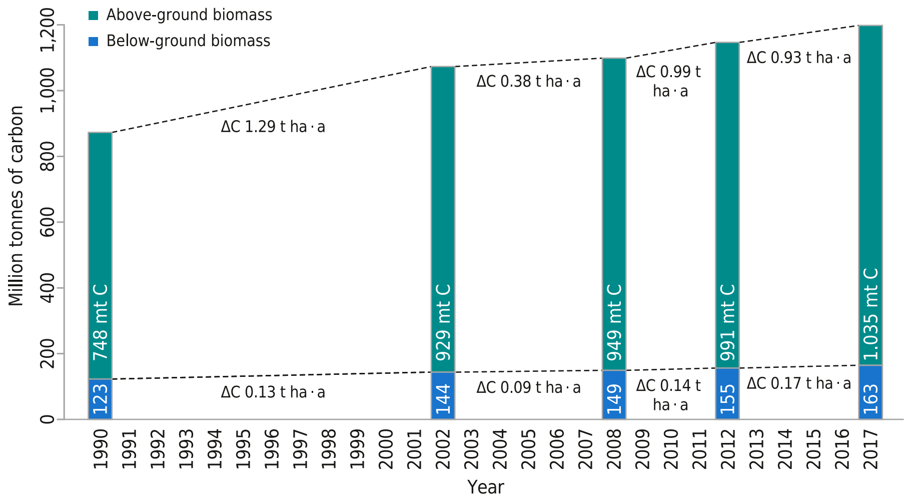
4.9 Above-ground biomass in forests

Forests in Germany represent an important biomass reservoir. The living biomass stocks of forests increased until 2017 to a new record of 227.4 tonnes per hectare of forest, with 86.3 % accumulated above ground and 13.7 % below ground in the roots. However, what is important is not only the forests' function as a reservoir but also their contribution as a CO_2 sink. Between 2012 and 2017, an additional 4.2 tonnes of CO_2 were accumulated per hectare and year in the living biomass. The impact of the calamities of recent years will be shown in the German National Forest Inventory (BWI) 2022.

◀ *Photo 4.9-1: Inventory team collecting data for a national forest inventory*

Evolution of carbon stocks in the living biomass



▲ *Figure 4.9-1: Carbon stocks and carbon-stock changes in the below- and above-ground forest biomass for 1987/1993, 2002, 2008, 2012 and 2017 (Source: TI)*

Climate trends

In order to comply with international treaty obligations, Germany must once a year produce a National Inventory Report (NIR) for the German Greenhouse Gas Inventory. This annual report documents the evolution of the carbon reservoir »above-ground biomass«. Estimates of the above-ground forest biomass are based on data of the national forest inventories (BWI) and the intermediary carbon inventories. The changes observed from one inventory date to the next provide information on the carbon evolution.

Data collection for the BWI 2022 has started in the spring of 2021 for completion in late 2022. It will be followed by a validation of the collected data and the derivation of additional parameters. Data will be aggregated according to a wide range of classification features as well as for different spatial units of reference. Results are expected to be published in 2024.

We know from the national forest inventories and other forestry inventories that since the Second World War there has been a continuous increase in the biomass stocks and therefore also in the above-ground biomass in German forests. At 2.07 billion tonnes, they have currently reached a record level, with the carbon share amounting to 50 %.

Legal framework

The national forest inventories serve as a basis for international reporting duties, such as given under the UN Framework Convention on Climate Change, the Paris Agreement, the Regulation (EU) 2018/1999 (Article 18), the FAO's Global Forest Resources Assessments and the Convention on Biological Diversity (CBD). Even beyond the climate sector, they provide important information for political and economic decision-making and research. The legal framework is laid down in Section 41a of the Federal Forest Act (BWaldG), which defines both the objectives of the national forest inventory and the division of labour between the Federation and the federal states. The act also enshrines in law not only the carbon inventories, carried out between two national forest inventories and under the sole responsibility of the Federal Government, but also the access rights of the inventory teams.

Except for the co-ordinates, protected to safeguard the samples' representativeness, the complete data of the inventories can be freely accessed at bwi.info.

Measurements in Germany

The German National Forest Inventory is based on a one-phase stratified cluster sampling scheme, with a 4 km square grid. If necessary, the federal states have the option of increasing the density of this basic grid to resolutions of 2.83 km by 2.83 km (doubled sampling density) or 2 km by 2 km (quadrupled sampling density) to improve the statistical significance of the inventory's results at a regional level. At the intersection points of the grid, square clusters with a size of 150 m by 150 m have been installed. Samples are taken at the four corners of the clusters (cluster points), if these are located in the forest. The cluster points are permanent but marked invisibly in the soil. This ensures that the samples are always taken at the same points, which increases the statistical reliability of the findings of any changes and enables specific evaluations of losses and gains.

Consequently, there are around 195,000 sampling points over the whole of Germany, of which approximately 75,000 are located in forests. The latter are visited on the ground and registered by specially trained inventory teams.

International context

Almost every country in the European Union carries out sample-based national forest inventories. The increasing necessity for independent inventories became clear to the various states in the second half of the 20th century for different reasons. This is why the forest inventories are structured differently and certain parameters are not defined uniformly. In order to overcome these differences and provide comparable results at a European level, the national institutions in charge of carrying out the inventories have joined forces. Under the umbrella of the European National Forest Inventory Network and, together with the European Union, they are pushing ahead projects aimed at harmonising the inventory dates.

Required resources

The German National Forest Inventory is a joint effort of the German Federation and the federal states. The Federation co-ordinates the survey. It is responsible for the sampling techniques and training events and for evaluating the inventory data. The federal states are responsible for the data collection. The Federation provides the public with online access to the results at both levels, Federation and federal states.

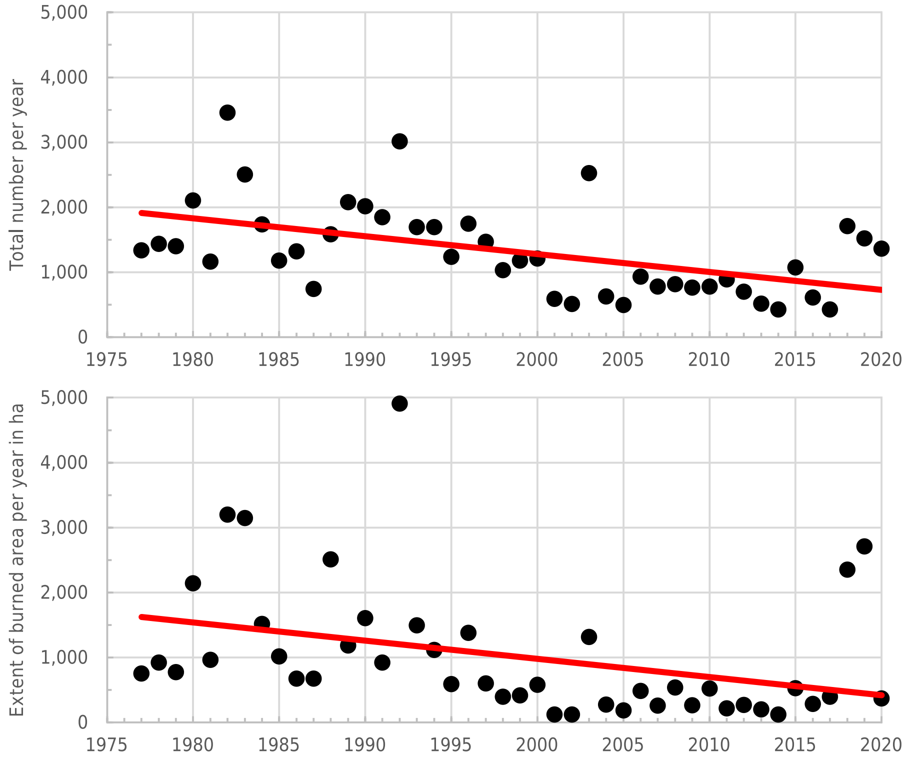
The third National Forest Inventory 2012 cost 21 million euros, of which 6 million were funded by the Federation and 15 million by the federal states.

bwi.info

4.10 Forest fires

In Germany, the pine forests of the eastern regions, which have a more continental climate, are most at risk of forest fires. A relatively dry state of vegetation, which may occur after a sufficiently long rainless period, is one of the preconditions of a forest fire. The drier the vegetation, the likelier a fire will ignite and the greater are both the fire-spread rate and the release of combustion heat. It is expected that climate change will cause summers to become dryer, causing the combustibility of forest floors to increase.

Annual number and extent of forest fires in Germany (1977–2020)

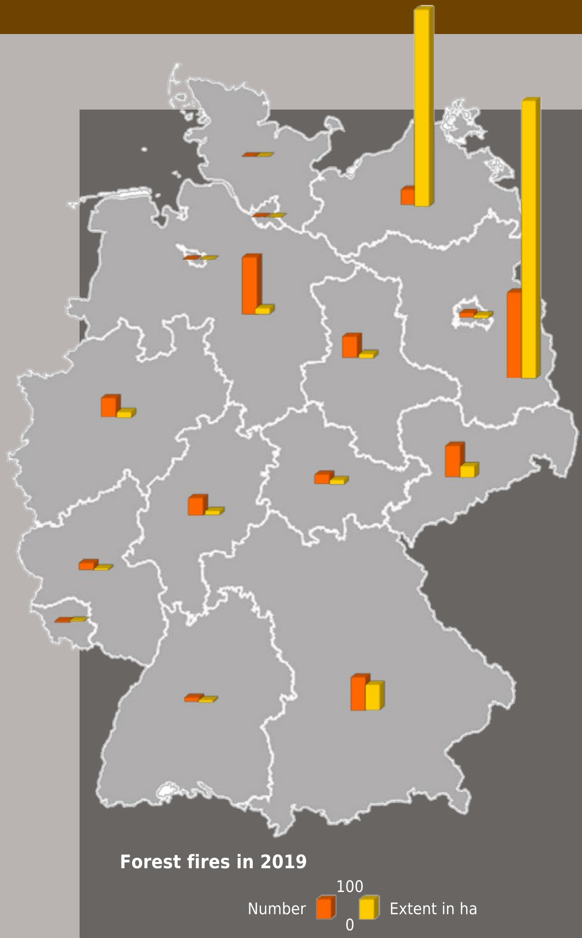


▲ *Figure 4.10-1: Annual number and extent of forest fires in Germany during the period 1977–2020 according to national forest fire statistics for Germany (Source: BLE)*

◀ *Photo 4.10-1: Forest fire near Ossendorf on 20.07.2006*
Inset picture: FireWatch camera for early forest fire detection

Climate signals

With some limitations, information on combustibility of vegetation, climate impact, speed of response and efficiency of prevention measures (i.e. the success or failure of early warnings, fire detection and firefighting) can be extracted from long-term records of the number of forest fires and extent of burned areas. Furthermore, long-term data sets of forest fire indices, which rate weather-dependent combustibility of forest floors, are needed for a more comprehensive climatological interpretation. The indices are calculated using fire-danger rating models populated with meteorological data relevant for forest fires (e.g. air temperature and humidity, wind, precipitation, snow depth as well as short- and long-wave radiation). The frequent occurrence ■ ■ ■



▲ *Figure 4.10-2: Number and extent (in ha) of forest fires in 2019 per federal state (Source: BLE)*

Measurements in Germany

Information on forest fires, i.e. place of ignition, extent, possible cause, time when the alarm was raised and firefighting begun, canopy type and extent of damage are registered by fire brigades and forest authorities of the German federal states and are condensed to monthly summaries. Excerpts from these are forwarded to the Federal Office for Agriculture and Food (BLE), which issues annual statistics for Germany. These national statistics provide a valuable summary of the fire situation in all federal states and serve to support the strategic focus on fire prevention and fire suppression.

After the once-in-a-hundred-years fires in Lower Saxony in August 1975, annual fire information became more important. As a consequence, the current reporting and statistical frameworks have been developed. During recent years, the establishment of the camera-based FireWatch system has significantly improved automatic forest fire detection and reporting. To provide a modern infrastructure for fire detection and suppression and see to continuous maintenance and improvement of the detection and reporting systems is a permanent key task in the provision of services for the protection of life and property.

The meteorological parameters required to forecast the risk of forest fire are collected at the weather stations of the DWD and those operated by partners. As a result, the data of around 500 weather stations in Germany enter into the forest fire forecasts, which are updated once a day. The measurement series are supplemented with data from numerical weather prediction.

■ ■ ■

of a very high number of fires with large extents of burned area can be a sign of deficits in the technical equipment of firefighters and a proof of the necessity to restructure forest fire suppression activities, initiate forest conversion measures and improve early-warning models.

International context

In accordance with the specifications of the European Forest Fire Information System (EFFIS), all forest fire data from moderately to highly fire-prone regions of Germany are reported to the Joint Research Centre (JRC) of the European Commission (EC) in Ispra, Italy, once a year. At this science hub of the EU, the data provided by the Member States are reprocessed, quality-checked and merged into European forest fire statistics. Based on these data sets, a European regional risk classification is made in order to manage financial support for forest protection. In addition, EFFIS data are used for model validation.

Independently of EFFIS, information on the forest fire situation in Germany is published on the website of the Global Fire Monitoring Center (GFMC) in Freiburg, Germany.

Legal framework

According to article 70 of the German Basic Law, responsibility for fire protection and emergency management lies with the federal states. Their laws on fire protection regulate how to control fire hazards while forest laws enable, for example, the banning of open fires and entry into forests when the danger of fire is high. Special regulations rule the burning of plant waste and controlled preventive burning of fields. In accordance with various bilateral administrative agreements, the Deutscher Wetterdienst (DWD) provides forecasts of fire weather danger.

Required resources

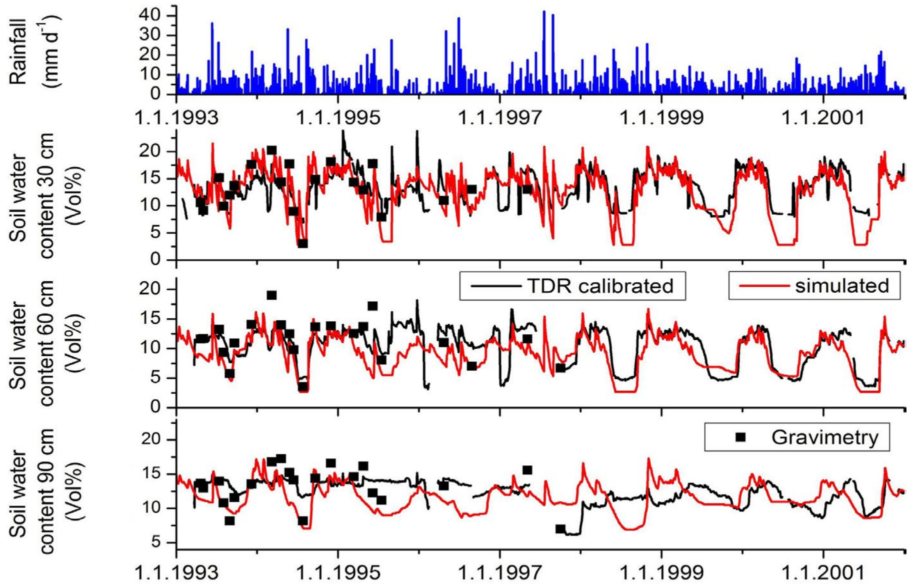
The registration of statistical information on forest fires is done at local and regional level by forest authorities and fire departments as part of their routine work. Responsibility for the compilation, presentation and distribution of data lies with the Federation, the costs are borne by the Federation and the Federal States. The funds required are considered as secured. The costs for meteorological forecasting of forest fire danger are borne by the DWD.

dwd.de/waldbrand **gfmc.online** **effis.jrc.ec.europa.eu**

4.11 Soil moisture

Area-covering information on soil moisture at high temporal and spatial resolutions is essential for many areas of agricultural and forest meteorology. It is also an important initial condition for model computations. Knowledge of current and future soil water availability in agricultural and forest areas as a function of the influence of soil type and vegetation is a vital basis for the planning of management measures at present and in future. As the flood disaster of July 2021 has shown, knowledge of the current soil moisture situation and thus the water absorption capacity of the soils is also of indispensable importance for flood forecasting.

Daily rainfall data compared to simulated and measured soil water content at Müncheberg experimental plot (1993–2001)



▲ *Figure 4.11-1: Daily rainfall during the period 01.01.1993–31.12.2001 at Müncheberg experimental plot (62 m a.s.l.; 52° 15′ N, 14° 07′ E) compared to soil water content data resulting from a model run by the Leibniz Centre for Agricultural Landscape Research (ZALF) as well as from TDR and gravimetry measurements in volume per cent (Vol%) at 0–30 cm (= 30 cm), 30–60 cm (= 60 cm) and 60–90 cm (= 90 cm) (Source: ZALF)*

Climate signals

Continuous measurement of soil moisture using automated instruments has been possible since about 1991. The range varies from time domain reflectometry (TDR) as well as frequency domain reflectometry (FDR) sensor systems for local profile measurements and their interlinking via wireless networks for recording the spatial distribution of soil water reservoirs (Vereecken et al. 2015) through to techniques such as cosmic-ray neutron sensing (CRNS) enabling integral, high temporal resolution measurements of areal averages for near-surface soil moisture within a radius of 150–250 m (Nguyen et al. 2019). A summary of the current state-of-art of this measurement technique can be found, for example, in Babaeian et al. (2019) and Nasta et al. (2020). Continuous measurement series of soil moisture are important for the further development and testing of soil moisture budget models (Wegehenkel et al. 2019) and for testing the soil module of the DWD's weather forecasting model COSMO-DE (Figure 4.11-1).

Legal framework

The activities of the Deutscher Wetterdienst (DWD) in the field of soil moisture monitoring are enshrined in the Deutscher Wetterdienst Act (DWDG). Long-term monitoring of soil moisture in agricultural and forest areas is carried out in accordance with the provisions of German soil protection law and regulations of the European Union.

International context

Internationally, area-covering soil moisture analyses lie in the responsibility of the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H SAF). Measurement series and data from experimental and permanent soil observation plots in Germany and neighbouring countries are increasingly gathered by data centres such as offered by BonaRes (see link below). Many in-situ data on soil moisture are also pooled by the International Soil Moisture Network (ISMN), initially set up by the TU Wien but now maintained and administered by the German Federal Institute of Hydrology (BfG). Furthermore, in-situ measurements using the CRNS technology are interlinked across Europe through the COSMOS-Europe network (Bogena et al. 2022). Further information on the climate variable Soil moisture can be found on the GCOS website (see link below).

Required resources

Measurement and evaluation of soil moisture data requires considerable material and human resources.

Measurements in Germany

Measurement and model calculations of soil moisture and its temporal dynamics are undertaken not only by the DWD but also by agencies at federal-state level on permanent observation plots (BDF II) in agricultural and forest environments. In addition, university and non-university research institutions participating in projects such as TERENO (see link below) conduct measurements and model calculations of soil moisture at different spatial scales, for example experimental plots and catchment areas. Despite automated recording devices, continuous soil moisture measurements are labour intensive and expensive as the systems require frequent calibration and servicing (Bogena et al. 2017, Montzka et al. 2017). The DWD has been conducting regular soil moisture measurements on different crop stands and using different measuring methods for several years at its agrometeorological measuring fields in Braunschweig and Weihenstephan-Dürnast and additionally since 1998 at the Falkenberg intensive observation plot of the Lindenberg Meteorological Observatory (Beyrich et al. 2006). Daily all year round, the DWD calculates soil moisture in 10 cm layers to a depth of 2 m for different crops and soils on a 1 km² grid using the agrometeorological model AMBAV, a development of its Agrometeorological Research Centre (ZAMF) in Braunschweig. The resulting data are made available via the soil moisture viewer on the DWD website. Direct nationwide measurement of near-surface soil moisture at a higher spatial (30 × 30 m) and temporal resolution by radar satellites (such as the environmental satellite ENVISAT) has so far been impossible or subject to severe limitations (Koyama et al. 2010). In contrast, previous evaluations of Sentinel-1 satellite data measured by a high-resolution C-band radar instrument (synthetic aperture of up to 5 metres) have yielded significantly better results (Benninga et al. 2020). Directly measured soil moisture data at coarser spatial resolutions (10 × 10 km) are available from various satellite platforms (e.g. the Soil Moisture and Ocean Salinity (SMOS) mission). More information is available on the website of the European Space Agency (ESA, see link below). In the field of numerical weather forecasting, areal data on regional soil moisture are calculated from models using measured land surface temperatures.

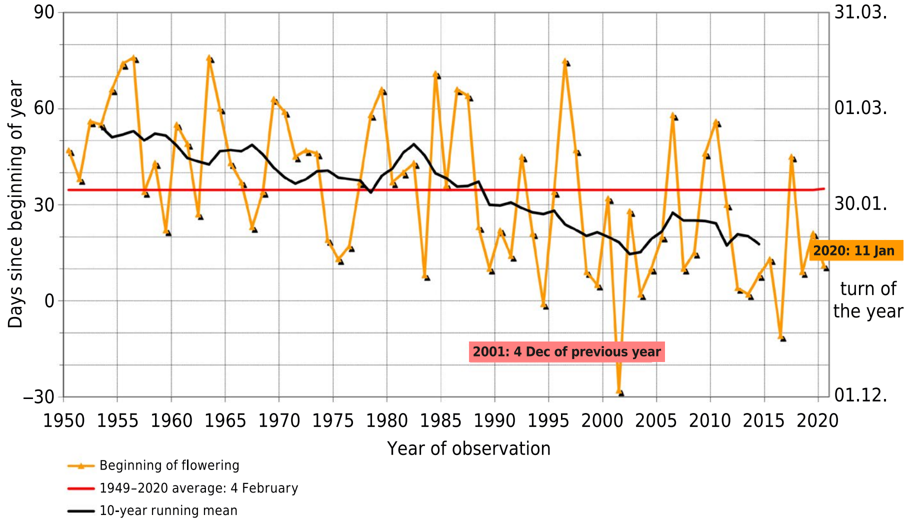
www.bonares.de/datacentre-de **climate.esa.int/en/odp/#/project/soil-moisture**

tereno.net **gcos.wmo.int/en/essential-climate-variables/soil-moisture** **www.zalf.de**

4.12 Phenology

Phenology deals with the periodically recurring patterns of growth and development of plants over the course of a year. The onset dates of characteristic phases of plant development (phenological phases) are observed and recorded. These are closely related to weather and climate and are therefore important indicators of the impact of climate change on the biosphere.

Beginning of flowering of hazel in Geisenheim since 1950



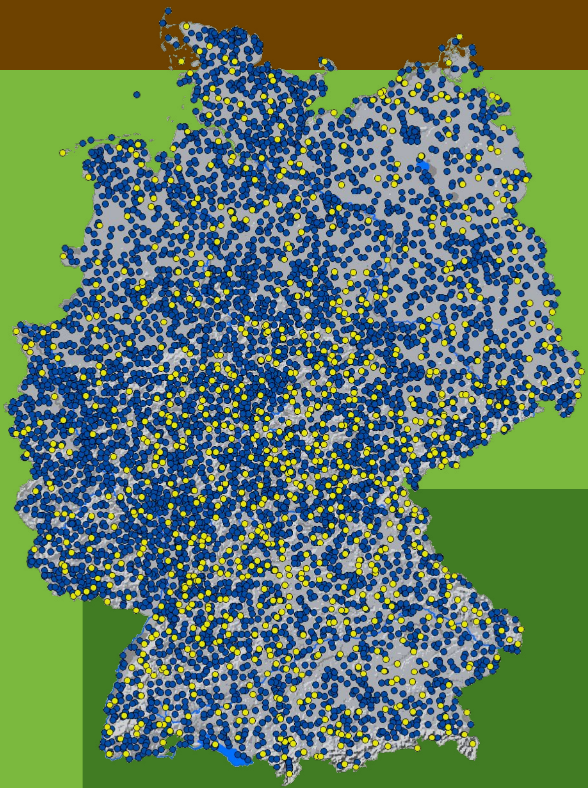
▲ *Figure 4.12-1: Temporal evolution of the beginning of hazel flowering in Geisenheim since 1950 (Source: DWD)*

Climate signals

Among the stations contained in the phenological database of the Deutscher Wetterdienst (DWD), 474 have records of observations covering more than 50 years, 164 stations even cover more than 60 years (between 1951 and 2020). However, the existence of records over several years does not imply that all of the phases have actually been observed on a continuous basis. In some cases, it was possible to reconstruct data before 1951 from historical records. Some of the phenological observations recorded at Geisenheim station on the river Rhine go back to before 1896. These show a marked shift towards earlier flowering times over the past 60 years.

Legal framework

According to the Deutscher Wetterdienst Act (DWDG, Section 4), responsibility for, among others, the operation of observing systems for recording meteorological processes and for the registration of interactions between the atmosphere and other areas of the environment lies with the DWD.



▲ *Figure 4.12-2: Phenological observation network of the DWD, with dark blue dots representing stations covering at least one observation year and yellow dots for stations with 50 or more observation years (Source: DWD)*

Measurements in Germany

The Societas Meteorologica Palatina carried out systematic phenological observations as early as between 1781 and 1792. However, the real breakthrough in phenology occurred in 1882, when the German university professor Hermann Hoffmann and his colleagues drew up and published guidelines for the observation of phenological phases, thereby laying the foundations for standardised observations not only in Germany but also in other European countries. This gave rise to a Europe-wide monitoring network, as well as to a number of regional networks in Germany.

The first long-term nationwide phenological observation network in Germany was set up by the Biological Institute for Agriculture and Forestry of the Reich and was run by this institute from 1922 to 1935. In 1936, the network was taken over by the Meteorological Service of the Reich and further extended by Dr Fritz Schnelle.

In 1946, phenological observations were resumed by the meteorological services in the US and Soviet occupation zones. Subsequently, these monitoring networks were run by the Meteorological Service of the former German Democratic Republic (MD) and the DWD after their foundation in 1950 and 1952, respectively. The two monitoring networks and their data archives were brought together in 1990.

As a result, the DWD now has an extensive archive of phenological data at its disposal. Alongside annual observations, the database collects immediate data, i.e. records that are submitted as soon as the phenological phase under observation occurs. These data, which provide up-to-date information on plant development, are used primarily for pollen count forecasts and for advice to farmers.

The annual observations, which are used for climate research, are contained in the DWD's database and cover the period from 1951 to the present. Currently, there are about 1,120 phenological observers contributing to the monitoring programme, providing information on about 160 phenological phases of wild plants, agricultural crops, fruit trees and bushes as well as grape vines (Kaspar et al. 2014).

Co-operation in Europe

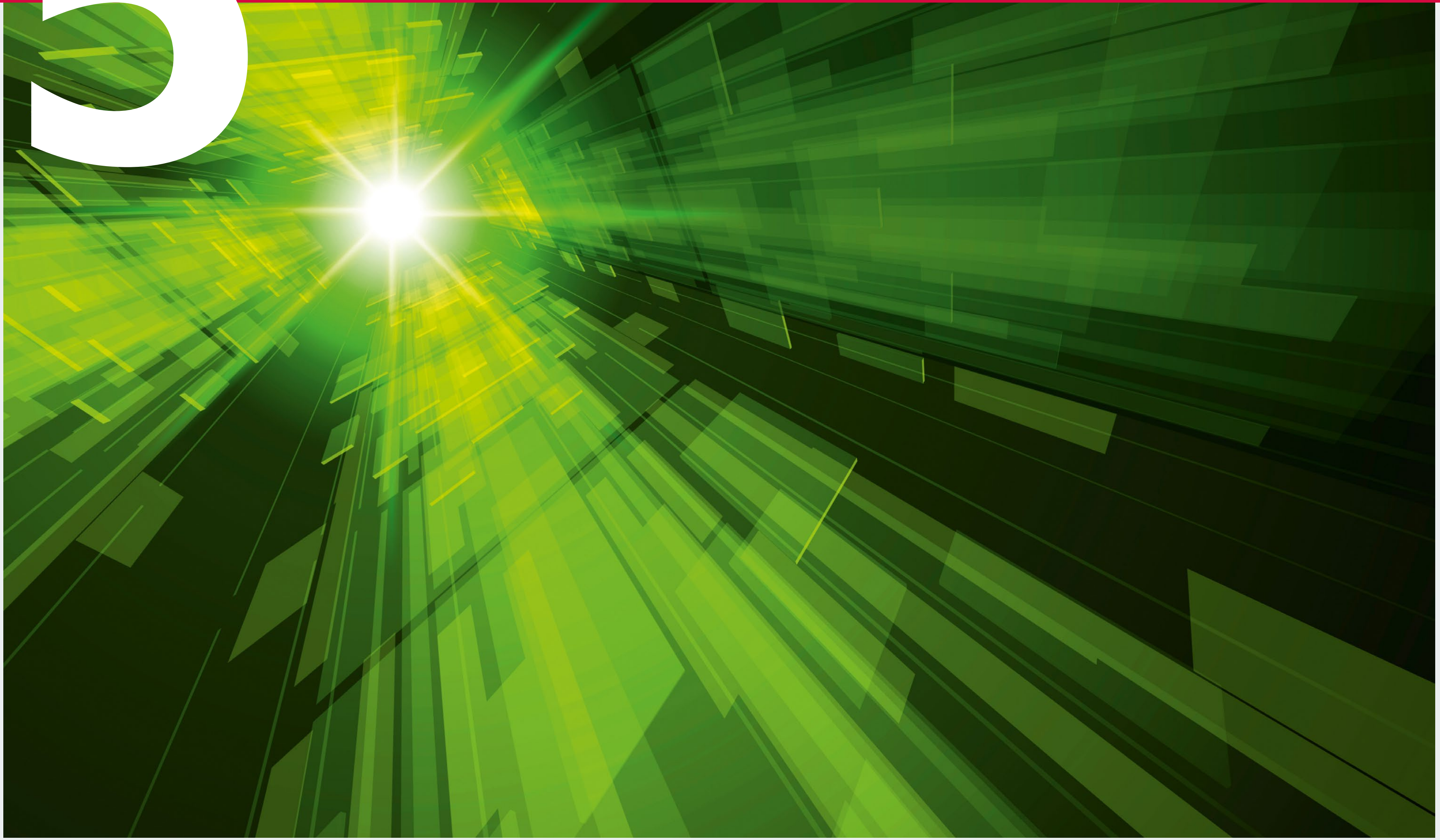
Germany is a member of the European Phenological Network (EPN) and, through observations in 32 gardens, also contributes to the monitoring programme of International Phenological Gardens (IPG). In 1996, responsibility for German participation in this monitoring network was transferred from the DWD to the Humboldt University in Berlin. The DWD was substantially involved in the initiation of the European Cooperation in Science and Technology project COST725 in 2003, whose main task was to establish a European-wide reference database of phenological observations. The DWD also participates in the follow-up project, the Pan European Phenology database (PEP725), which was set up by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG), the Austrian Federal Ministry of Science and Research and the Economic Interest Grouping of European National Meteorological Services (EUMETNET). The main aim of PEP725 is to promote and support phenological research by providing an annually updated pan-European database with unlimited open access to phenological data for science, research and training (Templ et al. 2018).

Required resources

The phenological monitoring network relies largely on volunteers. However, their number has declined continuously over past decades to currently about 1,120 honorary observers. In order to continue to benefit from people's willingness to assume honorary posts of this kind, appropriate publicity measures are required. The IPG monitoring network is also run by volunteers.

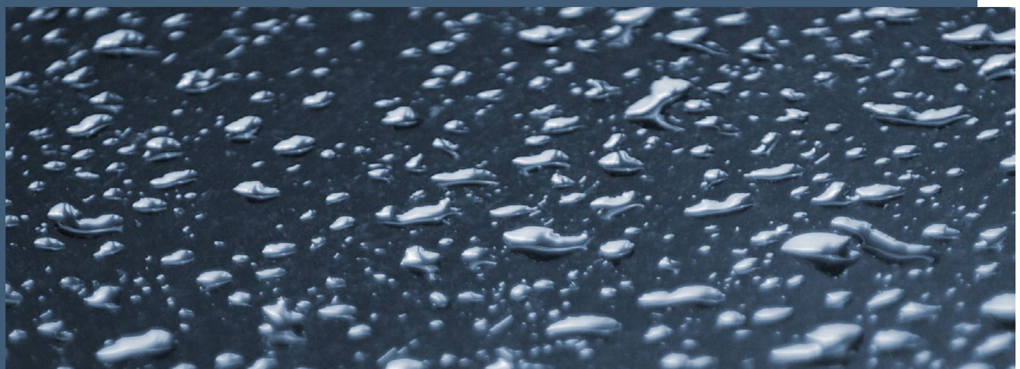
dwd.de/phaenologie   **opendata.dwd.de/climate_environment/CDC/observations_germany/phenology**

5 International data centres

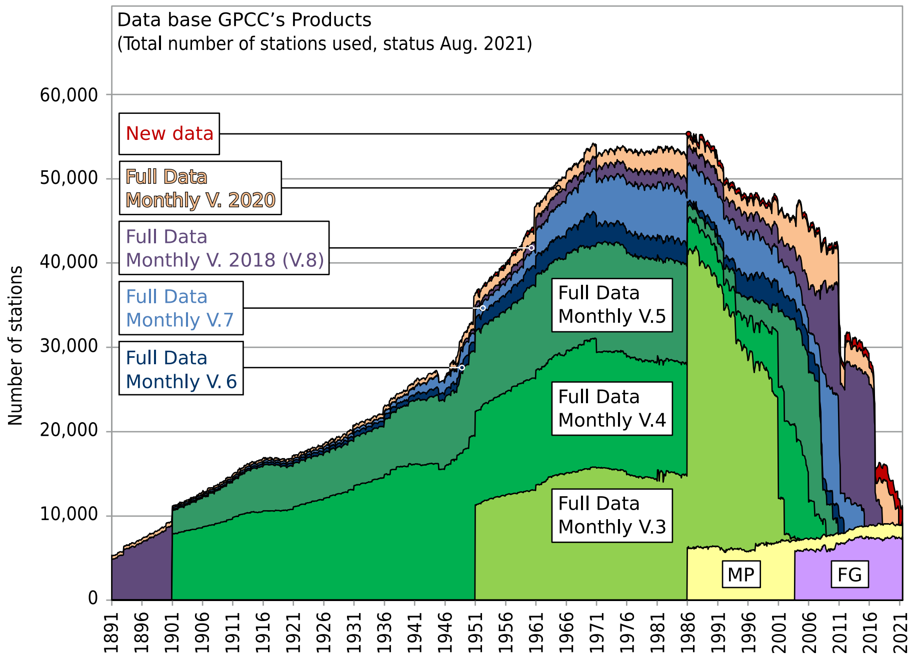


5.1 Global Precipitation Climatology Centre

By operating the world's largest archive of quality-controlled monthly in-situ precipitation observation series, the Global Precipitation Climatology Centre (GPCC) has built up a unique and worldwide renowned capacity for the global monitoring and analysis of land surface precipitation. The GPCC, which is operated by the Deutscher Wetterdienst (DWD), offers a number of different analysis products tailored to various requirements of its users, such as the Full Data Monthly V.2020 data set (since 1891). In 2012, the GPCC extended its processing activities from monthly data to include the analysis of daily precipitation data. Since then, daily precipitation products have also been on offer, such as the Full Data Daily data set (since 1982). All GPCC precipitation products are freely available on the Internet and are the reference for a wide spectrum of hydro-climatological applications.



Data resources for the different GPCC products over the last 130 years



▲ *Figure 5.1-1: The different colours illustrate the regularly issued products First Guess (FG) and Monitoring Product (MP) as well as the continuously growing data resources for the Full Data Monthly product from version 3 to 8 and V.2020 (released in 2005, 2008, 2010, 2011, 2015, 2018 and 2020, respectively). (Source: DWD)*

Significance for GCOS

As quantitative assessments of the global water cycle require a reliable diagnosis of global precipitation, the World Meteorological Organization (WMO), upon recommendation by its technical commissions, started the Global Precipitation Climatology Project (GPCP) as a contribution to the Global Energy and Water Exchanges (GEWEX) project of the World Climate Research Programme (WCRP). Given the impediments that exist for satellite-based remote sensing of precipitation over land due to ambiguities in the observed signal, the GPCC has a mandate to generate, based on the in-situ observations exchanged through the WMO's Global Telecommunication System (GTS), a monthly gridded precipitation monitoring product. The GPCC fulfilled the requirements stipulated in the WMO's Technical Document WMO/TD No. 367 in such a skilful way that it became a permanent component of the 1992- ■ ■ ■

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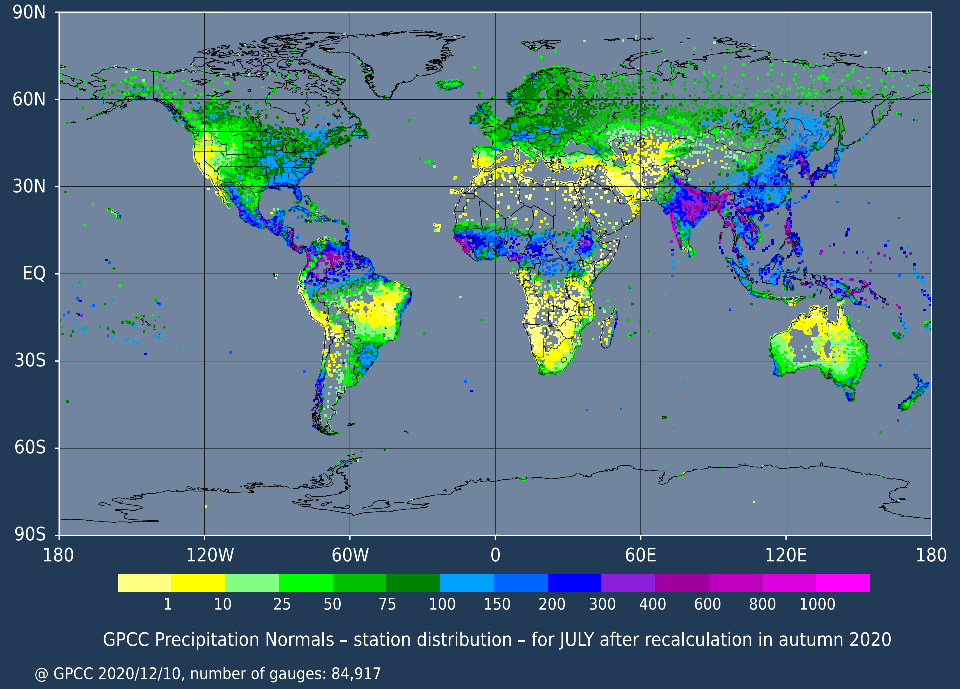
founded Global Climate Observing System (GCOS). Within the joint GCOS/GTOS activities, the GPCC is also a partner centre for the Global Terrestrial Network for Hydrology (GTN-H). And on grounds of its evaluations of the CLIMAT reports collected through the GTS, it furthermore acts as German Monitoring Centre of the GCOS Surface Network (GSN) for Precipitation.

Global measurements



▲ *Figure 5.1-2: Gridded spatial distribution of mean precipitation for July (1951–2000) from the data set Full Data Monthly V.2020 with 84,917 stations (Source: GPCC)*

International context

The GPCC monitors the global climate for the atmospheric Essential Climate Variable (ECV) Precipitation. It also contributes to GCOS and to the Global Terrestrial Observing System (GTOS), which is co-sponsored by the WMO, the United Nations Educational Scientific and Cultural Organization (UNESCO), the International Science Council (ISC), the United Nations Environment Programme (UNEP) and the United Nations Food and Agriculture Organization (FAO). Through its monthly Monitoring Product, the GPCC is a long-standing partner in the above-mentioned GEWEX project of the WCRP. In addition, as a reliable supplier of station-based reference precipitation products, the GPCC is also a key partner in the International Precipitation Working Group (IPWG), a joint working group of the WMO and the Coordination Group for Meteorological Satellites (CGMS). Founded 40 years ago, the latter is an association comprising all satellite-operating agencies and has the aim of ensuring the comparability of the measurements across the various platforms in orbit. The GPCC's preliminary First Guess product is utilised by the FAO for the purposes of drought warning. The global Full Data products serve the agendas of the Intergovernmental Hydrological Programme (IHP) of UNESCO and the WMO's Hydrology and Water Resources Programme (HWRP). The homogenised VASClimo V1.1 data set and its successor HOMPRA (Homogenized Precipitation Analysis) are suitable for climate research in the field of global precipitation trend analysis for recent decades (CLIVAR, IPCC).

Required resources

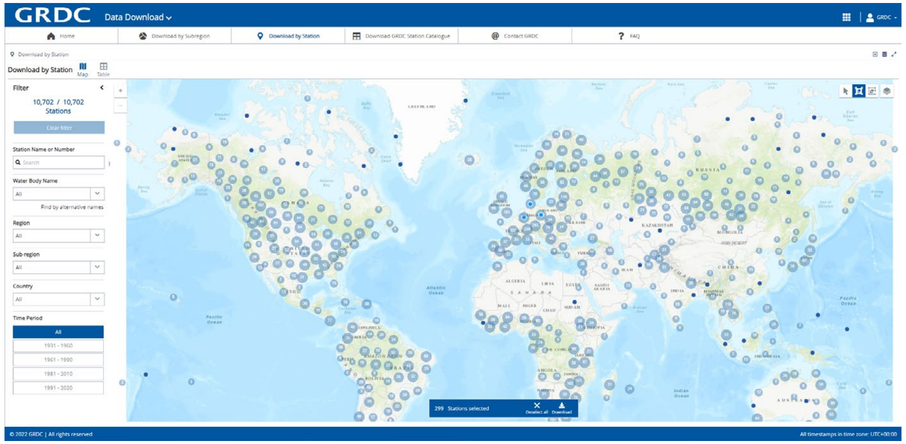
The continued operation of the GPCC at the DWD since 1989 demonstrates the sustained character of the engagement. No change in the status quo is currently foreseeable.

gpcc.dwd.de

5.2 Global Runoff Data Centre

The Global Runoff Data Centre (GRDC) holds mean daily and monthly river discharge data for currently more than 10,000 stations globally. These data are collected and held available in direct support of the climate-related programmes and projects of the United Nations system and the international research community working on climate change and cross-boundary water resources management.

Availability of historical discharge data in the GRDC database



▲ *Figure 5.2-1: The discharge data are available in different formats through the GRDC data portal. (Source: BfG)*

Significance for GCOS

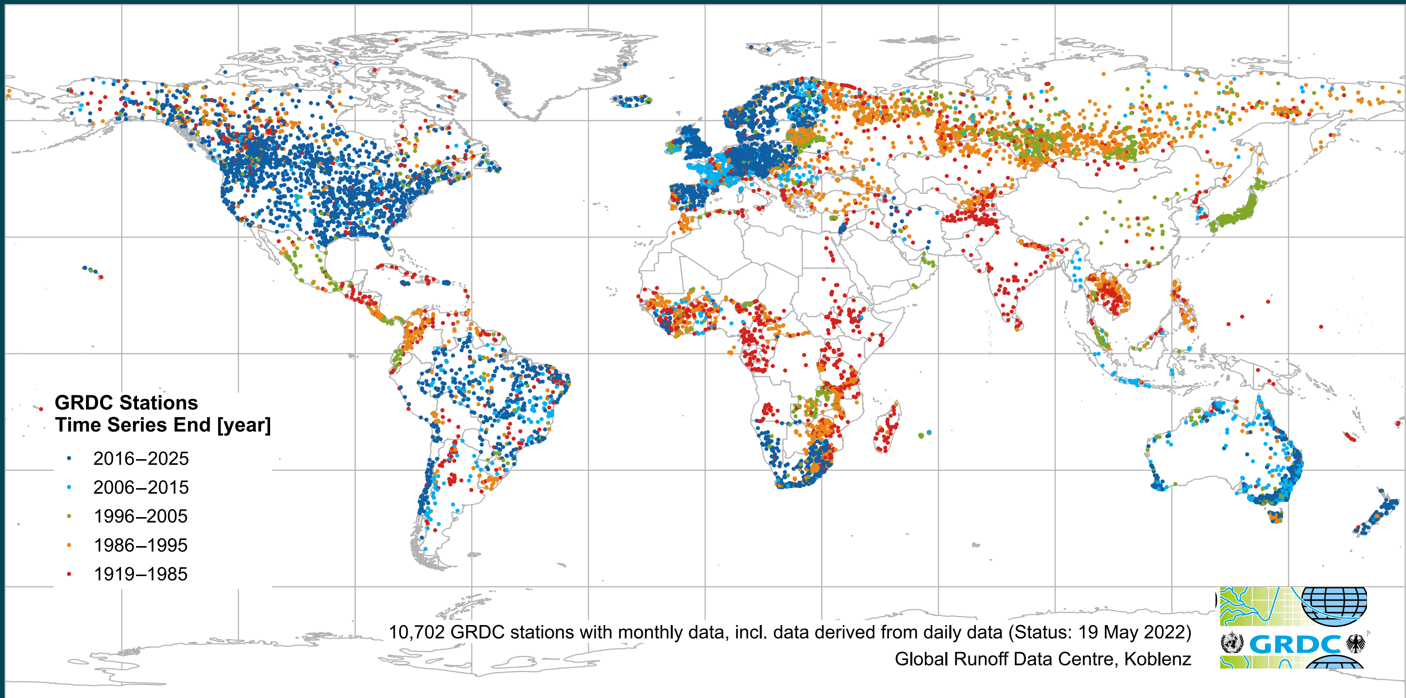
River discharge plays an important role in driving the climate system as the freshwater flow to the oceans may influence the global thermohaline circulation. River discharge is a reflection of changes in precipitation and evapotranspiration as well as of changing land use. Consequently, the statistical behaviour of river discharge serves as an indicator for climate variability and climate change. River discharge data are also required for the calibration and validation of global climate and impact models and for trend analyses and socio-economic investigations.

Monthly records of river discharge are generally sufficient to estimate continental runoff into the ocean. The statistical analysis of river discharge data and impact evaluation of extreme events require data at daily resolution. The GRDC has established a network of river discharge stations near the downstream ends of the largest rivers of the world. Today, this network, known as the Global Terrestrial Network for River Discharge (GTN-R) forms the baseline network for GCOS and the Global Terrestrial Observing System (GTOS).

International context

The GRDC was formally established in 1988 at the Federal Institute of Hydrology (BfG) and operates under the auspices of the World Meteorological Organization (WMO). It is a German contribution to the World Climate Programme (WCP) of the WMO and the United Nations Educational Scientific and Cultural Organization (UNESCO). The activities of the GRDC are monitored by an international steering committee with members from WMO, UNESCO, the United Nations Environment Programme (UNEP), the International Association of Hydrological Sciences (IAHS) and partner data centres advising it on the basic orientation of its work. WMO Resolutions 21 and 25 (WMO Congresses XII, 1995, and XIII, 1999, respectively) mandate the GRDC to collect river discharge data at global level in a free and unrestricted manner and in close co-operation with national hydrological services. At its Eighteenth Congress (Cg-18), the WMO endorsed this constantly growing collection of river discharge data and related station metadata, including it as one of the first data sets in the WMO's Climate Data Catalogue. The GRDC contributes its river discharge data to a number of international research programmes, such as the Global Energy and Water Exchanges Project (GEWEX) and the Climate and Cryosphere (CliC) project of the WMO's World Climate Research Programme (WCRP). Through its contribution to the Global Terrestrial Network for Hydrology (GTN-H), the GRDC is linked to the Global Earth Observation System of Systems (GEOSS).

Global measurements



▲ *Figure 5.2-2: With 10,702 discharge stations in 159 countries, the GRDC has the most comprehensive global discharge data archive (last updated: 19 May 2022). The data are made available worldwide via the GRDC data portal at portal.grdc.bafg.de. (Source: BfG)*

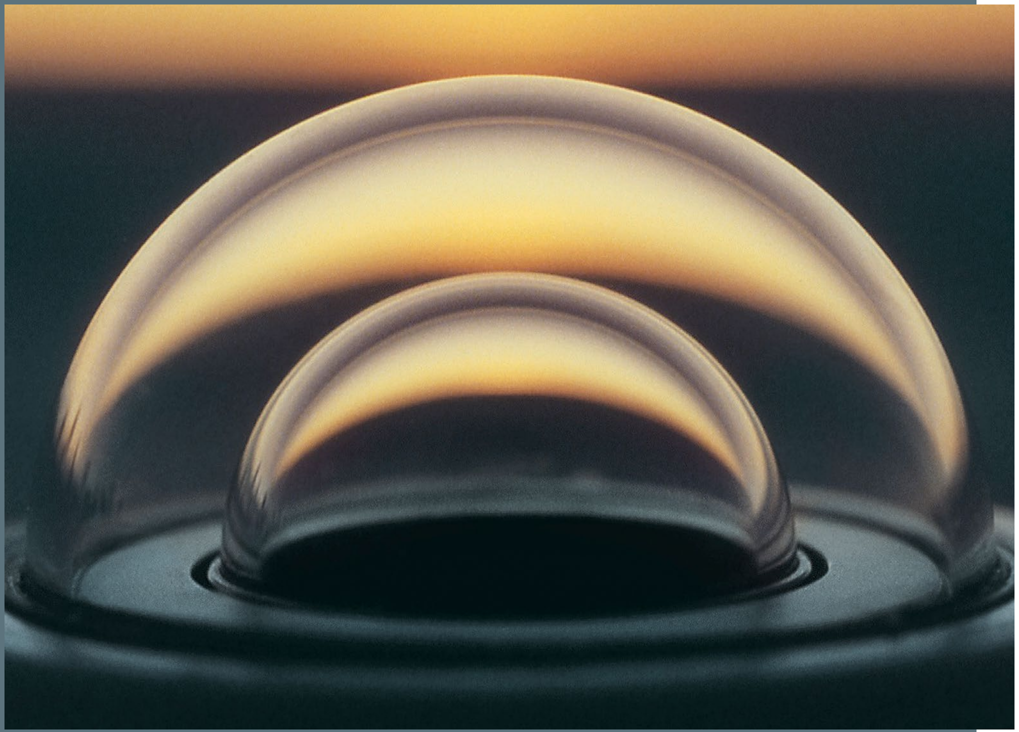
Required resources

Responsibility for running the GRDC lies with the BfG. This means that the funding of the GRDC's core functions is secured. Additional resources are required to extend data acquisition activities, to further develop the GTN-R baseline network and to develop the full potential of the GRDC and its relevance to the scientific community working on climate variability and global change.

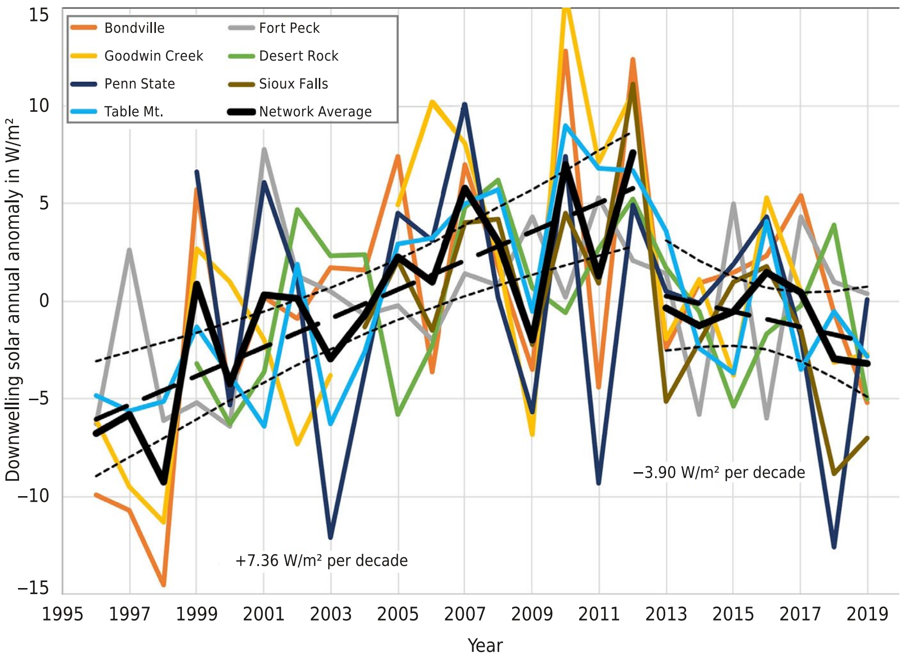
grdc.bafg.de **portal.grdc.bafg.de**

5.3 World Radiation Monitoring Center

The World Radiation Monitoring Center (WRMC) is the central archive of the Baseline Surface Radiation Network (BSRN). The objective of the BSRN is to provide data on short- and long-wave surface radiation fluxes in one-minute resolution and the best possible quality available in order to support the research programmes of the World Climate Research Programme (WCRP) and other scientific projects.



Anomaly of short-wave downward radiation



▲ *Figure 5.3-1: Time series of short-wave downward radiation anomalies relative to the 1996–2019 mean for the SURFRAD network of the US American BSRN stations (Source: DWD, modified from Augustine and Hodges 2021)*

◀ *Photo 5.3-1: Dome of a pyranometer*

Significance for GCOS

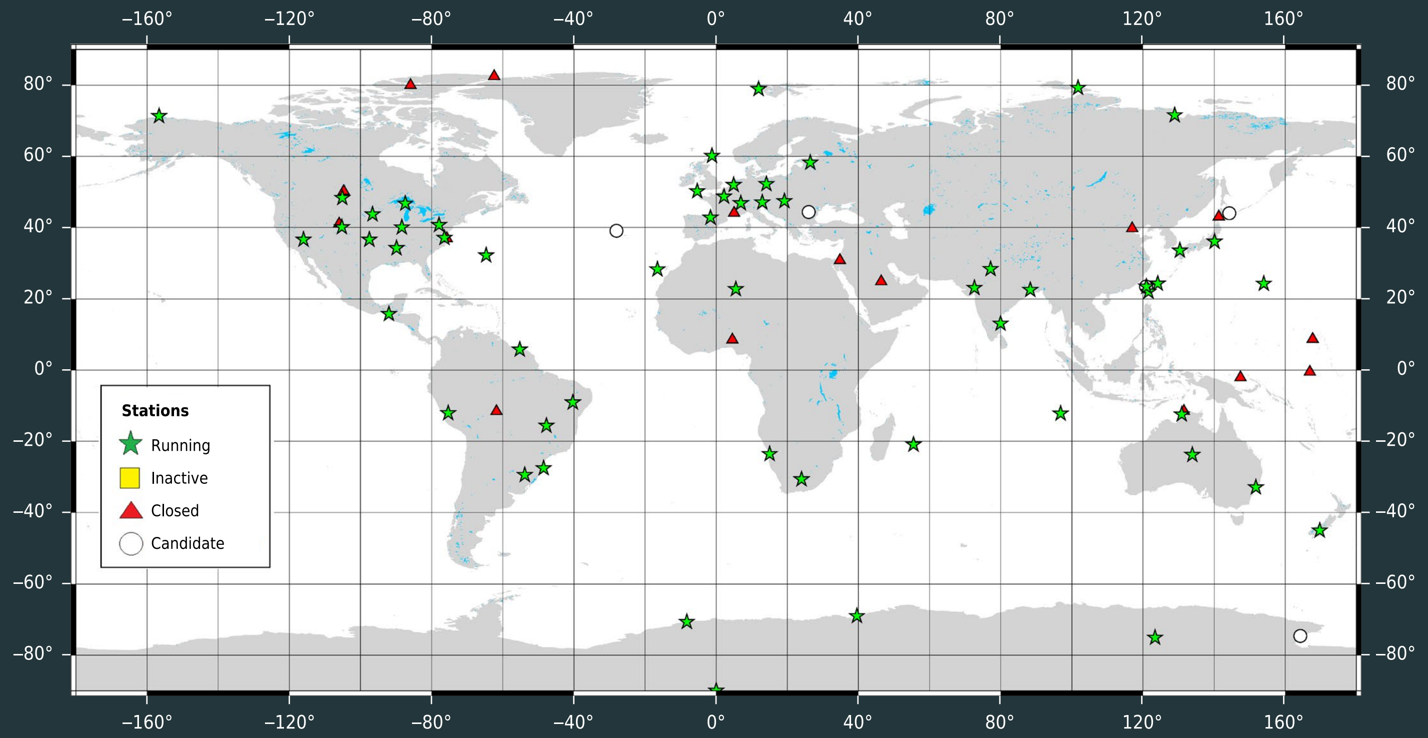
In 2004, the BSRN/WRMC was designated as the »global baseline network for surface radiation« for the Global Climate Observing System (GCOS). The high-quality, uniform and consistent measurements throughout the BSRN network are used for

- monitoring the short-wave and long-wave radiative components and their changes with the best methods currently available
- validating and evaluating satellite-based estimates of the surface radiative fluxes
- verifying the results of global climate models (GCMs).

The BSRN/WRMC started in 1992 with nine stations. By May 2021, more than 12,200 station-months of data from 74 stations (active: 58, closed: 16) all over the world were available in ■ ■ ■

the archive (see link at the end). Although the WRMC was originally designed especially for the needs of climate researchers, the archive is being used more and more in the context of renewable energy research.

Global measurements



▲ *Figure 5.3-2: Currently active, closed and candidate BSRN stations (May 2021) (Source: DWD, modified from WRMC)*

International context

The BSRN/WRMC was initiated by the World Climate Research Programme and contributes to the climate model assessment activities carried out within the WCRP's Global Energy and Water Exchanges (GEWEX) project. It is affiliated to the GEWEX Data and Analysis Panel (GDAP) and part of the GCOS network. The BSRN renewed its commitment to participate in the activities of GCOS in 2022 and has been redesignated as GCOS-recognised network for global surface radiation measurements. Already in 2011, the BSRN/WRMC and the Network for the Detection of Atmospheric Composition Change (NDACC, see link at the end) formally agreed to form a co-operative network. To ensure the close co-operation between the scientists at the BSRN stations and the BSRN user community, a joint meeting takes place every second year.

Required resources

In order to ensure effective operation of the WRMC at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven, one scientific position and one data curator are needed. Additionally, technical support from the AWI computing centre and from experts of PANGAEA® (Data Publisher for Earth & Environmental Science, see link at the end) is indispensable. At the moment, the AWI carries all costs (one data curator plus one position for technical support).

bsrn.awi.de ndacc.org pangaea.de

5.4 World Data Center for Climate at the German Climate Computing Centre

The World Data Center for Climate (WDCC) is maintained by the German Climate Computing Centre (DKRZ), whose mission is to provide users from the climate research community in Germany with access to high-performance computing and technical support. The main emphasis is on data from climate model calculations, but corresponding observational data from a variety of projects are also available.

◀ *Photo 5.4-1: The DKRZ's high performance data archive*

Examples of databases held at the DKRZ

Project	M/O	Coverage	Data type
CARIBIC	B	Flight routes Frankfurt-Caribbean 1997–2002	Upper atmosphere variables
CMIP6	M	Global data for model comparisons from different time periods	Numerous variables from international research centres
CORDEX	M	Europe until 2099	Multitude of variables on a 44/11 km grid; monthly means and hourly data
ReKliEs-De	M	Germany until 2100	Supplementing CORDEX, also supplying further indices (max/min periods)
ECMWF re-analyses	O/M	Global 1950–present day	Multitude of variables with 30 km resolution and higher
REMO-UBA	M	Germany 2001–2100	Multitude of variables on a 10 km grid; monthly means and hourly data

▲ *Table 5.4-1: Databases held at the DKRZ; M stands for model data, O for observation data. (Source: DKRZ)*

Significance for GCOS

The WDCC collects, archives and disseminates climate (model) data and products and provides these free of charge to the international research community. As reference archive of the Coupled Model Intercomparison Project (CMIP), it supports the IPCC process by data dissemination.

With a view to establishing a well organised network of data centres for Earth sciences, the WDCC co-operates closely with numerous institutions dedicated to related branches of study, such as Earth observation, meteorology, oceanography, paleo-climatology and environmental research. Model data include global as well as continental and national data sets (see Table 5.4-1). Disk storage capacity of 120 petabytes is available plus more than 100 exabytes on magnetic tapes due with next hardware generation in fall 2021. During recent years, data life cycle management has become more and more important. In addition to the long-term archival of results, this also includes advising the project partners during proposal-writing as well as during the lifetime of the project and the concluding data publication and dissemination phase. These long-term archived data can be marked with persistent digital object identifiers (DOI), which allow users to quickly locate the data even many years later.

▲ *Photo 5.4-2: View into the DKRZ's disk storage system*

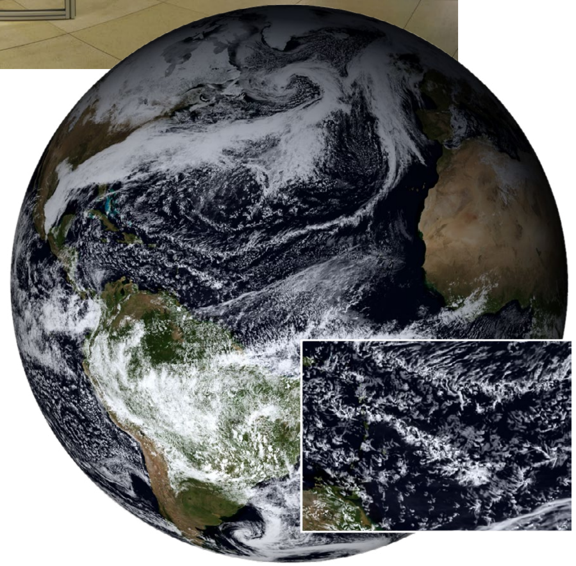
▲ *Photo 5.4-3: DKRZ supercomputer Mistral*

International context

Although the WDCC is internationally oriented and open to scientists from all over the world, most of the data are accessed from the research community in Germany. Here, co-operation with universities and major research centres and with institutes of the Max Planck Society or the Deutscher Wetterdienst (DWD) is equally important. International co-operation also exists for the utilisation of data for the preparation of the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). The WDCC, which is situated in Hamburg, is involved as part of the Data Distribution Centre (DDC) of the IPCC. It is one of the internationally leading data centres providing data for model comparison projects (e.g. CMIP6). In addition, software solutions from user interfaces to storage of data sets on magnetic tapes are jointly developed in international collaborations.

Required resources

The shareholders of DKRZ are the Max Planck Society and the Land Hamburg (University of Hamburg) as well as the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) and the Helmholtz-Zentrum hereon GmbH in Geesthacht. Financial support is also provided by the Federal Ministry of Education and Research (BMBF) for the procurement of the large-scale technology.



▲ *Figure 5.4-1: ICON model simulation of the Earth's atmosphere, 2.5 km resolution, by DKRZ, MPI-M and DWD. Inset: region around Barbados (Source: DKRZ)*

dkrz.de/en/dkrz-partner-for-climate-research **wdc-climate.de**

5.5 World Data Center for Remote Sensing of the Atmosphere

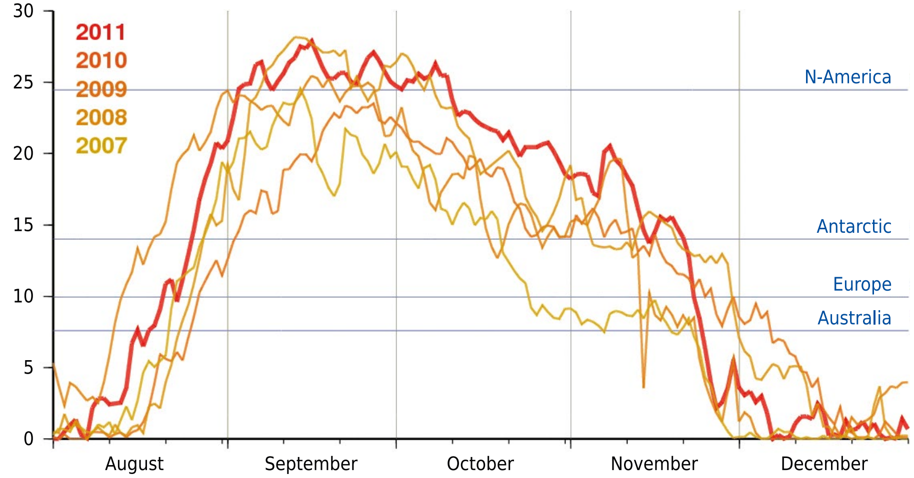
(The below text corresponds to the text published in the GCOS Inventory Report of 2013). Since 2003, the World Data Center for Remote Sensing of the Atmosphere (WDC-RSAT) has been hosted and operated by the German Remote Sensing Data Center (DFD) at the German Aerospace Center (DLR) under the auspices of both the World Meteorological Organization (WMO) and the non-governmental International Science Council (ISC). An external advisory board with experts from space agencies such as the European Space Agency (ESA), national meteorological services such as the Deutscher Wetterdienst (DWD) and scientific community bodies, such as the DLR and the Helmholtz Association of German Research Centers (HGF), was established in 2006 to help the WDC-RSAT to achieve its mission goals and serve user requirements. Currently, this advisory board is being extended to also include representatives from EUMETSAT, NASA and WMO.

Significance for GCOS

The WDC-RSAT offers, not just to scientists but also to the public, simple and free access to a continually growing collection of satellite-based data of the atmosphere and related products and services.

The data products are available online and include raw data as well as higher level value-added products. The current WDC-RSAT database provides information on trace gases, aerosols, clouds, land and sea surface parameters and solar radiation.

Trend of the size of the ozone hole (10^6 km², 2007–2011)



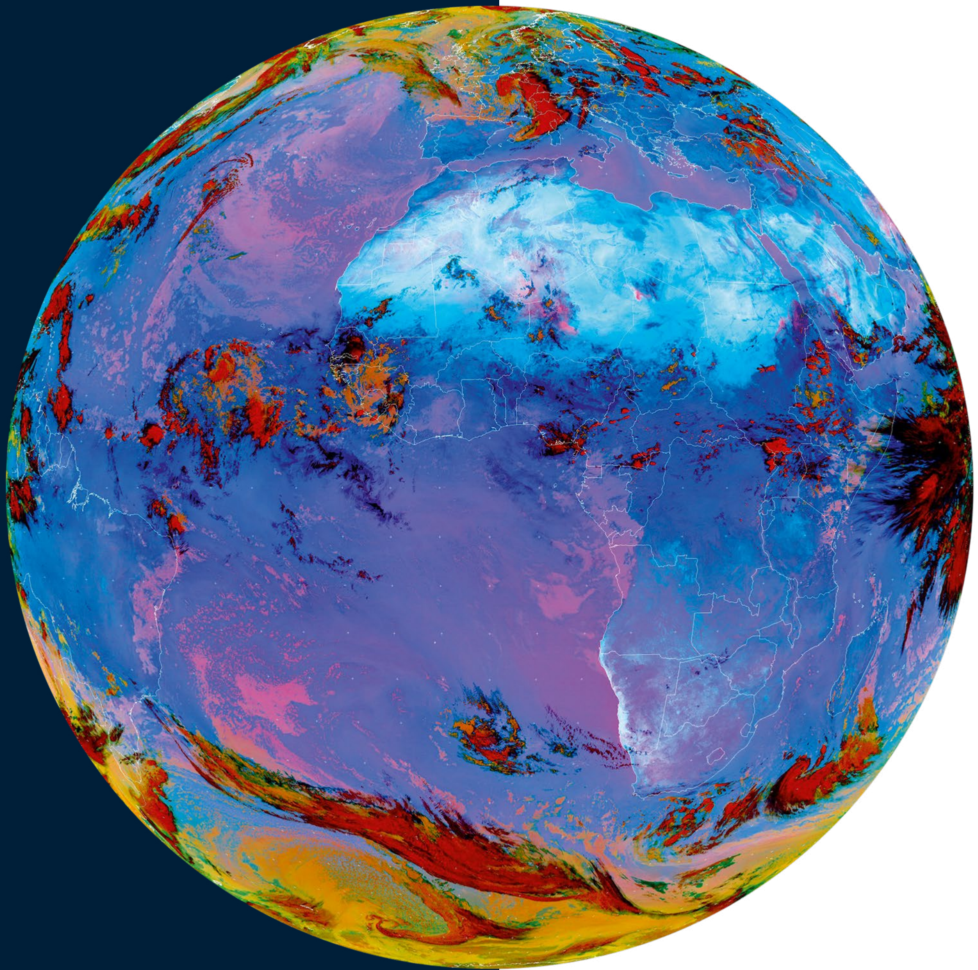
▲ *Figure 5.5-1: The area is derived by assimilating the total ozone concentrations from Metop/GOME2 measurements using the ROSE/DLR chemical transport model. The size of the ozone hole is defined as the area where the total ozone concentration is below 220 DU. (Source: WDC, EUMETSAT and DLR)*

Service for the Scientific Community

The WDC-RSAT is the most recent member in the WMO system of world data centres. Particularly in the context of the Integrated Global Atmospheric Chemistry Observations (IGACO) and in line with the GAW strategy plan 2008–2015, it is concerned with linking different GAW-relevant data sets with each other and with model data. In this context, the WDC-RSAT not only handles satellite data but also data from other sources that are important for validation purposes. Additionally, strategies and techniques are being developed and tested for this validation, taking account of, among other things, different assimilation methodologies. The data centre is also addressing the variability of the atmosphere at different time and space scales (»miss-integration error«). It operates as a »one-stop shop« that gives access to space-borne observations of the chemical composition of the atmosphere, at first, however, with a focus on a limited number of parameters, particularly those concerning ozone and aerosols. This is achieved by either direct access to the centre's data collection or indirectly by a portal of links to relevant satellite data and data products of other providers. Following the recommendations of the Committee on Earth Observation Satellites (CEOS), the WDC-RSAT is currently developing an Atmospheric Composition Portal (ACP) in co-operation with the National Aeronautics and Space Administra- ■ ■ ■

tion (NASA), which will eventually be integrated into the Global Earth Observation System of Systems (GEOSS). Similar co-operation is planned with the French Centre National d'Études Spatiales (CNES) and Centre national de la recherche scientifique (CNRS).

The WDC-RSAT is designated to play an important role within the recently established international and global Network for the Detection of Mesopause Change (NDMC). For this, international co-operation with scientific groups actively investigating the mesopause region (in ~80–100 km altitude) will be supported to detect long-term trends in airglow. The centre will also serve as a communication and data management platform for ground-based measurements from around the world. In addition, the WDC-RSAT supports the data management of the German Environmental Research Station Schneefernerhaus (UFS) on Zugspitze (2,650 m a.s.l.), which is also a GAW station. It is planned to establish a virtual association between the research station and the Norwegian ALOMAR observatory.



International context

The World Data Center for Remote Sensing of the Atmosphere is part of the ISC-WDC family and is therefore closely linked to all other world data centres. Further, the development of a sub-network of WDCs, which will focus on relevant aspects of the Earth system, will lead to increased synergy between the various data providing bodies. Such a co-ordinated approach, in which WDC-RSAT is involved, aims to give answers to questions on climate change and weather extremes. This is of basic importance for economic well-being and the understanding of both natural and man-made causes of climate variability. A large amount of data is necessary to describe the climate system and how it is changing, because it is determined by conditions and changes in the atmosphere and surface parameters of land and ocean. Many of the needed data sets are collected and archived by four ISC world data centres, amongst others the WDC-Climate (hosted by the German Climate Computing Centre, DKRZ), or by the publishing network for geoscientific and environmental data PANGAEA® (operated by the Alfred Wegener Institute (AWI) and the University of Bremen, see 5.6). In 2004, the four German ISC WDCs (Climate, Mare, Terra and RSAT) established the »WDC-Cluster on Earth System Research« to promote interdisciplinary research related to Earth sciences.

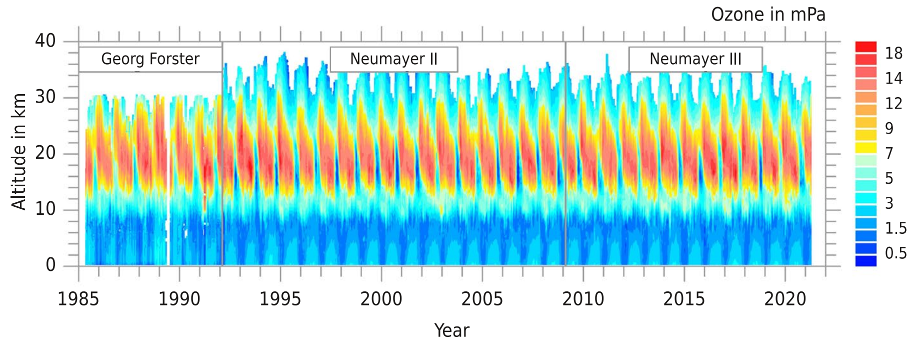
The WDC-RSAT also co-operates with various partners in the field of information technology (e.g. Grid) to improve the networking between providers and users. Remote sensing data sets and products now each have a digital object identifier (DOI) and can be unambiguously and effectively referenced and cited in scientific publications. The WDC-RSAT has also been designated as a Data Collection or Production Centre (DCPC) within the WMO Information System (WIS).

wdc.dlr.de **ndmc.dlr.de** **schneefernerhaus.de** wdc.dlr.de/acp (link as of 2013)

5.6 ISC World Data Center PANGAEA®

The World Data Center PANGAEA® (PANGAEA® Data Publisher for Earth & Environmental Science, formerly known as WDC-MARE), is a member of the World Data System (WDS) of the International Science Council (ISC). PANGAEA® is a CoreTrustSeal certified facility for the collection, processing, long-term archiving and publication of georeferenced data from Earth system research. PANGAEA® currently holds around 400,000 data sets comprising more than 19 billion data items from all Earth environments.

Ozone sonde measurements at Neumayer and Georg Forster stations during three »ozone hole periods« in October



▲ *Figure 5.6-1: Time series of ozone sonde measurements at Neumayer and Georg Forster stations in the Antarctic. All data are published in PANGAEA®. (Source: AWI)*

Significance for GCOS

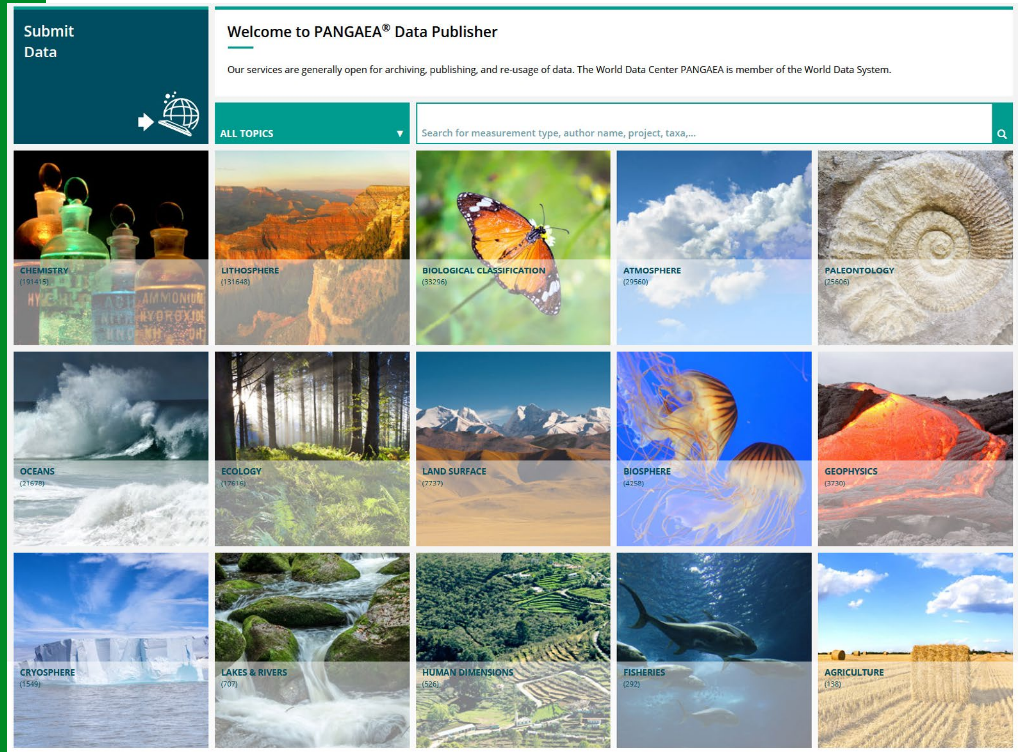
PANGAEA® holds an extensive collection of climate-related data, making it a valuable partner for climate research. PANGAEA® not only is a designated data archive of the ISC but also hosts the World Radiation Monitoring Center (WRMC) of the Baseline Surface Radiation Network (BSRN). As such, it is accredited as a Data Collection or Production Centre (DCPC) of the WMO Information System (WIS). PANGAEA® supports the free and unrestricted availability and distribution of climate-related data according to the ISC's rules for the WDS while at the same time protecting intellectual property by consequently using digital object identifiers (DOI) when publishing the data.

International context

PANGAEA® is part of the ISC World Data System (WDS). Since the launch of the Fifth Framework Programme of the European Union, PANGAEA® has supported more than 575 mainly high-level projects at global, European and national levels across all fields of environmental sciences (see pangaea.de/projects). Long-standing collaboration exists with the International Ocean Discovery Program (IODP). Co-operation with science publishers (Elsevier, Springer, Wiley, Oxford, AGU and Nature) has been established and extended.

Required resources

PANGAEA® is operated jointly by the Center for Marine Environmental Sciences (MARUM, anchored at the University of Bremen) and the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. The two partners together provide around 900,000 euros per year in-kind funding for the technical and personnel operation. Additional 900,000 euros per year for project work are funded by third-party grants. Further funding comes from the European Commission, the Federal Ministry of Education and Research (BMBF), the German Research Foundation (DFG) and the International Ocean Discovery Program (IODP).



▲ *Figure 5.6-2: Screenshot of the PANGAEA® web page showing the different topics for which data are available in the publisher (Source: AWI)*

pangaea.de

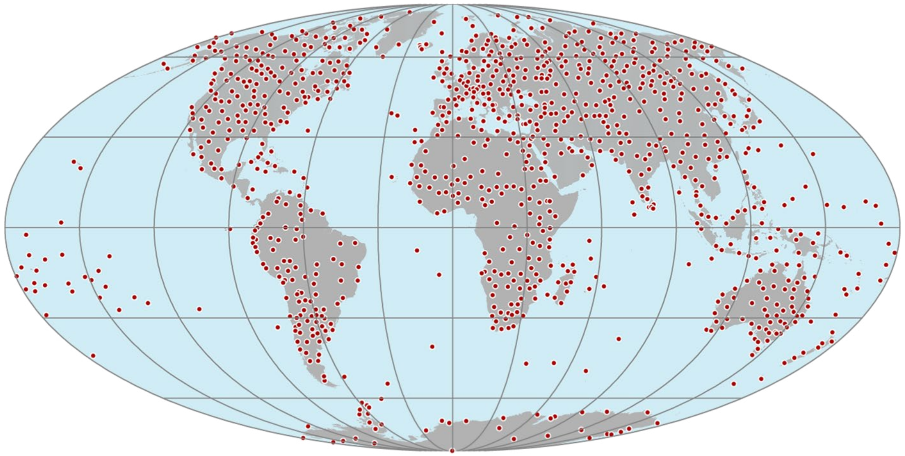
5.7 Data quality centres of GCOS

GCOS Surface Network (GSN)

The GCOS Surface Network (GSN) is a subset of the Regional Basic Climatological Network (RBCN) and the Antarctic Observing Network (AntON). Both networks submit monthly worldwide climate data (so-called CLIMAT reports) from the lower atmosphere near the Earth's surface shortly after the end of each month. The GSN comprises more than 1,000 land surface observation stations and stations on mid-oceanic islands. These were selected according to strict criteria, including length and quality of the time series, geographical representativeness of the observations and range of available parameters. A high level of reliability is expected from GSN stations concerning the continuity of observations and the quality of the monthly data reports. GSN data provide a basis not only for assessing climate variability and climate change but also for climate modelling and forecasting (for more information, please see gcos.wmo.int/en/networks/atmospheric/gsn).

In 1999, two GCOS Surface Network Monitoring Centres (GSNMC) were set up to supervise the performance of the GSN: one at the Deutscher Wetterdienst (DWD) and another at the Japan Meteorological Agency (JMA). They monitor the availability, timeliness and formal correctness of CLIMAT reports from GSN stations and check the mean monthly temperature, mean monthly maximum and minimum temperatures (JMA) and monthly precipitation (Global Precipitation Climatology Centre (GPCC) at the DWD). A range of monitoring products and the monthly climate data can be accessed at www.gsnmc.dwd.de.

With the aim of improving the quality and availability of the data from the GSN as well as from the GCOS Upper-Air Network (GUAN), nine CBS Lead Centres for GCOS were established in 2006/07. Their principal task is to liaise with the national meteorological services by their designated Focal Points for GCOS with a view to pointing out data problems that have been ■ ■ ■



▲ *Figure 5.7-1: Map of current GSN stations (as of July 2021) (Source: DWD and GSNMC)*

◀ *Photo 5.7-1: Launch of a balloon with several radiosondes for a comparison study*

▲ *Figure 5.7-2: Map of GRUAN stations (as of July 2021) (Source: DWD)*

detected. The DWD is responsible for Europe (WMO Region RA VI). In 2011, following the decisions by GCOS' Atmospheric Observation Panel for Climate (AOPC) and the Executive Council of WMO, the responsibility of the CBS Lead Centres was extended to include all approximately 2,900 stations of the RBCN and AntON networks.

All CLIMAT data exchanged worldwide are checked, completed and archived at the DWD.

The GCOS Reference Upper-Air Network (GRUAN)

The GCOS Reference Upper-Air Network (GRUAN) is the reference network for observations of Essential Climate Variables in the free atmosphere. The GRUAN sites conduct vertically resolved measurements of the parameters temperature, atmospheric water vapour, wind and pressure. GRUAN currently consists of 31 selected stations worldwide in different climate zones and is represented with at least one station on each continent. The aim is to establish additional stations in Africa, South America and the Pacific. GRUAN provides reference data for the purposes of long-term climate monitoring, validation of satellite observations and process studies. Essential criteria for GRUAN reference observations include traceability (to SI units or equivalent standards), correction of all known measurement errors and biases as well as measurement uncertainty analysis. Transparent and well-documented data processing of the GRUAN raw data includes correction algorithms that take account of a detailed characterisation of the measuring instrument and its sensors. The resulting GRUAN data products (GDP) are free from any manufacturer-dependent artefacts. Currently, GDPs have been developed for two radiosondes (Vaisala RS92 and Meisei RS-11G) and for the Global Navigation Satellite System Precipitable Water product (GNSS-PW). The GDP for lidar-based temperature and humidity profiles as well as further GDPs for other radiosonde models, such as Vaisala RS41, Modem M10, Meisei iMS-100 and Graw, are under development.

GRUAN was founded in 2008, with its Lead Centre hosted at the DWD's Meteorological Observatory Lindenberg – Richard Assmann Observatory. The Lead Centre is responsible for the daily management and co-ordination of the network, which includes data management (processing and archiving), co-ordination of the stations, reporting, issuance of guidelines, publication and maintenance of technical documentation and the GRUAN website.

A major challenge in recent years was the change from Vaisala RS92 to RS41 as operational radiosonde at a majority of GRUAN sites. GRUAN's strategy to prevent inhomogeneities in the data records due to this change consisted in carrying out RS92-RS41 twin soundings and in the parallel collection of data from satellite observations and other measurement systems for obtaining a characterisation of the differences between the two radiosonde types.

Furthermore, the Lead Centre participates in international radiosonde comparison campaigns and conducts independent tests and laboratory experiments on sounding equipment. For this purpose, the Lindenberg observatory hosts specialised laboratory facilities for characterising radiosonde sensors, such as used for the development of the GDP for the RS41 radiosonde for example.

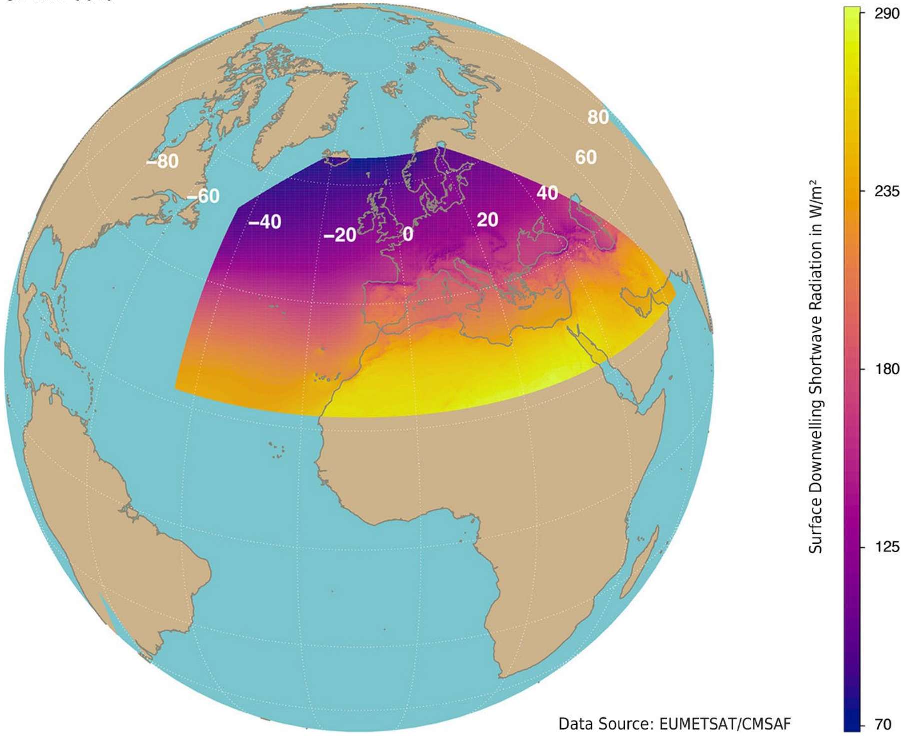
The GRUAN Lead Centre reports to the Atmospheric Observation Panel for Climate (AOPC) of GCOS and, in order to improve observations at sites that are not directly connected to GRUAN, co-operates closely with relevant committees of the World Meteorological Organization (WMO), such as the Standing Committee on Measurement Instrumentation and Traceability (SC-MINT) of the Commission for Observation, Infrastructure and Information Systems (INFCOM) and the Research Board on Weather, Climate, Water and the Environment, as well as with a number of other national meteorological services.

gsnmc.dwd.de **gruan.org**

5.8 EUMETSAT Satellite Application Facility on Climate Monitoring

Concerns about the changing global climate have highlighted the need for further enhancement of climate monitoring activities at regional and global levels. To this end, only satellite-based observations provide the necessary geographical coverage of timely, high-quality data. Especially over the oceans and in sparsely populated areas, satellites are generally the only source of data. The aim of the Satellite Application Facility on Climate Monitoring (CM SAF) operated on behalf of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is to provide the satellite-based geophysical climate data records that are required for climate monitoring. The CM SAF is part of EUMETSAT's network of Satellite Application Facilities (SAF), which in turn forms an integral part of the EUMETSAT Application Ground Segment.

Climatology of solar radiation for Europe, based on the combined set of SARAH and ICDR SEVIRI data



▲ *Figure 5.8-2: Climatology of solar radiation for Europe, based on the monthly means of the combined set of SARAH and ICDR SEVIRI data from 1983 to 2020 (Source: EUMETSAT/CM SAF)*

Significance for GCOS

The CM SAF provides a range of climatological parameters addressing some of the Essential Climate Variables (ECV) called for by the GCOS Implementation Plan in support of the United Nations Framework Convention on Climate Change (UNFCCC). According to GCOS' Second Report on the Adequacy of the Global Observing Systems for Climate, the CM SAF focuses on the provision of geophysical parameters describing elements of the energy and water cycles. The CM SAF supplies regional products with a comparatively high spatial ▪ ▪ ▪

◀ *Figure 5.8-1: The data delivered by polar-orbiting satellites, here a picture of one of EUMETSAT's Polar System satellites (EPS), are essential components of global climatologies. (Source: DWD, modified from ESA and EUMETSAT)* resolution as well as global products that complement ongoing international activities. As far as possible, this is done in compliance with the GCOS Climate Monitoring Principles.

Organisation

The CM SAF is part of EUMETSAT's SAF network, which consists of eight competence centres, each one dedicated to a specific scientific question. The operations and further development of the CM SAF are led by the Deutscher Wetterdienst (DWD) in collaboration with the Royal Meteorological Institute of Belgium (RMI), the Finnish Meteorological Institute (FMI), the Royal Netherlands Meteorological Institute (KNMI), the Swedish Meteorological and Hydrological Institute (SMHI), the UK's Meteorological Office (Met Office), the French Centre national de la recherche scientifique (CNRS) and the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss).

Products and services

The CM SAF provides geophysical data records for climate monitoring, deriving from measurements by different instruments on geostationary and polar-orbiting meteorological satellites, such as Meteosat and EPS. The data products of the CM SAF include monitoring data, made available in near real time and known as Interim Climate Data Records (ICDRs), as well as long-term data sets, produced based on precisely calibrated radiances and referred to as Thematic Climate Data Records (TCDRs). The homogeneous sets of high-quality data help scientists to investigate climate variability and its long-term changes.

The CM SAF's expanding product range is designed to address applications focusing on the Earth's atmospheric water and energy cycles at both global and regional scales. The products include

- macro- and microphysical cloud properties
- surface radiation parameters, including surface albedo and land surface temperature
- top-of-the-atmosphere radiation parameters
- water vapour and temperature
- precipitation.

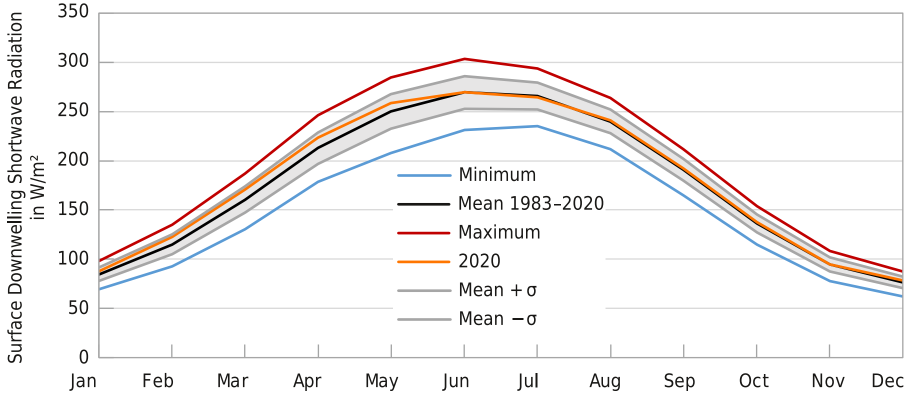
An example of a combination of a TCDR and an ICDR data set is shown in Figures 5.8-2 and 5.8-3.

The SARAH data set, which is based on measurements of the MVIRI and SEVIRI instruments on Meteosat, covers the period from 1983 to 2020 and is particularly well suited for climate studies for Europe and Africa. Figure 5.8-2 illustrates the climatology of solar radiation for Europe.

Figure 5.8-3 presents the ICDR series of current measurements for 2020 in relation to the mean annual variation of solar radiation, including the 30-year variability. The ICDR set thus makes it possible to assess whether a given year or month is an extreme or not. Figure 5.8-3 illustrates clearly that this was not the case in 2020.

The CM SAF offers all its products free of charge to the scientific community, including comprehensive documentation and information about validation. User services are provided through the website cmsaf.eu. Access to available CM SAF data is given through an online order platform that makes it easy for users to identify the products, data and additional services they need for a selected region of interest (see wui.cmsaf.eu).

Mean solar radiation (1983–2020) for Europe, based on the SARAH and ICDR SEVIRI data sets



▲ *Figure 5.8-3: Solar radiation (1983–2020) for Europe, based on the SARAH and ICDR SEVIRI data sets. The curves shown represent the long-term monthly mean (black), both the long-term monthly maximum (red) and minimum (blue), the monthly mean for 2020 (orange) and a standard deviation range around the long-term mean (grey). (Source: EUMETSAT/CM SAF)*

International context

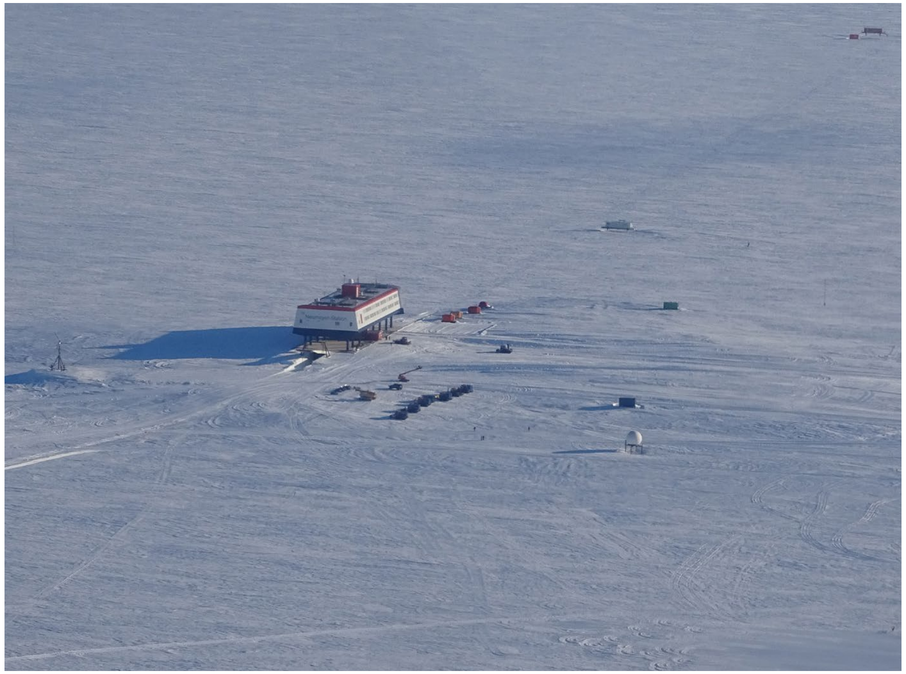
The products and procedures of the CM SAF not only respond to the aims of GCOS, they also contribute to other international programmes, for example the World Climate Programme (WCP) and the World Climate Research Programme (WCRP). CM SAF products are essential for the activities undertaken by the Group on Earth Observations (GEO) and under the Copernicus Earth observation programme. The DWD also participates in European activities, such as the ESA Climate Change Initiative, and in various EU-funded projects that interface with the CM SAF.

cmsaf.eu

6 Observations abroad

6.1 Meteorological observations at Neumayer station in the Antarctic

Regular meteorological measurements and observations have been carried out at the German Neumayer Antarctic research station since 1981. However, the station has not always been situated at the same place: the first »Georg von Neumayer Station« had to be abandoned in 1992 due to snow accumulation. It was replaced by the »Neumayer Station«, in turn abandoned in 2009 in favour of today's »Neumayer III« station. With each relocation, the Meteorological Observatory of Neumayer station moved further south, around 7 km in 1992 and around 6 km in 2009. However, this was not much of a change regarding the position of the observations, as the station is moving around 145 metres per year due to the flow velocity of the Ekström Ice Shelf. Over its four decades of existence, the Neumayer Meteorological Observatory has continuously developed further and seen extension. For instance, daily upper-air soundings have been carried out since 1983. In 1992, the station became a founding member of the Baseline Surface Radiation Network (BSRN) with the aim to conduct in situ long-term high-quality measurements of surface radiation. The upper-air sounding programme was extended in 1993 to include regular ozone soundings. Since 2019, Neumayer station has also been a member of the GCOS Reference Upper-Air Network (GRUAN).

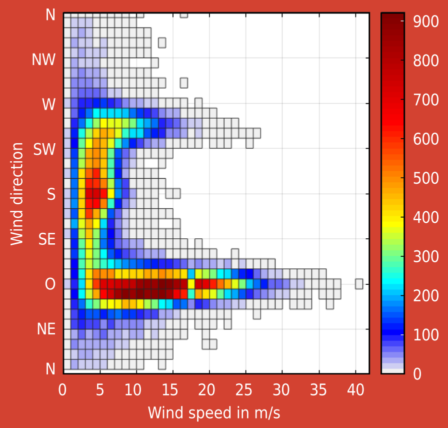


▲ *Photo 6.1-1: Neumayer III station (70° 40′ S, 8° 16′ W) on the Ekström Ice Shelf in December 2018. The measuring instruments of the observatory are situated 350 m to the south-west of the main building. Some others are installed on the roof of the station. The station's trace gas measuring site is situated 1,500 m further south; it can be seen in the top right corner of the picture.*

Significance for GCOS

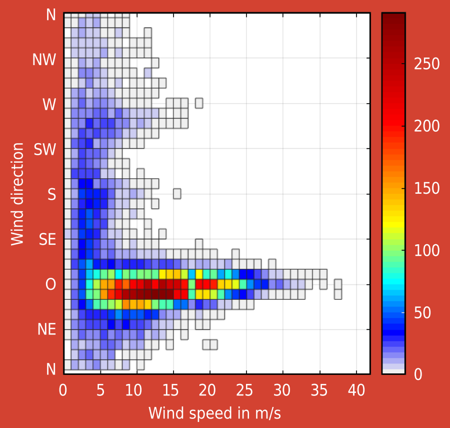
The mission of the Global Climate Observing System (GCOS) is to organise the observation of long-term changes in essential climate variables. The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) supports the tasks of GCOS in various areas. By operating the Neumayer Meteorological Observatory, the AWI makes a substantial contribution to data collection in the Antarctic, where data coverage otherwise is very poor. The purpose of the membership in the BSRN and GRUAN networks is therefore to enhance in particular the high-quality requirements for long-term time series.

All wind reports (1981–2021)



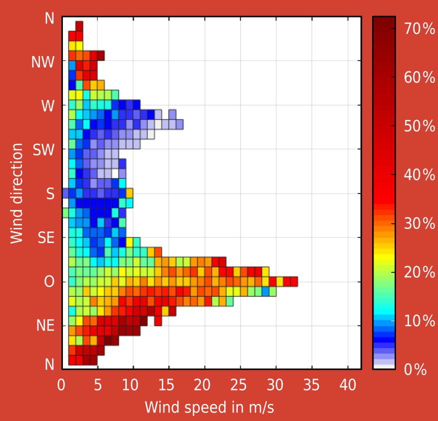
▲ *Figure 6.1-1a: Wind distribution at Neumayer station. There are three dominating weather regimes clearly visible: frequent and strong easterly winds due to cyclones to the north of the Ekström Ice Shelf, catabatic winds from the south and occasional south-westerlies due to high-pressure ridges above the Weddell Sea. Northerly inflows of air to the station are rare due to the topography of the ice shelf. (Source: AWI)*

Wind reports with snowfall (1981–2021)



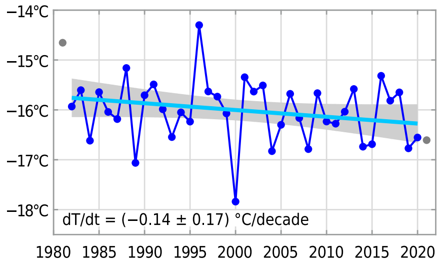
▲ *Figure 6.1-1b: Snowfall occurs in most cases together with easterly wind. (Source: AWI)*

Relative frequency of snowfall (1981–2021)



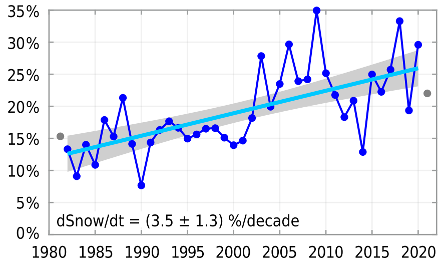
◀ *Figure 6.1-1c: Most cases of northerly air flows (up to more than 70 %) lead to snowfall at the station. Quite frequently, such situations are associated with »atmospheric rivers« transporting very much humidity from north to south. There are hardly no humid air flows from southern or south-western directions. (Source: AWI)*

2 m air temperature



▲ *Figure 6.1-2: Since measurements began in 1981, there has been no significant change, on average, in the 2 m temperature at Neumayer station. The statistical uncertainty (0.17 °C/decade) is larger than the calculated trend (−0.14 °C/decade). The grey dots at the beginning and end of the time series rely on incomplete annual data and have not been included in the trend analysis. (Source: AWI)*

Weather observations that include snowfall



▲ *Figure 6.1-3: At Neumayer station, 3-hourly synoptic weather reports have been produced since 1981. The diagram shows the proportion of weather reports that include observed precipitation (snowfall). There seems to be a distinct trend towards an increase in the number of snowfall events. The grey dots at the beginning and end of the time series rely on incomplete annual data and have not been included in the trend analysis. (Source: AWI)*

Required resources

The AWI in Bremerhaven runs the Neumayer Antarctic Research station (including the Meteorological Observatory) and bears all the necessary costs as part of Helmholtz funding for research infrastructure. The research station, as well as components of the observatory, are open to any researcher interested. Applications for use must be addressed to the AWI and are assessed by an international usage advisory board.

Data archive

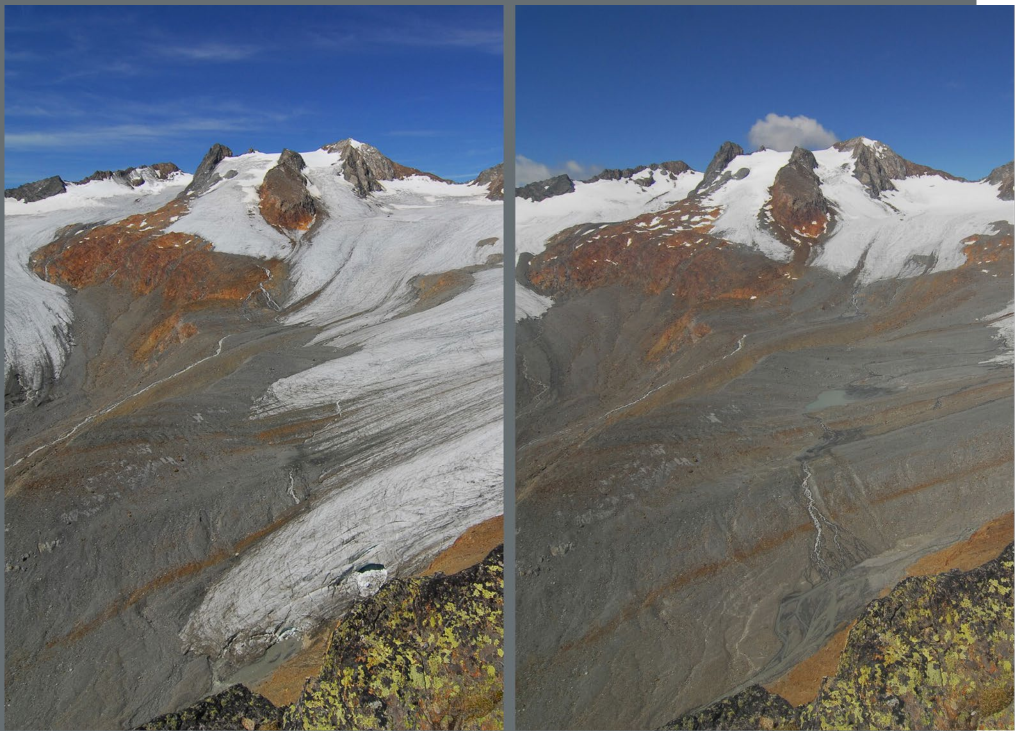
All data collected at Neumayer Meteorological Observatory are quality-controlled, usually once a year, and then archived in the scientific data repository PANGAEA®.

PANGAEA
Data Publisher for Earth & Environmental Science

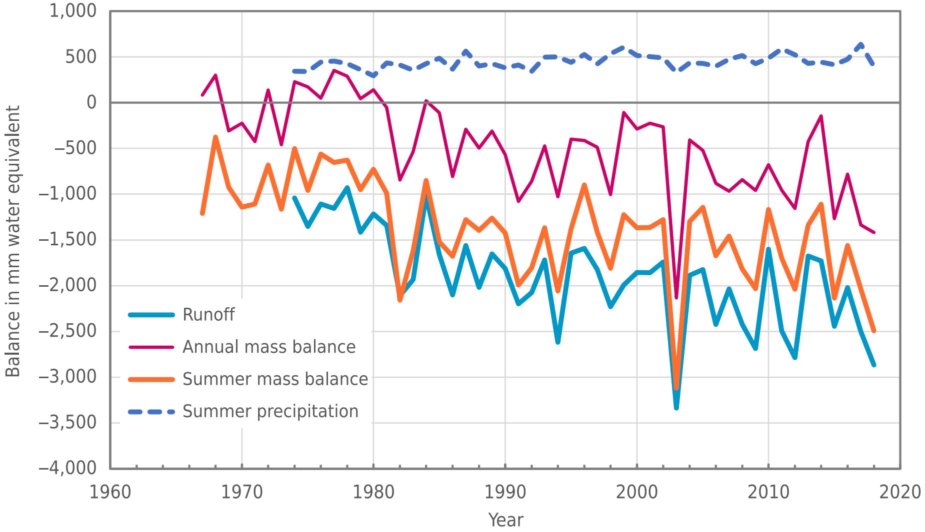
pangaea.de

6.2 Glacier monitoring abroad

The Geodesy and Glaciology group (KEG) of the Bavarian Academy of Sciences and Humanities (BAdW) has determined the changes in the area of ten Austrian glaciers at 10-year intervals since 1889. In addition, the annual sums of mass balance for the Vernagtferner glacier in the Ötztal valley have been analysed since 1964 whereas total glacier runoff has been recorded at hourly resolution since 1974.



Area-scaled glaciological annual and summer mass balances, annual totals of runoff and summer precipitation for the catchment area of the Vernagtferner gauging station



▲ *Figure 6.2-1: Time series of the mass balances determined for the Vernagtferner glacier, Ötztal valley, by means of the direct glaciological method for the entire year (purple) and the summer (May–October, orange) since 1964/65. The diagram also includes the annual sums of runoff recorded at Vernagtbach gauging station since 1974 (light blue) and summer precipitation (May–October, dashed dark blue line). The linear trend in runoff shows an increase from 1,300 mm to 2,500 mm from 1974 to 2018. For summer mass balance, the linear trend indicates an even greater increase. The absolute values in 1974 are around −990 mm water equivalent compared to more than −1,900 mm water equivalent at the end of the period. In contrast, summer precipitation shows only a weak tendency for increase from about 390 mm to 500 mm. (Source: BAdW)*

◀ *Photo 6.2-1: Pictures of the central part of the Vernagtferner glacier, taken by an automatic camera on 25.08.2010 (left) and 19.08.2021 (right)*

Description of measurements

Ten of the fifteen eastern Alpine glaciers monitored by the KEG are situated in Austria and are predominantly surveyed using the geodetic method. Four glaciers are in the Ötztal valley (Vernagt, Guslar, Hintereis and Gepatsch), two in the Stubai valley (Sulzenau and Grünau) and four in the Zillertal valley (Schwarzenstein, Horn, Waxegg and Schlegeis). The longest data series is available for Vernagtferner (see graph and measurement description in 4.6 Glaciers and permafrost), the second longest series exists for Hintereisferner (going back to 1894). Gepatschferner and all Zillertal ■ ■ ■

glaciers (»kees«) have been monitored since 1921, the Stubai glaciers since 1932. All time series of changes in mass show a similar pattern over time, with high losses until around 1950, slight gains mainly between 1960 and 1980 and thereafter even higher losses than in the first half of that century. The mean loss in ice thickness of Vernagtferner between 1889 and 1969 was about 30 cm/a, with a loss in area from 11.58 km² to 9.56 km². In 2009, the total area amounted to 7.92 km² and the glacier had split into two parts. Geo-radar measurements of the ice thickness carried out in 2006 resulted in a mean value of 31 m. Since then, the glacier area has reduced to 6.9 km² in 2018 and the mean ice thickness to about 20 m.

Since 1964, the mass balance of Vernagtferner has been determined separately for the accumulation and ablation periods using the glaciological method (Figure 6.2-1). The analysis of winter and summer balances shows that the high loss of ice mass does not result from lower precipitation in winter, but from higher amounts of melting during summer. The time series shows a mean total loss of 23.7 m water equivalent for the period 1964–2018, with the highest losses in 2003 (more than 2 m in a single year).

The Vernagtbach gauging and climate station was installed in 1973; at 2,640 m, it is the highest runoff measuring site in the eastern Alps. The station is not staffed, but monthly maintenance controls take place between April and November. Between 1974 and the mid-1980s, meteorological and hydrological parameters were recorded mainly during the summer, but measurements have been carried out more or less all year round for more than 30 years. Fully automatic registration was established in 2000. The data include values for runoff, precipitation and air temperature, the four radiation components, air pressure, air humidity, snow height and various other hydrological parameters. Daily photographs of the glacier are available for the summer months going back to 1976, direct ablation measurements of the ice surface date back to 2005. All meteorological and hydrological data sets can be obtained free of charge from the PANGAEA® database.

◀ *Photo 6.2-2: Automatic weather station on the Vernagt high plateau at 3,450 m. At this station, measurements are carried out to continuously monitor the evolution of snow cover and record the key meteorological components.*

Required resources

The monitoring tasks at KEG are covered by institutional funding. However, the massive amounts of continuous data and necessary maintenance work require additional human resources to ensure quality assessment, archiving and scientific exploitation. Options for funding this are currently being examined.

pangaea.de **https://geo.badw.de/en/the-project.html**

7 Conclusions and outlook

Political decisions needed to secure the continuity of observation series

The present report is based on the first Inventory Report on German Climate Observing Systems, published in 2013. It is a revised version of its predecessor and has been updated where possible. Where necessary, the list of ECVs considered has been adapted in accordance with the GCOS 2016 Implementation Plan (WMO 2016). The report gives an overall overview of the current state of the observation of relevant climate variables in Germany at both national and federal-state level and thus is a good documentation of Germany's contribution to GCOS. Based on the long time series that exist for many of the variables, it is possible to examine the development of the climate system in Germany. The report provides an outline of the legal foundations and points out deficiencies in the sustainability of observation activities (see Table 7-1). The new Inventory Report therefore constitutes an important planning basis for maintaining and further enhancing Germany's national climate observing system GCOS-DE.

Conclusions

As set out in the GCOS Implementation Plan (WMO 2016), GCOS as a global system strongly depends on well functioning components at the national level. Through its Resolution 39, the World Meteorological Organization (WMO) has therefore urged its Member States at its 17th Congress (WMO 2015) »[...]

1. To strengthen their national atmospheric, oceanographic and terrestrial climate observing networks and systems, including networks and systems for the hydrological and carbon cycles and the cryosphere within the framework of GCOS and in support of user needs;
2. To assist developing countries to strengthen their observing networks, to improve their capacity to acquire climate-relevant data, and to enhance their provision of climate services by implementing projects in the 10 GCOS Regional Action Plans, and by contributing to the implementation of the ClimDev Africa Programme and to similar initiatives in other regions;
3. To ensure, to the extent possible, the long-term continuity of the critical space-based components of GCOS, including the generation and dissemination of the satellite-based climate data and products based on the Essential Climate Variables that are required to meet the needs of NMHSs, the Conference of the Parties to UNFCCC, IPCC and other users of climate services;
4. To establish GCOS National Committees and to identify GCOS National Coordinators in order to facilitate coordinated national action on observing systems for climate, taking into account the joint international sponsorship of GCOS and the evolving international arrangements for GEOSS and GFCS;

[...].«

Alongside the Essential Climate Variables (ECVs) defined for data analysis at global, regional and national levels, other, locally-specific climate parameters may be of additional interest. In Germany, for example, the variables pollen and plant phenology have been identified to play such a nationally specific role. In some cases, there also exist Europe-wide observation networks.

Not all processes and interactions in the climate system are completely understood yet. Further to carrying out new, target-oriented studies, sustainable continuity of long-term series of observations is needed to continue collecting a large body of data for research and for the further development and enhancement of climate models. This will help to further reduce the uncertainties about the future of our climate.

The aim of this report therefore is to ensure the continuity of long-term series of observations, especially those for the ECVs. Table 7-1 highlights those areas where legal frameworks for running climate observations are lacking or could not be identified as well as the areas where the continuity of the observations is not secured and/or the necessary funding is missing. This ■ ■ ■

classification relies on an analysis and assessment carried out on the basis of the information provided by the various expert authors and contributors to this report.

Table 7-1: Overview of climate variables and their status in terms of legal framework, institutions in charge and funding. The contributions about ocean observations also include information about German activities outside German territory. (Source: DWD) ▼

Climate variable		Legal framework	Institution(s) in charge	Sustainability of observations (funding)
Atmospheric observations				
Near surface	2.1 Temperature and humidity	exists	Deutscher Wetterdienst	largely secured
	2.2 Wind	exists	Deutscher Wetterdienst	largely secured
	2.3 Air pressure	exists	Deutscher Wetterdienst	largely secured
	2.4 Precipitation	exists	Deutscher Wetterdienst	largely secured
	2.5 Radiation	exists	Deutscher Wetterdienst	largely secured
	2.6 Sunshine duration	exists	Deutscher Wetterdienst	largely secured
Free atmosphere	2.7 Temperature, wind and water vapour	exists	Deutscher Wetterdienst	largely secured
	2.8 Clouds	exists	Deutscher Wetterdienst	largely secured
	2.9 Lightning observations	exists	Deutscher Wetterdienst	largely secured
Atmospheric composition	2.10 Carbon dioxide	exists	Federal Environment Agency and research institutes	**partly secured**
	2.11 Methane	exists	Federal Environment Agency and research institutes	**partly secured**
	2.12 Other greenhouse gases	exists	Federal Environment Agency and research institutes	**partly secured**
	2.13 Anthropogenic greenhouse gas fluxes	exists	Deutscher Wetterdienst	largely secured
	2.14 Ozone	exists	Deutscher Wetterdienst, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) (polar stations), German Aerospace Center and University of Bremen (satellite data)	largely secured
	2.15 Aerosols	exists	Federal Environment Agency and research institutes	**partly secured**
	2.16 Pollen	exists	Deutscher Wetterdienst and German Pollen Information Service Foundation	**partly secured**

Climate variable		Legal framework	Institution(s) in charge	Sustainability of observations (funding)
Ocean observations				
Ocean physics	3.1 Sea surface temperature	exists	Federal Maritime and Hydrographic Agency and German federal states	largely secured
	3.2 Temperature in the water column	exists	Federal Maritime and Hydrographic Agency and research institutes	largely secured
	3.3 Salinity in the water column	exists	Federal Maritime and Hydrographic Agency and research institutes	largely secured
	3.4 Sea level	exists	Federal Maritime and Hydrographic Agency and German Federal Waterways and Shipping Administration	largely secured
	3.5 Sea state	exists	Federal Maritime and Hydrographic Agency, German federal states and research institutes	largely secured
	3.6 Sea ice	exists	Federal Maritime and Hydrographic Agency and research institutes	largely secured
	3.7 Ocean currents	exists	Federal Maritime and Hydrographic Agency and research institutes	largely secured
	3.8 Wind stress	exists	Deutscher Wetterdienst, Federal Maritime and Hydrographic Agency and research institutes	largely secured
	3.9 Ocean surface heat flux	exists	Deutscher Wetterdienst, Federal Maritime and Hydrographic Agency and research institutes	largely secured
Biogeochemistry	3.10 Biomass/Ocean colour	exists	Federal Maritime and Hydrographic Agency	largely secured
	3.11 Nutrients	exists	Federal Maritime and Hydrographic Agency, German federal states and research institutes	largely secured
	3.12 Oxygen	exists	Federal Maritime and Hydrographic Agency, German federal states and research institutes	largely secured
	3.13 Inorganic carbon in the ocean	none	Research institutes	**partly secured**
	3.14 Nitrous oxide (N_2O) in the ocean	none	Research institutes	**partly secured**
	3.15 Anthropogenic trace gases in the ocean	none	Research institutes	**not secured**
Ecosystems	3.16 Plankton	exists	German federal states and research institutes	**partly secured**
	3.17 Marine habitats	exists	German federal states and research institutes	**partly secured**

Climate variable		Legal framework	Institution(s) in charge	Sustainability of observations (funding)
Terrestrial observations				
Hydrosphere	4.1 Runoff	exists	German Federal Waterways and Shipping Administration, Federal Institute of Hydrology and German federal states	largely secured
	4.2 Water use	exists	German Federal Waterways and Shipping Administration and German federal states	largely secured
	4.3 Groundwater	exists	Federal Institute for Geosciences and Natural Resources and German federal states	largely secured
	4.4 Lakes	none	German federal states	largely secured
Cryosphere	4.5 Snow cover	exists	Deutscher Wetterdienst	largely secured
	4.6 Glaciers and permafrost	exists	Bavarian Academy of Sciences and Humanities and Bavarian Environment Agency	largely secured
Biosphere	4.7 Albedo	exists	Deutscher Wetterdienst	largely secured
	4.8 Soil carbon	none	Thünen Institute, German Federation and German federal states	**not secured**
	4.9 Above-ground biomass in forests	exists	German Federation and German federal states	largely secured
	4.10 Forest fires	exists	Deutscher Wetterdienst and German federal states	largely secured
	4.11 Soil moisture	exists	Deutscher Wetterdienst and German federal states	largely secured
	4.12 Phenology	exists	Deutscher Wetterdienst	largely secured

Climate variable	Legal framework	Institution(s) in charge	Sustainability of observations (funding)
International data centres			
5.1 Global Precipitation Climatology Centre	not required[1)]	Deutscher Wetterdienst	largely secured
5.2 Global Runoff Data Centre	not required[1)]	Federal Institute of Hydrology	largely secured
5.3 World Radiation Monitoring Center	not required[1)]	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI)	largely secured
5.4 World Data Center for Climate at the German Climate Computing Centre	not required[1)]	Max Planck Society, German federal state of Hamburg (University of Hamburg), Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), Helmholtz-Zentrum Hereon, Federal Ministry of Education and Research	largely secured
5.5 World Data Center for Remote Sensing of the Atmosphere	not required[1)] (contribution as of 2013)	German Remote Sensing Data Center and German Aerospace Center	largely secured
5.6 ISC World Data Centre PANGAEA®	not required[1)]	Center for Marine Environmental Science and Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI)	largely secured
5.7 Data quality centres of GCOS	not required[1)]	Deutscher Wetterdienst	largely secured
5.8 EUMETSAT Satellite Application Facility on Climate Monitoring	not required[1)]	Satellite Application Facility on Climate Monitoring (consortium partners: Deutscher Wetterdienst, European Organisation for the Exploitation of Meteorological Satellites and others)	largely secured
Observations abroad			
6.1 Meteorological observations at Neumayer station in the Antarctic	exists	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI)	largely secured
6.2 Glacier monitoring abroad	not required[1)]	Bavarian Academy of Sciences and Humanities	largely secured

1) usually by self-commitment of the Federation

The operation of observing systems for most of the ECVs – atmospheric, oceanic and terrestrial (Chapters 2 to 4) – has a legal foundation. In addition, the Federal Republic of Germany has to meet its commitments arising from international conventions and treaties, such as the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Paris Agreement, as well as from its participation in the Global Earth Observation System of Systems (GEOSS), the European Union's Earth observation programme Copernicus and GCOS. However, the observations of some ECVs must be considered as not secured, other activities are only partly secured or secured until a certain date, with large uncertainty regarding their continuity. What adds to this is that the data may not be exploited or analysed to their full extent due to lacking resources, plus the high risk of large data gaps, which makes climatological analysis of the data highly difficult.

Measures should therefore be taken to sustainably secure all statutory climate observations, but at least the observation of all those ECVs that are relevant to Germany. This applies to both in-situ and remote sensing observations and must include data analysis as well as quality assurance, data storage and availability. In this context, operators of observing systems must report about how the GCOS Climate Monitoring Principles are met (WMO 2003a, see Table 1-2).

Germany also makes valuable contributions to GCOS in the field of international data and product centres. These centres provide the various application areas with data sets and products that are of highest quality and in many respects unique. Most of the international data centres can be considered as secured. The Global Fire Monitoring Center (GFMC), which was mentioned in the inventory of 2013, is no longer included in the present report as it does not qualify as (climate) data centre.

Alongside the collection of information about the state and history of the climate system in its own country, Germany has also several contributions to GCOS ongoing outside its territory. With the exception of the observations at the Neumayer station in the Antarctic, the future of all of these is considered as not secured (see Table 7-1). The long-term, continuous recording of atmospheric processes over centuries has created a wealth of scientific data that has proven to be a real »treasure trove« for understanding the climate. To detect and understand critical changes, for example in connection with ocean acidification or the intensity of thermohaline circulation, as early as possible, we must continue to aim for sustainable observation of all ECVs also in the oceans and at their surface.

Evaluation

On the whole, the state of the German GCOS segment, GCOS-DE, can continue to be considered as good. This applies to the quality of the data collected just as much as to the sustainability of observation programmes – but for a few exceptions.

However, shortcomings still exist regarding sustainable observations of greenhouse gases as key climate drivers. For this reason, in particular the programmes under which greenhouse gases are observed should become permanent both due to their importance as core parameters for the description of the climate system and with a view to successful climate protection. Initial steps have already been taken and the establishment of an operational verification scheme for greenhouse gas emissions will further increase the significance of observations and improve their robustness.

As additional need for data analysis is reported for several of the climate variables, the resources endowed should be reviewed to ensure optimal exploitation of the data.

With the responsibilities for some of the climate variables being distributed widely, the compilation of this nearly complete overview of climate observation in Germany required the collaboration of many experts and authors. We would like to thank everyone for their valuable contributions.

An overall, Internet-based climate information system to provide an always up-to-date overview of the state and trends of the climate system in Germany and to present the findings obtained through GCOS-DE and list all responsible institutions would be a useful tool of support just as much for political and economic decision-making as for the general public.

Outlook

The primary aim should be to sustainably secure the continuity of those German climate observations that are of major importance. Germany's National GCOS Coordinator, who is seated at the Deutscher Wetterdienst (DWD), will continue to strive for this goal. In support of this, the results of this report as well as the recommendations adopted at the annual national GCOS meetings are regularly presented to the Interministerial Working Group on Adaptation to Climate Change (IMAA) for further action. Special attention should be paid to respecting the Climate Monitoring Principles of GCOS (see Table 1-2) to assure that data are free from any undesired interference signals. In addition, accurate documentation of the metadata must be guaranteed to assure the correct assessment of today's data also in the future.

Apart from in-situ observations, remote sensing-based data (e.g. satellite and radar data) are increasingly used for climatological applications. Provided that GCOS' special principles for satellite-based climate monitoring are followed adequately, the resulting data provide a good supplement with complementary information to in-situ data. Satellite data are especially well suited for filling spatial data gaps in global climate observation coverage as well as for the derivation of global data sets (see Table 1-1; WMO 2016).

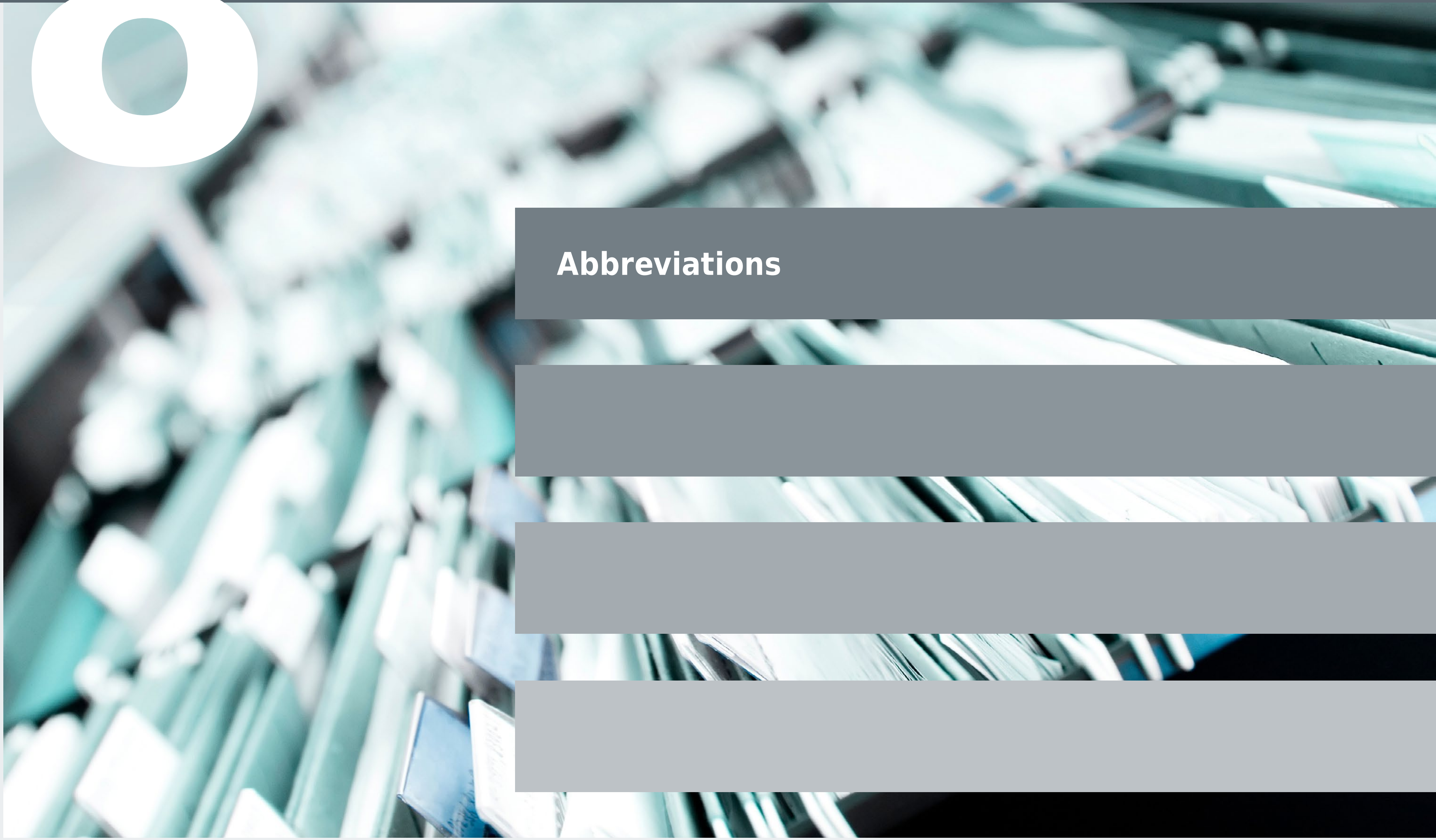
The list of ECVs is variable; advancing climate research and measurement technologies will enable new variables to be added to it. New requirements from the users, for example in the context of planning measures for adaptation to climate change, may also cause changes to the list. The significance of new ECVs for Germany must be verified and co-ordinated as part of the implementation of the GCOS Implementation Plans (WMO 2010, 2016, 2022).

If any synergies between the measuring networks were detected, this would possibly mean potential for optimising observation activities and help to improve the understanding of the climate system in whole. In this context, integrated analyses of several climate variables could be of valuable use.

For this reason, a well functioning national climate observation system at the same time is one of the main pillars for national implementation of the Global Framework for Climate Services (GFCS).

8 Lists and references

8 Lists and references



Abbreviations

A

AABW
Antarctic Bottom Water

AAIW
Antarctic Intermediate Water

AARI
Arctic and Antarctic Research Institute

ACP
Atmospheric Composition Portal

ACTRIS
Aerosol, Clouds and Trace Gases Research Infrastructure

ADCP
Acoustic Doppler current profiler

AG
Aktiengesellschaft
(Stock corporation)

AGU
American Geophysical Union

ALOMAR
Arctic Lidar Observatory for Middle Atmosphere Research

AMBAV
Agrarmeteorologisches Modell zur Berechnung der aktuellen Evapotranspiration
(Agrometeorological model for the calculation of current evapotranspiration)

AMSeL
KFKI-Projekt zur Analyse von hochaufgelösten Tidewasserständen und Ermittlung des MSL an der deutschen Nordseeküste
(KFKI-led reseach project Mean Sea Level and Tidal Analysis at the German North Sea Coastline)

AntarktUmwSchProtAG
Gesetz zur Ausführung des Umweltschutzprotokolls
(Act Implementing the Protocol on Environmental Protection)

AntON
Antarctic Observing Network

AOPC
Atmospheric Observation Panel for Climate

Argo
Array for Real-time Geostrophic Oceanography

ATDnet
Arrival Time Difference Network of the UK's Met Office for lightning detection

AtlantOS
All-Atlantic Ocean Observing System

AutoPollen
EUMETNET Automatic Pollen Monitoring Programme

AWI
Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung (AWI)
(Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI))

AWZ
Ausschließliche Wirtschaftszone
(Exclusive Economic Zone, EEZ)

B

BAdW
Bayerische Akademie der Wissenschaften
(Bavarian Academy of Sciences and Humanities)

BATS
Bermuda Atlantic Time-series Study

BBodSchG
Bundes-Bodenschutzgesetz
(Federal Soil Protection Act)

BC
Black carbon

BCO-DMO
Biological and Chemical Oceanography Data Management Office

BDF
Boden-Dauerbeobachtungsflächen
(permanent observation plots)

BfG
Bundesanstalt für Gewässerkunde
(Federal Institute of Hydrology)

BfN
Bundesamt für Naturschutz
(Federal Agency for Nature Conservation)

BfS
Bundesamt für Strahlenschutz
(Federal Office for Radiation Protection)

BGC-Argo
Biogeochemical Argo

BGR
Bundesanstalt für Geowissenschaften und Rohstoffe
(Federal Institute for Geosciences and Natural Resources)

BImSchG
Bundesimmissionsschutzgesetz
(Federal Immission Control Act)

BImSchV
Bundesimmissionsschutzverordnung
(Ordinance on the Implementation of the Federal Immission Control Act)

BLANO
Bund/Länder Arbeitsgemeinschaft Nord- und Ostsee
(Federal/State Working Group North Sea and Baltic Sea)

BLE
Bundesanstalt für Landwirtschaft und Ernährung
(Federal Office for Agriculture and Food)

BLIDS
Siemens Blitz Informationsdienst
(lightning information service of Siemens)

BLMP
Bund/Länder-Messprogramm Meeresumwelt
(German Marine Monitoring Programme)

BMBF
Bundesministerium für Bildung und Forschung
(Federal Ministry of Education and Research)

BMDV
Bundesministerium für Digitales und Verkehr
(Federal Ministry for Digital and Transport)

BMEL
Bundesministerium für Ernährung und Landwirtschaft
(Federal Ministry of Food and Agriculture)

BMU (until 2021, now BMUV)
Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
(Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)

BMUV
Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz
(Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection)

BonaRes
Boden als nachhaltige Ressource für die Bioökonomie
(Soil as a sustainable resource for the bioeconomy. Funding initiative of the German Federal Ministry for Education and Research (BMBF))

BOOS
Baltic Operational Oceanographic System

BSAP
Baltic Sea Action Plan

BSH
Bundesamt für Seeschifffahrt und Hydrographie
(Federal Maritime and Hydrographic Agency)

BSRN
Baseline Surface Radiation Network

BWaldG
Bundeswaldgesetz
(Federal Forest Act)

BWI
Bundeswaldinventur
(national forest inventory)

BZE
Bodenzustandserhebung
(national soil survey)

BZE-LW
Bodenzustandserhebung Landwirtschaft
(national survey for agricultural soils)

BZE-Wald
Bodenzustandserhebung im Wald
(national survey for forest soils)

C

C
Carbon

C3S
Copernicus Climate Change Service

CAL
Cloud albedo

Caltech
California Institute of Technology

CAMS
Copernicus Atmosphere Monitoring Service

C_{ant}
Anthropogenic carbon/anthropogenic carbon dioxide

CARBOCHANGE
Changes in carbon uptake and emissions by oceans in a changing climate

CarboEurope
Integrated Project CarboEurope-IP, Assessment of the European Terrestrial Carbon Balance

CARBOOCEAN
Marine carbon sources and sinks assessment

CARIBIC
Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container

CBD
Convention on Biological Diversity

CBS
WMO Commission for Basic Systems (since 2019 INFCOM)

CC0
Creative Commons Zero

CEMEMS
Custom Embedded MEMS solutions

CEMS
Copernicus Emergency Management Service

CEOS
Committee on Earth Observation Satellites

CFC
Chlorofluorocarbon

CGMS
Coordination Group for Meteorological Satellites

CH_4
Methane

CHARM-F
Airborne scientific instrument for the remote monitoring of CH_4

CHL
Chlorophyll

CHMI
Czech Hydrometeorological Institute

CliC
Climate and Cryosphere Project

CLIMAT
A code for reporting monthly climatological data

ClimDev Africa
Climate for Development in Africa

CLIVAR
Climate Variability and Predictability

CM SAF
Satellite Application Facility on Climate Monitoring

CMEMS
Copernicus Marine Service

CMIP
Coupled Model Intercomparison Project

CNES
Centre National d'Etudes Spatiales

CNRS
Centre national de la recherche scientifique

CO_2
Carbon dioxide

CO2M
Copernicus Carbon Dioxide Monitoring

COCCON
COllaborative Carbon Column Observing Network

COMFORT
Our common future ocean in the Earth system – quantifying coupled cycles of carbon, oxygen, and nutrients for determining and achieving safe operating spaces with respect to tipping points

COMPONUT
Towards comparability of global oceanic nutrient data

COP
Conference of the Parties of the UNFCCC

COPEPOD
Coastal & Oceanic Plankton Ecology, Production, & Observation Database

Copernicus
Earth observation programme of the European Union

CORDEX
Coordinated Regional Climate Downscaling Experiment

COSMO-DE
Consortium for Small-Scale Modelling for Germany

COSMO-EU
Consortium for Small-Scale Modelling for Europe

COSMOS-Europe
European network of cosmic-ray neutron soil moisture sensors

COST
European Cooperation in Science and Technology

COSYNA
Coastal Observing System for Northern and Arctic Seas

CRITTERBASE
Science-driven data warehouse for marine biota

CRNS
Cosmic-ray neutron sensing

CSIRO
Commonwealth Scientific and Industrial Research Organisation

CTM
Chemistry and Transport Model

CVOO
Cape Verde Ocean Observatory

D

D-A-CH
Deutschland-Österreich-Schweiz (Co-operation between Germany, Austria and Switzerland)

DAM
Deutsche Allianz Meeresforschung e. V. (German Marine Research Alliance)

DAS
Deutsche Anpassungsstrategie (German Strategy for Adaptation to Climate Change)

DBCP
Data Buoy Cooperation Panel

DCPC
Data Collection or Production Centre

DDC
Data Distribution Centre

Destatis
Statistisches Bundesamt (Federal Statistical Office)

DFD
Deutsches Fernerkundungsdatenzentrum (German Remote Sensing Data Center)

DFG
Deutsche Forschungsgemeinschaft (German Research Foundation)

DGJ
Deutsches Gewässerkundliches Jahrbuch (German Hydrological Yearbook)

DGzRS
Deutsche Gesellschaft zur Rettung Schiffbrüchiger (German Maritime Search and Rescue Service)

DIAL
Differential Absorption Lidar

DKRZ
Deutsches Klimarechenzentrum (German Climate Computing Centre)

DLR
Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)

DOD
Deutsches Ozeanographisches Datenzentrum (German Oceanographic Data Centre)

DOI
Digital Object Identifier

DSOW
Denmark Strait Overflow Water

DU
Dobson unit

DUETT
DWD project on the integrated use of in-situ and satellite-based data

DWD
Deutscher Wetterdienst (German Meteorological Service)

DWDG
Gesetz über den Deutschen Wetterdienst (Deutscher Wetterdienst Act)

E

EAN
European Aeroallergen Network

EarthCARE
Earth Clouds, Aerosols and Radiation Explorer

EBAS
Database of atmospheric chemical composition and physical properties

EC
European Commission

ECMWF
European Centre for Medium-Range Weather Forecasts

ECV
Essential Climate Variable

EEA
European Environment Agency

EEZ
Exclusive Economic Zone

EFAS
European Flood Awareness System

EFFIS
European Forest Fire Information System

EMEP
European Monitoring and Evaluation Programme

EMODnet
European Marine Observation and Data Network

ENVISAT
Environmental Satellite

EPA
Environmental Protection Agency

EPN
European Phenological Network

EPS
Ensemble Prediction System

ERA5
ECMWF Reanalysis v5

ESA
European Space Agency

ESRL
Earth System Research Laboratories

ESTOC
European Station for Time series in the Ocean, Canary Islands

E-Surfmar
EUMETNET Surface Marine observation programme

EU
European Union

EUCLID
EUropean Cooperation for LIghtning Detection

EUMETNET
Economic Interest Grouping (EIG) of European National Meteorological Services

EUMETSAT
European Organisation for the Exploitation of Meteorological Satellites

EURO4M
EUropean Reanalysis and Observations for Monitoring

EURO-FRIEND
EUropean Flow Regimes from International Experimental and Network Data

EuroGOOS
European Global Ocean Observing System

EUROWATERNET
Monitoring and Information Network for Inland Water Resources of the European Environment Agency

EUSAAR
EUropean Supersites for Atmospheric Aerosol Research

F

Fach-AG EuNäP
BLANO expert working group on eutrophication, nutrients and plankton

FAO
Food and Agriculture Organization of the United Nations

FD
Floods Directive

FDR
Frequency domain reflectometry

FG
First Guess Product

FINO
Forschungsplattformen in Nord- und Ostsee (research platforms in the North and Baltic Sea)

FMI
Finnish Meteorological Institute

FONA
Forschung für Nachhaltigkeit (Research for Sustainability strategy)

FS
Designation for German research vessels (Forschungsschiff)

FTIR
Fourier Transform Infrared Spectroscopy

G

GAW
Global Atmosphere Watch

GCM
Global Climate Model

GCOS
Global Climate Observing System

GCOS-DE
GCOS Deutschland, the German component of GCOS

GCP
Global Carbon Project

GDAC
Global Data Assembly Centre

GDAP
GEWEX Data and Analysis Panel

GDI-DE
Geodateninfrastruktur Deutschland (Spatial Data Infrastructure Germany)

GDP
GRUAN Data Product

GEO
Group on Earth Observations

GEOMAR
GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel (GEOMAR Helmholtz Centre for Ocean Research Kiel)

GeoNutzV
Geodatennutzungsverordnung (Ordinance Setting the Terms of Use for the Provision of Federal Spatial Data)

GEOSS
Global Earth Observation System of Systems

GEWEX
Global Energy and Water Exchanges

GFCS
Global Framework for Climate Services

GFMC
Global Fire Monitoring Center

GHG
Greenhouse gas

GIA
Glacial isostatic adjustment

GLD360
Global Lightning Detection Network

GlobWave
Global Wave Data Portal

GLODAP
Global Ocean Data Analysis Project

GLOSS
Global Sea Level Observing System

GmbH
Gesellschaft mit beschränkter Haftung (company with limited liability)

GME
Global Model Extended (global numerical weather forecasting model of the DWD)

GMSL
Global Mean Sea Level

GNSS
Global Navigation Satellite System

GO_2DAT
Global Ocean Oxygen Database and ATlas

GOME
Global Ozone Monitoring Experiment

GOOS
Global Ocean Observing System

GOSAT
Greenhouse Gases Observing Satellite

GO-SHIP
Global Ocean Ship-based Hydrographic Investigations Program

GPCC
Global Precipitation Climatology Centre

GPCP
Global Precipitation Climatology Project

GPS
Global Positioning System

GRACE
Gravity Recovery and Climate Experiment

GRDC
Global Runoff Data Centre

GRUAN
GCOS Reference Upper-Air Network

GrwV
Grundwasserverordnung (Groundwater Ordinance)

GSN
GCOS Surface Network

GSNMC
GCOS Surface Network Monitoring Centre

GTN-H
Global Terrestrial Network for Hydrology

GTN-R
Global Terrestrial Network for River Discharge

GTOS
Global Terrestrial Observing System

GTS
Global Telecommunication System

GUAN
GCOS Upper-Air Network

GUAN (2.15)
German Ultrafine Aerosol Network

GWD
Groundwater Directive 2006/118/EC

H

H_2
Hydrogen

H_2S
Hydrogen sulphide

HELCOM
Helsinki Commission

HGF
Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren e. V. (Helmholtz Association of German Research Centers)

HOAPS
Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data

HOMPRA
GPCC Homogenized Precipitation Analysis

HOT
Hawaii Ocean Time-series

hPa
Hectopascal

H_S
Significant wave height

H SAF
Satellite Application Facility on Support to Operational Hydrology and Water Management

HWRP
Hydrology and Water Resources Programme

HYDROLARE
International Data Centre on the Hydrology of Lakes and Reservoirs

Hydroweb
Data portal for time series of water levels in rivers and lakes

I

IAGOS
In-service Aircraft for a Global Observing System

IAHS
International Association of Hydrological Sciences

IAP
Institute of Atmospheric Physics

ICDR
Interim Climate Data Record

ICES
International Council for the Exploration of the Sea

ICOADS
International Comprehensive Ocean-Atmosphere Data Set

ICON
ICOsahedral Nonhydrostatic circulation model of the DWD

ICON-ART
ICOsahedral Nonhydrostatic circulation model – Aerosols and Reactive Trace gases

ICON-EU
ICOsahedral Nonhydrostatic circulation model for Europe

ICOS
Integrated Carbon Observation System

ICP Forests
International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests

IfM
Institut für Meereskunde, Universität Hamburg (Institute of Oceanography, Hamburg University)

IG³IS
Integrated Global Greenhouse Gas Information System

IGACO
Integrated Global Atmospheric Chemistry Observations

IGB
Leibniz-Institut für Gewässerökologie und Binnenfischerei
(Leibniz Institute of Freshwater Ecology and Inland Fisheries)

IGRAC
International Groundwater Resources Assessment Centre

IGY
International Geophysical Year

IHP
Intergovernmental Hydrological Programme

IICWG
International Ice Charting Working Group

ILTER
International Long Term Ecological Research

IMAA
Interministerielle Arbeitsgruppe Anpassung an den Klimawandel
(Interministerial Working Group on Adaptation to Climate Change)

INFCOM
Commission for Observation, Infrastructure and Information Systems

INSPIRE
Infrastructure for Spatial Information in Europe

INSTAAR
Institute of Arctic and Alpine Research

IOC
Intergovernmental Oceanographic Commission

IOCCG
International Ocean-Colour Coordinating Group

IOCCP
International Ocean Carbon Coordination Project

IODP
Integrated Ocean Discovery Program

IOW
Leibniz-Institut für Ostseeforschung Warnemünde
(Leibniz Institute for Baltic Sea Research Warnemünde)

IPCC
Intergovernmental Panel on Climate Change

IPG
International Phenological Gardens

IPWG
International Precipitation Working Group

IR
Infrared

ISC
International Science Council

ISF
Institut für Seenforschung
(Institute for Lake Research)

ISMN
International Soil Moisture Network

ISOW
Iceland–Scotland Overflow Water

ITMS
Integriertes Treibhausgas-Monitoringsystem
(Integrated Greenhouse Gas Monitoring System)

IUP
Institut für Umweltphysik, Universität Bremen
(Institute of Environmental Physics, University of Bremen)

J

JCOMM
Joint Technical Commission for Oceanography and Marine Meteorology

JGOFS
Joint Global Ocean Flux Study

JJA
June, July, August

JMA
Japan Meteorological Agency

JRC
Joint Research Centre

K

K
Kelvin

kA
Kiloampere

KEG
Gruppe Erdmessung und Glaziologie
(Geodesy and Glaciology group (KEG) of the Bavarian Academy of Sciences and Humanities (BAdW))

KFKI
Kuratorium für Forschung im Küsteningenieur-wesen
(Coastal Engineering Research Council)

KIT
Karlsruher Institut für Technologie
(Karlsruhe Institute of Technology)

KLIDADIGI
Klimadatendigitalisierung
(DWD project to digitise historical data)

KLiVO
Deutsches Klimavorsorgeportal
(Climate Preparedness Portal)

KNMI
Koninklijk Nederlands Meteorologisch Instituut
(Royal Netherlands Meteorological Institute)

KSG
Bundes-Klimaschutzgesetz
(German Federal Climate Protection Act)

L

LAWA
Bund/Länder-Arbeitsgemeinschaft Wasser
(German Working Group on water issues of the Federal States and the Federal Government)

LfU Bayern
Bayerisches Landesamt für Umwelt
(Bavarian Environment Agency)

LfUG
Gesetz über das Bayerische Landesamt für Umwelt
(Law on the Bavarian Environment Agency)

Lidar
Light Detection And Ranging

LINET
Lightning Detection Network

LKN.SH
Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (Schleswig-Holstein's Government-owned Company for Coastal Protection, National Parks and Ocean Protection)

LLCF
Long-lived climate forcers

LLUR
Landesamt für Landwirtschaft, Umwelt und ländliche Räume
(State Agency for Agriculture, Environment and Rural Areas)

LMT
Local mean time

LMU Munich
Ludwig-Maximilians-Universität München
(Ludwig Maximilian University of Munich)

LSA SAF
Satellite Application Facility on Land Surface Analysis

LSW
Labrador Sea Water

LT
Lighthouse

LUCAS
Land Use and Coverage Area frame Survey

LUNG
Landesamt für Umwelt, Naturschutz und Geologie
(State Agency for Environment, Nature Conservation and Geology)

M

MAMAP
Methane Airborne MAPper

MARNET
Marines Umweltmessnetz in Nord- und Ostsee
(Marine Environmental Monitoring Network in the North Sea and Baltic Sea)

MARUM
Zentrum für Marine Umweltwissenschaften
(Center for Marine Environmental Sciences of the University of Bremen)

MCAP
Monte-Carlo autoregressive padding

MCDS
Marine Climate Data System

MD
Meteorologischer Dienst der ehemaligen Deutschen Demokratischen Republik
(Meteorological Service of the former German Democratic Republic)

MEMENTO
MarinE MethanE and NiTrous Oxide

MERLIN
Methane Remote Sensing Lidar Mission

Meteosat
Meteorological satellite

MeteoSwiss
Swiss Federal Office of Meteorology

Met Office
United Kingdom Meteorological Office

Metop
Meteorological Operational Satellite

MIK Brandenburg
Ministerium des Innern und für Kommunales des Landes Brandenburg
(Brandenburg Ministry of the Interior and for Municipal Affairs)

ML Niedersachsen
Niedersächsisches Ministerium für Ernährung, Landwirtschaft und Verbraucherschutz
(Ministry for Food, Agriculture and Consumer Protection of Lower Saxony)

MOHp
Meteorologisches Observatorium Hohenpeißenberg
(Hohenpeissenberg Meteorological Observatory)

MOL
Meteorologisches Observatorium Lindenberg
(Lindenberg Meteorological Observatory)

MOL-RAO
Meteorologisches Observatorium Lindenberg – Richard-Aßmann-Observatorium
(Lindenberg Meteorological Observatory – Richard Assmann Observatory)

MoMoK
Moorbodenmonitoring für den Klimaschutz
(Peatland Monitoring Program for Climate Protection)

MOSAiC
Multidisciplinary drifting Observatory for the Study of Arctic Climate

MP
Monitoring Product

mPa
Millipascal

MPI-M
Max-Planck-Institut für Meteorologie
(Max Planck Institute for Meteorology)

MQ
Mean runoff

MRI
Meteorological Research Institute

MSE
Mean squared error

MSFD
Marine Strategy Framework Directive

MSL
Mean Sea Level

M. S.
Maria Sibylla

MTG
Meteosat Third Generation

MUDAB
Meeresumweltdatenbank
(Marine Environmental Database)

MUNSTAR
Projekt »Methodische Untersuchungen zur Novellierung der Starkregenstatistik für Deutschland«
(project for the investigation of methods for revising and updating heavy rainfall statistics in Germany)

N

N_2O
Nitrous oxide

NADW
North Atlantic Deep Water

NASA
National Aeronautics and Space Administration

NDACC
Network for the Detection of Atmospheric Composition Change

NDMC
Network for the Detection of Mesospheric Change

NEMO
Nucleus for European Modelling of the Ocean

NF_3
Nitrogen trifluoride

NFSI
National forest soil inventory

NILU
Norsk institutt for luftforskning
(Norwegian Institute for Air Research)

NIMH
National Institute of Meteorology and Hydrology

NIR
National Inventory Report

NLWKN
Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz
(State Enterprise for Water Management, Coastal and Nature Conservation)

NMFS
National Marine Fisheries Service

NMHS
National Meteorological and Hydrological Service

NO
Nitrogen monoxide

NO_2
Nitrogen dioxide

NOAA
National Oceanic and Atmospheric Administration

NODC
National Oceanographic Data Center

NOOS
North West European Shelf Operational Oceanographic System

NO_x
Nitrogen oxides

NPGO
North Pacific Gyre Oscillation

NSIDC
National Snow and Ice Data Center

NSSS
North Sea Summer Survey

O

O_3
Ozone

OC
Ocean Colour

OC TAC
Ocean Colour Thematic Assembly Center

OceanGLIDERS
GCOS component for the global collection of glider observations

OceanSITES
Worldwide system of deepwater reference stations

OCO
Orbiting Carbon Observatory

OECD
Organisation for Economic Co-operation and Development

OGewV
Oberflächengewässerverordnung (Surface Waters Regulation)

OSI SAF
Satellite Application Facility on Ocean and Sea Ice

OSPAR
Convention for the Protection of the Marine Environment of the North-East Atlantic replacing the Oslo and Paris Conventions; also name of the related international commission

P

P_{95}
95th percentile

PANGAEA®
Data Publisher for Earth & Environmental Science

PDO
Pacific Decadal Oscillation

PEG
Phytoplankton Expert Group

PEP
Pan European Phenology database

PermaNET
Permafrost Long-term Monitoring Network

PermaNET-BY
Bavarian component of the PermaNet network for monitoring permafrost

PID
Stiftung Deutscher Polleninformationsdienst (German Pollen Information Service Foundation)

PM2.5
Particulate Matter 2.5 µm

PM10
Particulate Matter 10 µm

ppb
Parts per billion

ppm
Parts per million

ppt
Parts per trillion

PSS-78
Practical Salinity Scale 1978

PW
Precipitable Water

Q

Q
Runoff

R

R&D
Research and development

RA
Regional Association

Radar
Radio Detection And Ranging

RADOLAN
Radar-Online-Aneichung
(system for real-time online adjustment of radar-based precipitation data)

RBCN
Regional Basic Climatological Network

RCA4
Rossby Centre regional atmospheric mode, fourth version

RCC-CM
Regional Climate Centre Network Node on Climate Monitoring

RCP
Representative Concentration Pathway

RDCC
Regional Dobson Calibration Center

ReKliEs-De
Regionale Klimaprojektionen Ensemble für Deutschland
(BMBF-funded project Regional Climate projections Ensemble for Germany)

REMO-UBA
Regionales Klimamodell – Umweltbundesamt
(regional climate model of the German Federal Environment Agency)

RM
Reference material

RMI
Royal Meteorological Institute of Belgium

RMSL
Relative Mean Sea Level

ROOS
Regional Operational Oceanographic Systems

RPI
Rensselaer Polytechnic Institute, USA

RS
Radiosonde

S

S5P/S5
Sentinel-5P/Sentinel-5

SAF
Satellite Application Facility

SAL
Surface albedo

SAR
Synthetic Aperture Radar

SARAH
Surface Radiation Data Set – Heliosat

SBSTA
Subsidiary Body for Scientific and Technological Advice

SCAPP
SCAnning Pyrheliometer/Pyranometer

SCIAMACHY
SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY

SC-MINT
Standing Committee on Measurements, Instrumentation and Traceability

SCOR
Scientific Committee on Oceanic Research

SCOR COMPONUT
SCOR Working Group 147 »Towards comparability of global oceanic nutrient data«

SeaDataNet
Pan-European infrastructure for ocean & marine data management

SeeAufgG
Gesetz über die Aufgaben des Bundes auf dem Gebiet der Seeschifffahrt
(Maritime Shipping Responsibilities Act)

SEVIRI
Spinning Enhanced Visible and InfraRed Imager

SF_6
Sulphur hexafluoride

SI
Système international d'unités

SMHI
Sveriges meteorologiska och hydrologiska institut
(Swedish Meteorological and Hydrological Institute)

SMOS
Soil Moisture and Ocean Salinity

SO_2
Sulphur dioxide

SOCAT
Surface Ocean CO_2 Atlas

SONIe
Instrument for measuring sunshine duration

SOOP
Ship Of Opportunity Programme

SOT
Ship Observations Team

SPNAtl
Subpolar North Atlantic

SSA
Singular system analysis

SURFRAD
Surface Radiation Budget

Sv
Sverdrup

SWOT
Surface Water and Ocean Topography

Synop
Numerical code used for reporting weather observations

T

TCCON
Total Carbon Column Observing Network

TCDR
Thematic Climate Data Records

TD
Technical Document

TDR
Time domain reflectometry

TERENO
Terrestrial Environmental Observatories

TGZ
Tide gauge zero

TI
Thünen-Institut
(Thünen Institute)

TROPOS
Leibniz-Institut für Troposphärenforschung
(Leibniz Institute for Tropospheric Research)

TU Wien
Technische Universität Wien

U

UBA
Umweltbundesamt
(Federal Environment Agency)

UFP
Ultrafine Particles

UFS
Umweltforschungsstation Schneefernerhaus
(Environmental Research Station Schneefernerhaus)

UIG
Umweltinformationsgesetz
(Environmental Information Act)

UK
United Kingdom

UN
United Nations

UNECE
United Nations Economic Commission for Europe

UNEP
United Nations Environment Programme

UNESCO
United Nations Educational, Scientific and Cultural Organization

UNFCCC
United Nations Framework Convention on Climate Change

US
United States

USA
United States of America

UStatG
Umweltstatistikgesetz
(Environmental Statistics Act)

UTC
Universal Time Coordinated

UV
Ultraviolet

V

VASClimO
Variability Analysis of Surface Climate Observations

VIIRIS
Visible Infrared Imaging Radiometer Suite

VOS
Voluntary Observing Ships scheme

VWFS
Vermessungs-, Wracksuch- und Forschungs-schiff
(surveying, wreck search and research vessel)

W

WaStrG
Bundeswasserstraßengesetz
(Federal Waterways Act)

WCC
World Climate Conference

WCP
World Climate Programme

WCRP
World Climate Research Programme

WDC
World Data Center

WDCC
World Data Center for Climate

WDCGG
World Data Centre for Greenhouse Gases

WDC-MARE
World Data Center for Marine Environmental Sciences

WDC-RSAT
World Data Center for Remote Sensing of the Atmosphere

WDS
World Data System

WFD
Water Framework Directive

WG125
Working Group 125 on Global Comparisons of Zooplankton Time Series

WGMS
World Glacier Monitoring Service

WGPME
Working Group on Phytoplankton and Microbial Ecology

WGZE
Working Group on Zooplankton Ecology

WHG
Wasserhaushaltsgesetz
(Federal Water Act)

WHYMAP
World-wide Hydrogeological Mapping and Assessment Programme

WIGOS
WMO Integrated Global Observing System

WIS
WMO Information System

WISE
Water Information System for Europe

WMO
World Meteorological Organization

WMO RA VI
WMO Regional Association VI (Europe and Middle East)

WOCE
World Ocean Circulation Experiment

WRDC
World Radiation Data Centre

WRMC
World Radiation Monitoring Center

WSA
Wasser- und Schifffahrtsamt
(German Waterways and Shipping Office)

WSV
Wasser- und Schifffahrtsverwaltung des Bundes
(German Federal Waterways and Shipping Administration)

WW
Wasserwert
(water equivalent)

WWLLN
World Wide Lightning Location Network

Z

ZALF
Leibniz-Zentrum für Agrarlandschafts-forschung (ZALF) e. V.
(Leibniz Centre for Agricultural Landscape Research)

ZAMF
Zentrum für Agrarmeteorologische Forschung Braunschweig
(Braunschweig Agrometeorological Research Centre)

ZAMG
Zentralanstalt für Meteorologie und Geodynamik
(Austrian Central Institute for Meteorology and Geodynamics)

ZMMF
Zentrum für Medizin-Meteorologische Forschung
(Research Centre Human-Biometeorology)

8 Lists and references

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Klein, Holger (retired)	Federal Maritime and Hydrographic Agency (BSH)	3.10
Kleta, Henry	Deutscher Wetterdienst (DWD)	3.8, 3.9
Kock, Annette	GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR)	3.14
Kohlhas, Eckhard	Ministry for Climate Protection, Agriculture, Rural Areas and the Environment of the State of Mecklenburg-Vorpommern	4.3, 4.4

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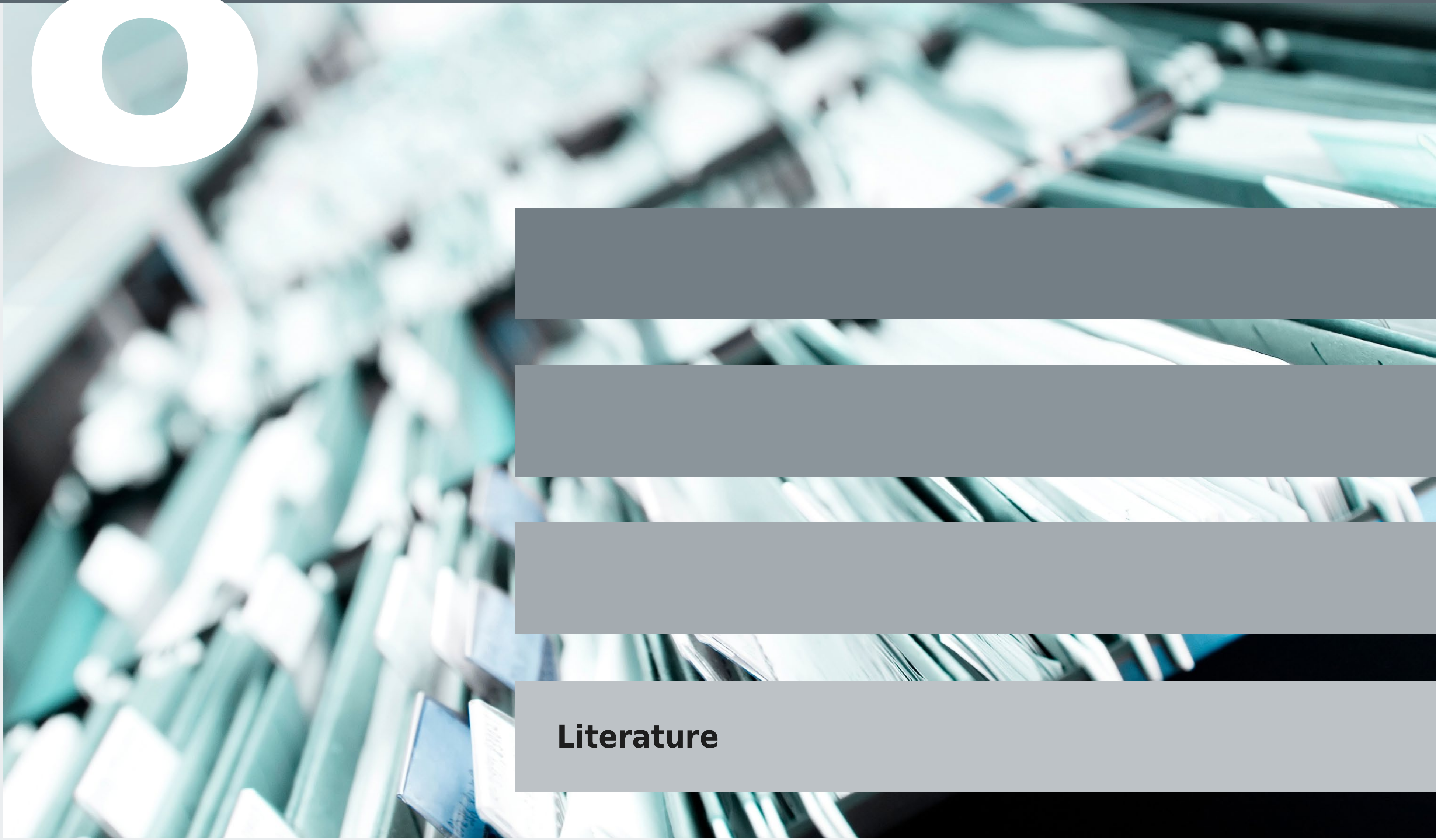
Körtzinger, Arne	GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR)	3.13
Kothe, Steffen	Deutscher Wetterdienst (DWD)	5.8
Kraberg, Alexandra	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI)	3.17
Lammert, Andrea	German Climate Computing Centre (DKRZ)	5.4
Lanconelli, Christian	Unisystems SA c/o, EC Joint Research Centre	5.3
Latarius, Katrin	Federal Maritime and Hydrographic Agency (BSH)	3.7
Looser, Ulrich	Federal Institute of Hydrology (BfG)/ Global Runoff Data Centre (GRDC)	5.2
Mayer, Christoph	Geodesy and Glaciology group (KEG) of the Bavarian Academy of Sciences and Humanities (BAdW)	4.6, 6.2
Möller, Jens	Federal Maritime and Hydrographic Agency (BSH)	3.4
Müller, Richard	Deutscher Wetterdienst (DWD)	4.7
Naumann, Michael	Leibniz Institute for Baltic Sea Research Warnemünde (IOW)	3.12
Pfeifroth, Uwe	Deutscher Wetterdienst (DWD)	4.7
Reißmann, Jan Hinrich	Federal Maritime and Hydrographic Agency (BSH)	3.1
Rhein, Monika	University of Bremen, Institute of Environmental Physics (IUP)	3.15
Riedel, Thomas	Thünen Institute of Forest Ecosystems	4.9
Riihimaki, Laura	NOAA Global Monitoring Laboratory G-RAD	5.3
Rosenke, Friedhelm †	Lower Saxony Ministry of the Interior and Sports	4.10
Rüdiger, Julian	Federal Environment Agency (UBA)	2.10, 2.11, 2.12, 2.15
Schlundt, Michael	GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR)	3.8
Schmithüsen, Holger	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI)	6.1
Schneider, Udo	Deutscher Wetterdienst (DWD)	5.1

Name	Institution/Company	Item
Schrader, Dieter (retired)	Federal Maritime and Hydrographic Agency (BSH)	3.5
Schrobitz, Karsten	Deutscher Wetterdienst (DWD)	2.7
Schröder, Marc	Deutscher Wetterdienst (DWD)	5.8
Schulte, Sven	Federal Environment Agency (UBA)	2.14
Schulz, Oliver	Federal Statistical Office (Destatis)	4.2
Senet, Christian	Federal Maritime and Hydrographic Agency (BSH)	3.5
Stammer, Detlef	Hamburg University, Institute of Oceanography (IfM)	3.4
Steinbrecht, Wolfgang	Deutscher Wetterdienst (DWD)	2.14
Steinfeldt, Reiner	University of Bremen, Institute of Environmental Physics (IUP)	3.15
Supper-Nilges, Daniela	Federal Institute of Hydrology (BfG)	4.1
Tanhua, Toste	GEOMAR Helmholtz Centre for Ocean Research Kiel (GEOMAR)	3.11
Thern, Stephan	Siemens AG	2.9
Tinz, Birger	Deutscher Wetterdienst (DWD)	2.2
Toussaint, Frank (retired)	German Climate Computing Centre (DKRZ)	5.4
Uhlmann, Astrid	Federal Office for Agriculture and Food (BLE)	4.10
Wacker, Stefan	Deutscher Wetterdienst (DWD)	2.5
Walawender, Ewelina	Deutscher Wetterdienst (DWD)	2.4
Wegehenkel, Martin (retired)	Leibniz Centre for Agricultural Landscape Research (ZALF)	4.11
Weigl, Elmar	Deutscher Wetterdienst (DWD)	2.4
Wellbrock, Nicole	Thünen Institute of Forest Ecosystems	4.8
Wilms, Mayumi	Federal Maritime and Hydrographic Agency (BSH)	3.5
Wittich, Klaus-Peter (retired)	Deutscher Wetterdienst (DWD)	4.10
Zimmermann, Kirsten	Deutscher Wetterdienst (DWD)	4.12

8 Lists and references



Literature

Augustin, J., Sauerborn, R., Burkart, K., Endlicher, W., Jochner, S., Koppe, C., Menzel, A., Mücke, H.-G., Herrmann, A., 2017: Gesundheit. In: Brasseur, G., Jacob, D., Schuck-Zöller, S. (Eds.), Klimawandel in Deutschland. *Springer Spektrum*, Berlin, Heidelberg, Germany, 137–149, DOI: 10.1007/978-3-662-50397-3_14.

Augustine, J.A., Hodges, G.B., 2021: Variability of surface radiation budget components over the U.S. from 1996 to 2019 – Has Brightening Ceased? *Journal of Geophysical Research: Atmospheres* **126**, 7, e2020JD033590, DOI: 10.1029/2020JD033590.

Babaeian, E., Sadeghi, M., Jones, S.B., Montzka, C., Vereecken, H., Tuller, M., 2019: Ground, proximal, and satellite remote sensing of soil moisture. *Reviews of Geophysics* **57**, 2, 530–616, DOI: 10.1029/2018RG000618.

Bakker, D.C.E., Pfeil, B., Landa, C.S. et al., 2016: A multi-decade record of high quality fCO_2 data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT). *Earth System Science Data* **8**, 2, 383–413, DOI: 10.5194/essd-8-383-2016.

Benninga, H.-J.F., van der Velde, R., Su, Z., 2020: Sentinel-1 soil moisture content and its uncertainty over sparsely vegetated fields. *Journal of Hydrology X* **9**, 100066, DOI: 10.1016/j.hydroa.2020.100066.

Betz, H.D., Schmidt, K., Laroche, P., Blanchet, P., Oettinger, W.P., Defer, E., Dziewit, Z., Konarski, J., 2009: LINET—An international lightning detection network in Europe. *Atmospheric research* **91**, 2–4, 564–573, DOI: 10.1016/j.atmosres.2008.06.012.

Beyrich, F., Lepsi, J.P., Mauder, M., Bange, J., Foken, Th., Huneke, S., Lohse, H., Lüdi, A. Meijninger, W. M. L., Mironov, D., Weissensee, U., Zittel, P., 2006: Area-averaged surface fluxes over the LITFASS-region based on Eddy-Covariance Measurements. *Boundary-Layer Meteorology* **121**, 1, 33–65, DOI: 10.1007/s10546-006-9052-x.

Bogena, H.R., Huisman, J.A., Schilling, B., Weuthen, A., Vereecken, H., 2017: Effective calibration of low-cost soil water content sensors. *Sensors* **17**, 1, 208, DOI: 10.3390/s17010208.

Bogena, H.R., Schrön, M., Jakobi, J. et al., 2022: COSMOS-Europe: a European network of cosmic-ray neutron soil moisture sensors, *Earth System Science Data* **14**, 3, 1125–1151, DOI: 10.5194/essd-14-1125-2022.

Bundesanstalt für Gewässerkunde, 2021: Geoportal der BfG. Accessed on 18 October 2021, https://geoportal.bafg.de/ggina-portal.

Bundesregierung, 2002: Third Report by the Government of the Federal Republic of Germany in accordance with the Framework Convention of the United Nations. Accessed on 28 April 2023, https://unfccc.int/sites/default/files/resource/gernc3%20Germany.pdf.

Bundesregierung, 2023: Eighth National Communication and fifth Biennial Report of the Federal Republic of Germany under the United Nations Framework Convention on Climate Change. Accessed on 28 April 2023, https://unfccc.int/sites/default/files/resource/8th%20National%20Communication_5th%20BR%20Germany.pdf.

Bundesverfassungsgericht, 2021: Constitutional complaints against the Federal Climate Change Act partially successful. Press Release No. 31/2021 of 29 April 2021. Order of 24 March 2021 - 1 BvR 2656/18, 1 BvR 288/20, 1 BvR 96/20, 1 BvR 78/20. Accessed on 28 April 2023, https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/EN/2021/bvg21-031.html.

Copernicus, 2019: European State of the Climate 2019. Greenhouse gas fluxes. Accessed on 28 April 2023, https://climate.copernicus.eu/ESOTC/2019/greenhouse-gas-fluxes.

Cunze S., Leiblein, M.C., Tackenberg, O., 2013: Range Expansion of Ambrosia artemisiifolia in Europe Is Promoted by Climate Change. *International Scholarly Research Notices Ecology* **2013**, 610126, DOI: 10.1155/2013/610126.

Deutscher Wetterdienst, 2021: Klimareport Hamburg. Deutscher Wetterdienst, Offenbach am Main, Germany, 56 pp.

Dieterich, C., Wang, S., Schimanke, S., Gröger, M., Klein, B., Hordoir, R., Samuelsson, P., Liu, Y., Axell, L., Höglund, A., Meier, H.E.M., 2019: Surface Heat Budget over the North Sea in Climate Change Simulations. *Atmosphere* **10**, 5, 272, DOI: 10.3390/atmos10050272.

EPA United States Environmental Protection Agency, 2021: Climate Change Indicators: Ocean Heat. Accessed on 28 April 2023, https://www.epa.gov/climate-indicators.

Feistel, S., Feistel, R., Nehring, D., Matthäus, W., Nausch G., Naumann, M., 2016: Hypoxic and anoxic regions in the Baltic Sea, 1969 - 2015. Meereswissenschaftliche Berichte 100. Leibniz-Institut für Ostseeforschung Warnemünde, Warnemünde, Germany, 85 pp, DOI: 10.12754/msr-2016-0100.

Friedlingstein, P., Jones, M.W., O'Sullivan, M. et al., 2021: Global Carbon Budget 2021, DOI: 10.5194/essd-2021-386.

Govaerts, Y.M., Lattanzio, A., Taberner, M., Pinty, B., 2008: Generating global surface albedo products from multiple geostationary satellites. *Remote Sensing of Environment* **112**, 6, 2804–2816, DOI: 10.1016/j.rse.2008.01.012.

Grüneberg, E, Ziche, D., Wellbrock, N., 2014: Organic carbon stocks and sequestration rates of forests soils in Germany. *Global change Biology* **20**, 8, 2644–2662, DOI: 10.1111/gcb.12558.

Haigh, I.D., Nicholls, R.J., Wells, N.C., 2009: Mean sea-level trends around the English Channel over the 20th century and their wider context. *Continental Shelf Research* **29**, 2083–2098, DOI: 10.1016/j.csr.2009.07.013.

Hannak, L., Brinckmann, S., 2020: Parallelmessungen an deutschen Klimareferenzstationen: Schlussfolgerungen im Hinblick auf Homogenität und Messunsicherheiten. *Berichte des Deutschen Wetterdienstes* **253**. Deutscher Wetterdienst, Offenbach am Main, Germany, 101 pp.

Hannak, L., Friedrich, K., Imbery, F., Kaspar, F., 2019: Comparison of manual and automatic daily sunshine duration measurements at German climate reference stations. *Advances in Science and Research* **16**, 175–183, DOI: 10.5194/asr-16-175-2019.

IOCCG International Ocean-Colour Coordinating Group, 2022: Missions & Instruments. Accessed on 28 April 2023, https://ioccg.org/resources/missions-instruments.

IPCC, 1990: Climate Change. The IPCC Scientific Assessment. Houghton, J.T., Jenkins, G.J., Ephraums, J.J. (Eds.), Cambridge University Press, Cambridge, United Kingdom, 365 pp.

Jacobs, A., Flessa, H., Don, A. et al., 2018: Landwirtschaftlich genutzte Böden in Deutschland – Ergebnisse der Bodenzustandserhebung. *Thünen Report* **64**. Johann Heinrich von Thünen-Institut, Braunschweig, Germany, 316 pp, DOI: 10.3220/REP1542818391000.

Jakobi, J., Huisman, J.A., Vereecken, H., Diekkrüger, B., Bogena, H.R., 2018: Cosmic Ray Neutron Sensing for Simultaneous Soil Water Content and Biomass Quantification in Drought Conditions. *Water Resources Research* **54**, 10, 7383–7402, DOI: 10.1029/2018WR022692.

Jobbágy, E.G., Jackson, R.B., 2000: The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* **10**, 2, 423–436.

Johnson, G.C., Lumpkin, R. (Eds.), 2021: Global Oceans. In: State of the Climate in 2020. American Meteorological Society (Ed.), *Bulletin of the American Meteorological Society* **102**, 8, S143–S198, DOI: 10.1175/BAMS-D-21-0083.1.

Kaminski, U., Glod, T., 2011: Are there changes in Germany regarding the start of the pollen season, the season length and the pollen concentration of the most important allergenic pollens? *Meteorologische Zeitschrift* **20**, 5, 497–507, DOI: 10.1127/0941-2948/2011/0297.

Karl, T.R., Derr, V.E., Easterling, D.R., Folland, C.K., Hofmann, D.J., Levitus, S., Nicholls, N., Parker, D.E., Withee, G.W., 1995: Critical issues for long-term climate monitoring. *Climatic Change* **31**, 185–221, DOI: 10.1007/BF01095146.

Kaspar, F., Hannak, L., Schreiber, K.-J., 2016: Climate reference stations in Germany: Status, parallel measurements and homogeneity of temperature time series. *Advances in Science and Research* **13**, 163–171, DOI: 10.5194/asr-13-163-2016.

Kaspar, F., Müller-Westermeier, G., Penda, E., Mächel, H., Zimmermann, K., Kaiser-Weiss, A., Deutschländer, T., 2013: Monitoring of climate change in Germany – data, products and services of Germany's National Climate Data Centre. *Advances in Science and Research* **10**, 1, 99–106, DOI: 10.5194/asr-10-99-2013.

Kaspar, F., Niermann, D., Borsche, M., Fiedler, S., Keller, J., Potthast, R., Rösch, T., Spangehl, T., Tinz, B., 2020: Regional atmospheric reanalysis activities at Deutscher Wetterdienst: review of evaluation results and application examples with a focus on renewable energy. *Advances in Science and Research* **17**, 115–128, DOI: 10.5194/asr-17-115-2020.

Kaspar, F., Tinz, B., Mächel, H., Gates, L., 2015: Data rescue of national and international meteorological observations at Deutscher Wetterdienst. *Advances in Science and Research* **12**, 1, 57–61, DOI: 10.5194/asr-12-57-2015.

Kaspar, F., Zimmermann, K., Polte-Rudolf, C., 2014: An overview of the phenological observation network and the phenological database of Germany's national meteorological service (Deutscher Wetterdienst). *Advances in Science and Research* **11**, 1, 93–99, DOI: 10.5194/asr-11-93-2014.

Key, R.M., Olsen, A., van Heuven, S. et al., 2015: Global Ocean Data Analysis Project, Version 2 (GLODAPv2), ORNL/CDIAC-162, NDP-093. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee, United States, DOI: 10.3334/CDIAC/OTG.NDP093_GLODAPv2.

Kniebusch, M., Meier, H.E.M., Neumann, T., Börgel, F., 2019: Temperature variability of the Baltic Sea since 1850 and attribution to atmospheric forcing variables. *Journal of Geophysical Research: Oceans* **124**, 6, 4168–4187, DOI: 10.1029/2018JC013948.

Koyama C.N., Korres W., Fiener P., Schneider, K., 2010: Variability of Surface Soil Moisture Observed from Multitemporal C-band SAR and Field Data. *Vadose Zone Journal* **9**, 4, 1014–1024, DOI: 10.2136/vzj2009.0165.

Kuttler, W., 2011: Climate change in urban areas, Part 1, Effects. *Environmental Sciences Europe* **23**, 1, 11, DOI: 10.1186/2190-4715-23-11.

Lake, I.R., Jones, N.R., Agnew, M., Goodess, C.M., Giorgi, F., Hamaoui-Laguel, L., Semenov, M.A., Solomon, F., Storkey, J., Vautard, R., Epstein, M.M., 2017: Climate Change and Future Pollen Allergy in Europe. *Environmental Health Perspectives* **125**, 3, 385–391, DOI: 10.1289/EHP173.

Lauvset, S.K., Key, R.M., Olsen, A. et al., 2016: A new global interior ocean mapped climatology: the 1° × 1° GLODAP version 2. *Earth System Science Data* **8**, 2, 325–340, DOI: 10.5194/essd-8-325-2016.

Lauvset, S.K., Lange, N., Tanhua, T. et al., 2021: An updated version of the global interior ocean biogeochemical data product, GLODAPv2.2021. *Earth System Science Data* **13**, 12, 5565–5589, DOI: 10.5194/essd-13-5565-2021.

Lehmann, A., Getzlaff, K., Harlaß, J., 2011: Detailed assessment of climate variability of the Baltic Sea area for the period 1958–2009. *Climate Research* **46**, 2, 185–196, DOI: 10.3354/cr00876.

Lennartz, S.T., Lehmann, A., Herrford, J., Malien, F., Hansen, H.-P., Biester, H., Bange, H. W., 2014: Long-term trends at the Boknis Eck time series station (Baltic Sea), 1957–2013: does climate change counteract the decline in eutrophication? *Biogeosciences* **11**, 22, 6323–6339, DOI: 10.5194/bg-11-6323-2014.

Llovel, W., Purkey, S., Meyssignac, B., Blazquez, A., Kolodziejczyk, N., Bamber, J., 2019: Global ocean freshening, ocean mass increase and global mean sea level rise over 2005–2015. *Scientific Reports* **9**, 1, 17717, DOI: 10.1038/s41598-019-54239-2.

Löwe, P. (Ed.), 2009: System Nordsee – Zustand 2005 im Kontext langzeitlicher Entwicklungen. *Berichte des BSH* **44**, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg und Rostock, Germany, 270 pp.

Ma, X., Lennartz, S.T., Bange, H.W., 2019: A multi-year observation of nitrous oxide at the Boknis Eck Time Series Station in the Eckernförde Bay (southwestern Baltic Sea), *Biogeosciences* **16**, 20, 4097–4111, DOI: 10.5194/bg-16-4097-2019.

Mayer, C., Weber, M., Wendt, A., Hagg, W., 2021: Die bayerischen Gletscher, die verbliebenen Eisreserven Deutschlands, *Polarforschung* **89**, 1, 7, DOI: 10.5194/polf-89-1-2021.

Montzka, C., Bogena, H.R., Zreda, M., Monerris, A., Morrison, R., Muddu, S., Vereecken, H., 2017: Validation of Spaceborne and Modelled Surface Soil Moisture Products with Cosmic-Ray Neutron Probes. *Remote Sensing* **9**, 2, 103, DOI: 10.3390/rs9020103.

Mueller, R., Trentmann, J., Träger-Chatterjee, C., Posselt, R., Stöckli, R., 2011: The Role of the Effective Cloud Albedo for Climate Monitoring and Analysis. *Remote Sensing* **3**, 11, 2305–2320, DOI: 10.3390/rs3112305.

Nasta, P., Bogena, H.R., Sica, B., Weuthen, A., Vereecken H., Romano, N., 2020: Integrating Invasive and Non-invasive Monitoring Sensors to Detect Field-Scale Soil Hydrological Behavior. *Frontiers in Water* **2**, 26, DOI: 10.3389/frwa.2020.00026.

National Marine Fisheries Service, 2022: Species Presence Plots. A figure layout created for the ICES WGPME working group. Accessed on 28 April 2023, https://www.st.nmfs.noaa.gov/copepod/time-series/de-30201/html/zoom-speciesbox.html.

Nguyen, H.H., Jeong, J., Choi, M., 2019: Extension of cosmic-ray neutron probe measurement depth for improving field scale root-zone soil moisture estimation by coupling with representative in-situ sensors. *Journal of Hydrology* **571**, 679–696, DOI: 10.1016/j.jhydrol.2019.02.018.

OceanOps, 2021: Integrated information, maps and tools to help coordinate and monitor global ocean observation efforts. Accessed on 28 April 2023, https://www.ocean-ops.org/board.

Pessi, A.T., Businger, S., Cummins, K.L., Demetriades, N.W.S., Murphy, M., Pifer, B., 2009: Development of a Long-Range Lightning Detection Network for the Pacific: Construction, Calibration, and Performance, *Journal of Atmospheric and Oceanic Technology* **26**, 2, 145–166, DOI: 10.1175/2008JTECHA1132.1.

Pohjola, H., Mäkelä, A., 2013: The comparison of GLD360 and EUCLID lightning location systems in Europe, *Atmospheric Research* **123**, 117–128, DOI: 10.1016/j.atmosres.2012.10.019.

Quante, M., Colijn, F. (Eds.), 2016: North Sea Region Climate Change Assessment. Regional Climate Studies, *Springer International Publishing*, Basel, Switzerland, DOI: 10.1007/978-3-319-39745-0.

Said, R.K., Cohen, M.B., Inan, U.S., 2013: Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations, *Journal of Geophysical Research: Atmospheres* **118**, 13, 6905– 6915, DOI: 10.1002/jgrd.50508.

Said, R., Murphy, M., 2016: GLD360 Upgrade: Performance Analysis and Applications. 24th International Lightning Detection Conference and 6th International Lightning Meteorology Conference, 18–21 April 2016, San Diego, California, United States. Accessed on 28 April 2023, https://www.vaisala.com/sites/default/files/documents/Ryan%20Said%20and%20Martin%20Murphy.%20GLD360%20Upgrade%20Performance%20Analysis%20and%20Applications.pdf.

Schiermeier, Q., 2020: Global methane levels soar to record high. *Springer Nature*, DOI: 10.1038/d41586-020-02116-8.

Seiz, G., Foppa, N., 2007: Nationales Klima-Beobachtungssystem (GCOS Schweiz). MeteoSwiss, Zurich and ProClim, Bern, Switzerland, 92 pp.

Siegel, H., Gerth, M., 2019: Sea Surface Temperature in the Baltic Sea in 2018. HELCOM Baltic Sea Environment Fact Sheets 2019. Accessed on 28 April 2023, https://helcom.fi/wp-content/uploads/2020/07/BSEFS-Sea-Surface-Temperature-in-the-Baltic-Sea-2018.pdf.

Smith, S.R., Alory, G., Andersson, A. et al., 2019: Ship-Based Contributions to Global Ocean, Weather, and Climate Observing Systems. *Frontiers in Marine Science* **6**, DOI: 10.3389/fmars.2019.00434.

Stramma, L., Schmidtko, S., Bograd, S.J., Ono, T., Ross, T., Sasano, D., Whitney, F.A., 2020: Trends and decadal oscillations of oxygen and nutrients at 50 to 300 m depth in the equatorial and North Pacific, *Biogeosciences* **17**, 3, 813–831, DOI: 10.5194/bg-17-813-2020.

Sun, J., Birmili, W., Hermann, M. et al., 2020: Decreasing trends of particle number and black carbon mass concentrations at 16 observational sites in Germany from 2009 to 2018, *Atmospheric Chemistry and Physics* **20**, 11, 7049–7068, DOI: 10.5194/acp-20-7049-2020.

Sun, J., Hermann, M., Yuan, Y. et al., 2021: Long-term trends of black carbon and particle number concentration in the lower free troposphere in Central Europe, *Environmental Sciences Europe* **33**, 1, 47, DOI: 10.1186/s12302-021-00488-w.

Templ, B., Koch, E., Bolmgren, K. et al., 2018: Pan European Phenological database (PEP725): a single point of access for European data. *International Journal of Biometeorology*, **62**, 6, 1109–1113, DOI: 10.1007/s00484-018-1512-8.

Umweltbundesamt, 2019: Monitoringbericht 2019 zur Deutschen Anpassungsstrategie an den Klimawandel. Bericht der Interministeriellen Arbeitsgruppe Anpassungsstrategie der Bundesregierung. Umweltbundesamt, Dessau-Rosslau, Germany, 276 pp.

UNECE ICP Forests Programme Co-ordinating Centre (Ed.), 2016: Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Thünen Institute of Forest Ecosystems, Eberswalde. Accessed on 28 April 2023, http://www.icp-forests.net/page/icp-forests-manual.

UNFCCC, 2000: Report of the Conference of the Parties on its fifth session, held at Bonn from 25 October to 5 November 1999. Addendum. Part two: Action taken by the Conference of the Parties at its fifth session. FCCC/CP/1999/6/Add.1. Decision 5/CP.5. Accessed on 28 April 2023, https://unfccc.int/sites/default/files/resource/docs/cop5/06a01.pdf.

UNFCCC, 2022a: Draft decision -/CP.27 Implementation of the Global Climate Observing System. Accessed on 28 April 2023, https://unfccc.int/sites/default/files/resource/cop27_auv_RSO.pdf.

UNFCCC, 2022b: Subsidiary Body for Scientific and Technological Advice. Fifty-seventh session. Sharm el-Sheikh, 6–12 November 2022. Agenda item 10(a). Matters related to science and review. Research and systematic observation. Draft conclusions proposed by the Chair. Accessed on 28 April 2023, https://unfccc.int/sites/default/files/resource/sbsta2022_L20E.pdf.

Vaisala, 2022: Global Lightning Detection Network GLD360. Accessed on 28 April 2023, https://www.vaisala.com/en/products/systems/lightning/gld360.

Vereecken, H., Huisman, J.A., Hendricks-Franssen, H.-J., Brüggemann, N., Bogena, H.R., Kollet, S., Javaux, M., van der Kruk, J., Vanderborght, J., 2015: Soil hydrology: recent methodological advances, challenges, and perspectives. *Water Resources Research* **51**, 4, 2616–2633. DOI: 10.1002/2014WR016852.

Wahl, T., Jensen, J., Frank, T., Haigh, I., 2011: Improved estimates of mean sea level changes in the German Bight over the last 166 years. *Ocean Dynamics* **61**, 5, 701–715, DOI: 10.1007/s10236-011-0383-x.

Wapler, K., 2013: High-resolution climatology of lightning characteristics within Central Europe. *Meteorology and Atmospheric Physics* **122**, 3, 175–184, DOI: 10.1007/s00703-013-0285-1.

Wegehenkel, M., Luzi, K., Sowa, D., Barkusky, D., Mirschel, W., 2019: Simulation of Long-Term Soil Hydrological Conditions at Three Agricultural Experimental Field Plots Compared with Measurements. *Water* **11**, 5, 989, DOI: 10.3390/w11050989.

Wellbrock, N., Bolte, A., Flessa, H. (Eds.), 2016: Dynamik und räumliche Muster forstlicher Standorte in Deutschland: Ergebnisse der Bodenzustandserhebung im Wald 2006 bis 2008. *Thünen Report* **43**. Johann Heinrich von Thünen-Institut, Braunschweig, Germany, 558 pp, DOI: 10.3220/REP1473930232000.

WMO, 1990: Second World Climate Conference. International Conference Centre, Geneva, Switzerland, 29 October–7 November 1990: Abstracts of Scientific/technical Papers. World Meteorological Organization, Geneva, Switzerland, 87 pp.

WMO, 2003a: Fourteenth World Meteorological Congress. Geneva, 5-14 May 2003. Abridged Final Report with Resolutions. WMO-No. 960. World Meteorological Organization, Geneva, Switzerland, 233 pp.

WMO, 2003b: The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC. April 2003. GCOS-82 (WMO/TD No. 1143). World Meteorological Organization, Geneva, Switzerland, 85 pp.

WMO, 2010: Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update). August 2010. GCOS-138 (GOOS-184, GTOS-76, WMO-TD/No. 1523). World Meteorological Organization, Geneva, Switzerland, 186 pp.

WMO, 2015: Seventeenth World Meteorological Congress, Geneva, 25 May–12 June 2015. Abridged Final Report with Resolutions. WMO-No. 1157. World Meteorological Organization, Geneva, Switzerland, 708 pp.

WMO, 2016: The Global Observing System for Climate: Implementation Needs. GCOS-200 (GOOS-214). Accessed on 28 April 2023, https://library.wmo.int/doc_num.php?explnum_id=3417.

WMO, 2022: The 2022 GCOS Implementation Plan GCOS-244 GOOS-272. Accessed on 28 April 2023, https://library.wmo.int/doc_num.php?explnum_id=11317.