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National Climate Observing System

Global Climate Observing System – GCOS Switzerland

Foreword

Climate is changing – the latest published Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) confirmed the clear and growing human influence on the climate system, with impacts observed across all continents and oceans. High-quality, long-term climate data from all around the globe have been instrumental for these analyses. It is owing to such data that, today, we are able to assess past climate variability and quantify the many changes that have taken place in the past 150 years. This allows us to appreciate the impacts of projected future changes and to better prepare our societies for the imminent challenges.

Switzerland, as a mountain region, is particularly affected by climate change. The recent report "Brennpunkt Klima Schweiz" concludes that the Alpine region has been warming at an alarming rate of around twice the global average since the middle of the 19th century. But rising temperatures are only one of many indicators of climate change. In Switzerland, the systematic observation of more than thirty essential climate variables provides the quantitative basis for robust knowledge about changes in our environment. These data are required for informed decisions that are central to adaptation to, and mitigation of, climate change and its impact in Switzerland.

Switzerland has a great tradition in climate observation and maintains some of the world's longest observation series. Thus, Switzerland has a responsibility towards the international community and must secure the sustainable existence of its National Climate Observing System (GCOS Switzerland). Its aim is to ensure that high-quality data on our climate system will continue to be available also in the future. This report constitutes the logical follow-up to the 2007 report "National Climate Observing System – GCOS Switzerland". An enhanced set of data series meeting diversified user requirements in science and administration alike will be an indispensable tool for informed decisions that regard our environment and our home – locally and globally.

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Chair of the GCOS Switzerland Steering Committee

Imprint

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Citation
MeteoSwiss 2018.
National Climate Observing System (GCOS Switzerland).
Update 2018.

Design
BBGmarconex AG, Thalwil

Proofreading
Brigitta Klingler

With the kind support by
ProClim

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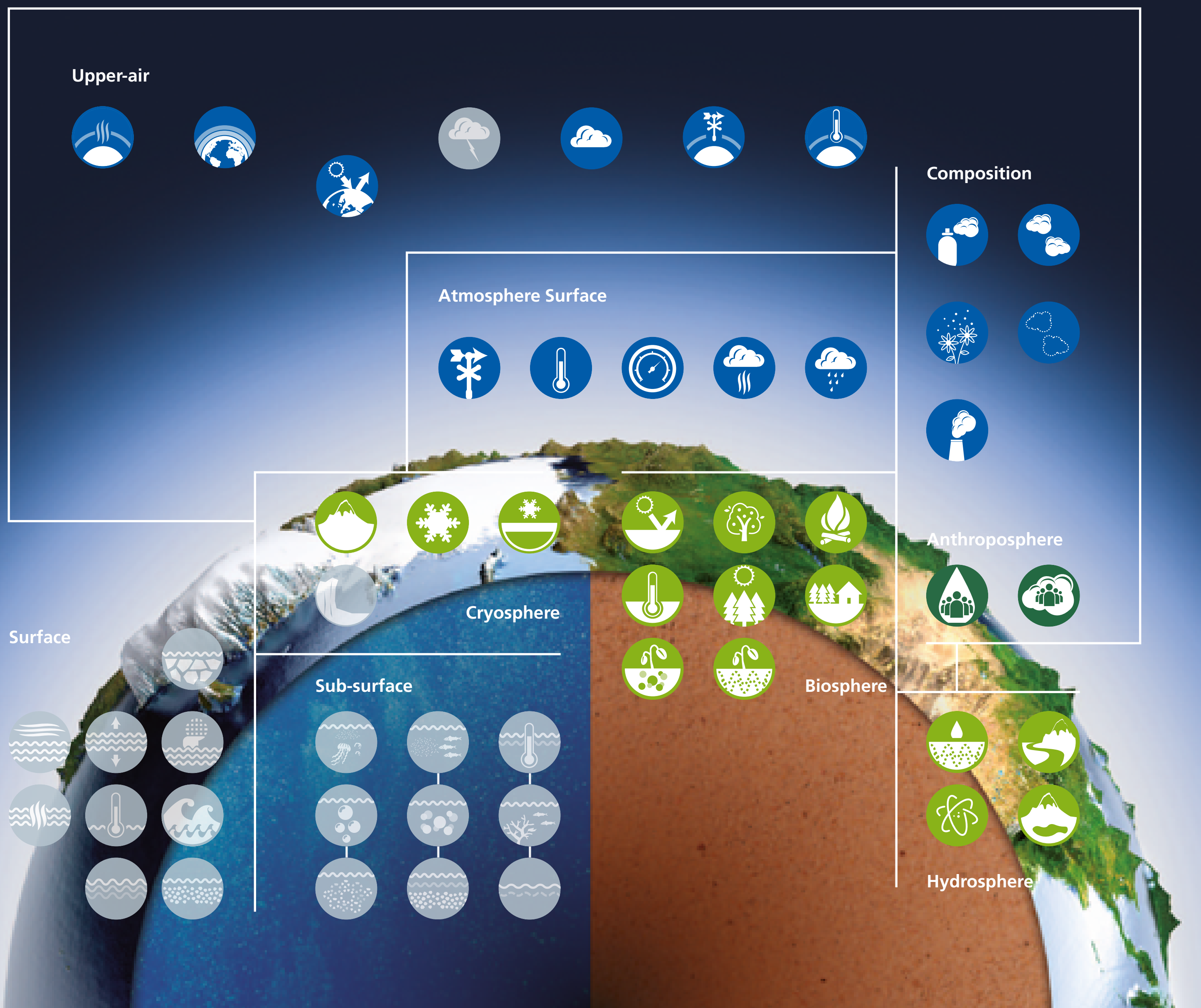
1.0 Introduction



Background

Global climate change is continuing: the year 2016 was the hottest on record with a global mean temperature of approximately 1.1 °C warmer compared to the pre-industrial period (WMO 2017). In 2014/15, glaciers for which observations exist lost more than 1100 liters of water reserve per square meter of ice cover. This is two to three times the ice loss rate of the 1990s (WGMS 2017). Furthermore, carbon dioxide concentration in the atmosphere has crossed the symbolic threshold of 400 parts per million (WMO 2017). Many of the observed changes in the climate system are unprecedented in their magnitude and rate over the last decades or in some cases even up to the last millennia. According to the latest assessment report by the Intergovernmental Panel on Climate Change (IPCC), a human influence on the climate system is clear (IPCC 2014).

Climate change has widespread, global effects on human and natural systems, and meeting related challenges requires joint action by all countries worldwide. Therefore, in 1992, the global community adopted the United Nations Framework Convention on Climate Change (UNFCCC), with the aim of stabilising greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system" (United Nations 1992). On this basis, the Kyoto Protocol (UNFCCC 1997) and the Paris Agreement (UNFCCC 2015) further specified the common goals with regard to mitigation (reducing GHG emission) and, in the case of the Paris Agreement, also with regard to adaptation (limiting the adverse effects of climate change).

Any action on climate change relies on a sound description of climate variability and change. For that purpose, high quality systematic observation of the Earth's climate is fundamental. Accordingly, the UNFCCC explicitly requests its Parties to promote and cooperate in systematic observation of the climate system. Article 7 of the Paris Agreement reaffirmed the importance of "strengthening scientific knowledge on climate, including research, systematic observation of the climate system and early warning systems, in a manner that informs climate services and supports decision-making" (UNFCCC 2015).

The Global Climate Observing System GCOS

In 1992, the Global Climate Observing System (GCOS) was established to coordinate systematic climate observation globally. Its objective is to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. GCOS is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the UN Environment Programme (UN Environment) and the International Council for Science (ICSU). Building on existing networks and systems, GCOS encompasses the entire climate system including observations of the atmosphere, the ocean and the land surface. GCOS is coordinated by the GCOS Secretariat located at the World Meteorological Organization (WMO) in Geneva, Switzerland.

The GCOS programme is requested by the UNFCCC to elaborate and regularly revise an implementation plan, specifying requirements and recommendations for a global climate observing system. One important element of the GCOS IP is the definition of a set of atmospheric, oceanic, and terrestrial Essential Climate Variables (ECVs) that critically contribute to characterising Earth's climate (see Box 1). Monitoring of these ECVs should adhere to the GCOS Climate Monitoring Principles (see Box 2). The latest update of the IP, published in 2016, not only details the explicit requirements as regards the observations of these ECVs but also emphasises their relevance for climate change adaptation and mitigation, and the characterisation of the three Earth system cycles of water, carbon and energy (WMO 2016). For the first time, the IP also highlights the importance of ancillary data sets such as Digital Elevation Models (DEMs).

Climate Observations in Switzerland

In Switzerland, climate change is evident: annual mean temperature in 2016 was 2 °C warmer when compared to the beginning of the measurements (1863; MeteoSwiss 2017a) and Swiss glaciers lost more than 10 % of their volume only between 2011 and 2016 (Glaciological Reports 2013–2017). Climate change is expected to be particularly pronounced in mountain areas such as the European Alps, with wide-spread effects on natural and human systems (Kohler and Maselli 2009). An overview of observed and future climatic changes in Switzerland, expected impacts, and necessary actions for climate change adaptation and mitigation is provided in the report 'Brennpunkt Klima Schweiz' published by the Swiss Academies of Arts and Sciences (2016).

Long term data series of ECVs collected in Switzerland contributed significantly to the findings of this report. Indeed, Switzerland has a very long tradition in climate observation: temperature and precipitation series of more than 150 years, the world's longest total ozone series, glacier measurements dating back to the end of the 19th century and the recent 30-year anniversary of the World Glacier Monitoring Service (WGMS) are some of the highlights of the Swiss contribution to GCOS. The coordination of systematic climate observation in Switzerland is under the responsibility of the Swiss GCOS Office at MeteoSwiss. The office was formally established as the national focal point for GCOS at MeteoSwiss in 2006.

Motivation

A key task of the Swiss GCOS Office is to maintain a national inventory of the most valuable climatological time series and international centers in Switzerland. Such an inventory was first published in 2007 (Seiz and Foppa 2007). For each ECV and international center, the inventory report identified possible gaps regarding the legal basis, definition of responsibilities, and availability of financial resources for the continuation of observations and operation, respectively. Considering the findings of this report, the Federal Council in 2008 approved a financial contribution to secure the continuation of time series and international centers at risk of discontinuation, as a long-term contribution to GCOS.

In line with the publication of the latest GCOS IP in 2016, MeteoSwiss initiated the elaboration of a new GCOS Switzerland Strategy for the period 2017 – 2026. Through the strategy, MeteoSwiss seeks to ensure that the activities of GCOS Switzerland meet the national and international requirements for an effective climate monitoring system, today and in the future (MeteoSwiss 2017b). The strategy was elaborated by the Swiss GCOS Office in close collaboration with its national partner institutions and under the guidance of the GCOS Switzerland Steering Committee (StC). A key element of the strategy is to maintain an up-to-date inventory of the most important climatological time series and international centers in Switzerland. This report represents an update of the inventory report as it was first published in 2007.

ECVs (Box 1)

Essential Climate Variables for which global observation is currently feasible and that satisfy the requirements of the UNFCCC and broader user communities according to the GCOS IP 2016. **New ECVs compared to previous IPs are in *Italics*, additional variables considered essential for Switzerland in bold.**

Measurement Domain		**Essential Climate Variables**
Atmospheric	Surface	Air temperature, Wind speed and direction, Water vapor (humidity), Pressure, Precipitation, Surface radiation budget,
	Upper-air	Temperature, Wind speed and direction, Water vapor, Cloud properties, Earth radiation budget, *Lightning*
	Composition	Carbon dioxide, Methane, Other long-lived greenhouse gases, Ozone, Aerosol, Precursors for aerosol and ozone, **Pollen**
Oceanic	Physics	Temperature: Sea-surface and Subsurface, Salinity: Sea-surface and Subsurface, 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,* Ocean colour
	Biology/ecosystems	Plankton, *Marine habitat properties*
Terrestrial	Hydrology	Rivers (discharge, **temperature**), Groundwater, Lakes, Soil moisture, **Isotopes**
	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*

Procedure

Taking into consideration the latest update of the GCOS IP, in particular the updated list of ECVs, the national inventory compiled in 2007 was reviewed and complemented in a joint effort by the Swiss GCOS Office and more than 90 authors from over 20 partner institutions. The StC provided guidance throughout the process.

The criteria defining the scope of the inventory were set as follows, whereas at least one criterion of **A)** and one criterion of **B)** needed to be met:

A) A variable is considered if:

1. it corresponds to an ECV as defined by the GCOS programme, i. e. in the GCOS IP; **or**
2. it contributes significantly to meeting UNFCCC's or other multilateral agreeement's requirements; **or**
3. it is of special importance to Switzerland and the measurements are technically and cost-effectively feasible;

B) For each variable, a measurement series is considered if:

1. it is of appropriate length. This includes either
   a. the coverage of a time period of more than 50 years; **or**
   b the measurement series is longer than comparable series abroad; **or**
2. it has been recently initiated, e. g. based on new observation methods.

As a result, the inventory today includes 33 ECVs of the atmospheric and terrestrial domain and two ancillary datasets. As a land-locked country, Switzerland does not maintain oceanic observations. The list also includes climate variables that are not defined as ECVs in the IP but are considered essential from a Swiss perspective (pollen, river temperature, isotopes, phenology). On the other hand, the ECV 'lightning' was not included in this update, given that it was considered to be a European dataset rather than a Swiss dataset. With regard to international centers, six data and calibration centers hosted by Swiss institutions were identified, representing an essential part of Switzerland's contribution to GCOS.

This report reflects the state of the national climate observing system in 2018. It will be updated regularly, including regular reviews of the list of variables and time series according to the criteria above.

GCOS Climate Monitoring Principles (Box 2)

Effective monitoring systems for climate should adhere to the following principles:

- a The impact of new systems or changes to existing systems should be assessed prior to implementation;
- b A suitable period of overlap for new and old observing systems is required;
- c 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;
- d The quality and homogeneity of data should be regularly assessed as a part of routine operations;
- e Consideration of the needs for environmental and climate-monitoring products and assessments, such as Intergovernmental Panel on Climate Change assessments, should be integrated into national, regional and global observing priorities;
- f Operation of historically-uninterrupted stations and observing systems should be maintained;
- g 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;
- h 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;
- i The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted;
- j Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

An additional set of principles was defined providing guidance to satellite operators with respect to, e. g., planning of satellite systems, sensor calibration, and design of data systems to facilitate user access (WMO 2016).

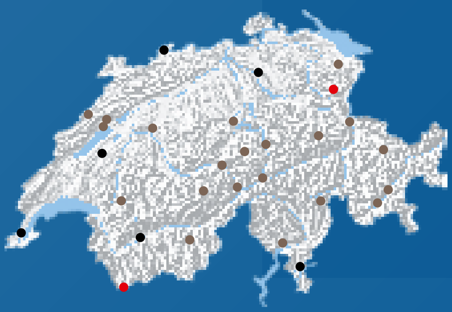
(Revised Reporting Guidelines as agreed by the UNFCCC at Bali, December 2007, decision 11/CP.13)

2.1 Air temperature

Temperature is a key indicator of changes in the climate. As long time series of measurements of ground-level temperature in Switzerland are available, dating back to the mid-19th century, long-term trends can be analysed. These analyses provide a sound basis for investigating long-term climate variations and change, and its relation to anthropogenic global warming.

Measurements in Switzerland

Air temperature at ground level is now measured by the Federal Office of Meteorology and Climatology MeteoSwiss at almost 150 stations. In some cases, these systematic measurements extend as far back as December 1863, when Switzerland's first nationwide meteorological observation network came into operation. Some measurements are also available from earlier periods, e. g. for Basel (from 1755), Geneva (1768) or Grand St. Bernard (1817). Since 1980, about 70 stations have been automated (ANETZ). All of these stations together with the conventional climate stations and the complementary automated meteorological monitoring network (ENET) stations have been integrated into the unified automatic SwissMetNet network since 2015 (about 160 sites in total). In addition to the MeteoSwiss stations, air temperature is also measured at numerous other weather stations by cantonal and communal authorities and private operators. As well as meeting climatological needs, the MeteoSwiss stations provide services for other user groups, e. g. warnings and aviation weather. The network of stations is continually reviewed on the basis of analyses of requirements. At each SwissMetNet station values are recorded every 10 minutes and transmitted to the central database in Zurich. Quality-control procedures are run automatically on 10-minute values and are performed manually in addition. Measurements of surface air temperature are used to calculate hourly, daily, monthly and annual means, together with medians, absolute extremes and numerous other parameters, such as frost days or heat days. In addition, they are also a primary input for spatially comprehensive temperature analyses over Switzerland (Frei 2014). In these datasets climate variables are represented on a regular grid with a spacing of 1 km. Such grid datasets integrate observational data with knowledge of their representativeness and physical understanding of involved processes using statistical procedures. They are a key resource for environmental modelling, the management and planning of natural resources, the protection against natural hazards and climate monitoring.

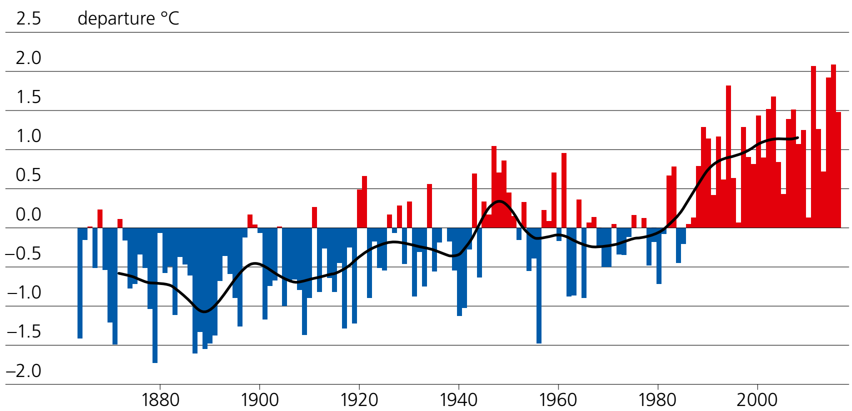


Stations of the Swiss NBCN (black, red and brown) with temperature measurements at least since 1900 in most cases. Two stations belong to the GSN (red) and eight to the RBCN (red and black).

Long time series and their importance

At many of the sites chosen in 1863 stations are still in operation today. The stations of the greatest climatological importance were designated as the Swiss National Basic Climatological Network (Swiss NBCN). These stations cover the different climate regions of Switzerland, and long-term temperature series from at least 1900 are available in most cases. All the data series were digitised, analysed for artificial discontinuities and trends caused, for example, by station relocation or change of instrumentation, and homogenised. The homogeneous long-term temperature series of the Swiss NBCN are a key ingredient of the operational monitoring of the Swiss climate. For this purpose, the station series are assembled into one national and several regional series. The series are used for regular public information on the evolution of the climate in Switzerland.

Temperature in Switzerland 1864–2016



The deviation of the annual mean temperature in Switzerland from the multiyear average (norm 1961–1990) offers a striking example of climate change. The linear trend between 1864 and 2016 is +1.29 °C per 100 years, yielding a total warming of +1.97 °C from 1864 to 2016. From a global perspective, temperature is the variable best suited to demonstrating the anthropogenic influence on the climate system. Long-term temperature series are therefore crucial for the observation, analysis and quantification of climate change.

International integration

Within the GCOS Surface Network (GSN), temperature is measured at around 990 stations worldwide and transmitted as CLIMAT messages on a monthly basis using the Global Telecommunication System (GTS). These messages are collected and stored at the GSN Monitoring Centres (e. g. Japanese Meteorological Agency (JMA) in Tokyo). In Switzerland, eight NBCN stations (Säntis, Grd. St. Bernard, Geneva, Sion, Basel, Zurich, Payerne and Lugano) belong to the Regional Basic Climatological Network (RBCN) of the World Meteorological Organization (WMO) and two of them were selected as GSN stations (Säntis, Grd. St. Bernard).

Resources required

Operation of the NBCN stations is assured under the legal mandate of MeteoSwiss. However, in the case of station renewals, it has been shown that budgets do not always cover the parallel measurements required for a 3-year period to meet GSN standards.

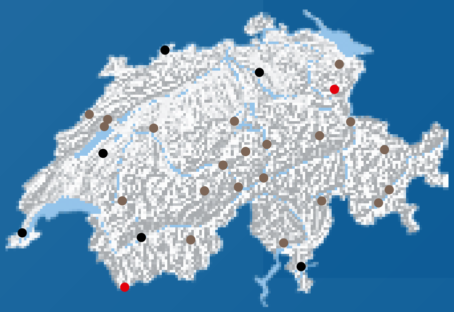
MeteoSwiss – Climate trends in Switzerland

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.2 Wind speed and direction

Wind speed and direction are crucial variables for predicting and monitoring global climate and weather patterns. They affect the rates of evaporation, the exchange of moisture, aerosol and heat as well as the mixing of surface waters. Wind is the driver for oceanic circulation, waves and storm surges. Measurements on the surface are fundamental for many fields, such as weather, climatology, the energy sector and transportation. The social relevance of wind spans over various sectors as agriculture, forestry, health and hazards.



Swiss NBCN (black, red and brown). Two stations belong to the GSN (red) and eight to the RBCN (red and black).

Measurements in Switzerland

Wind speed and direction at ten meters above ground level are now measured by the Federal Office of Meteorology and Climatology MeteoSwiss at almost 150 stations. In some cases, these systematic measurements extend as far back as December 1863, when Switzerland's first nationwide meteorological observation network came into operation. Since 1980, about 70 stations have been automated (ANETZ). All of these stations together with the conventional climate stations and the additional automatic observation network (ENET) were converted and extended until 2015 to form the automated SwissMetNet network (about 160 sites in total). As for other variables the stations of the Swiss National Basic Climatological Network (Swiss NBCN → 2.1. Air temperature) also provide long series of wind measurements. However, the series were only homogenized back to 1981, when the first measurements were automated.

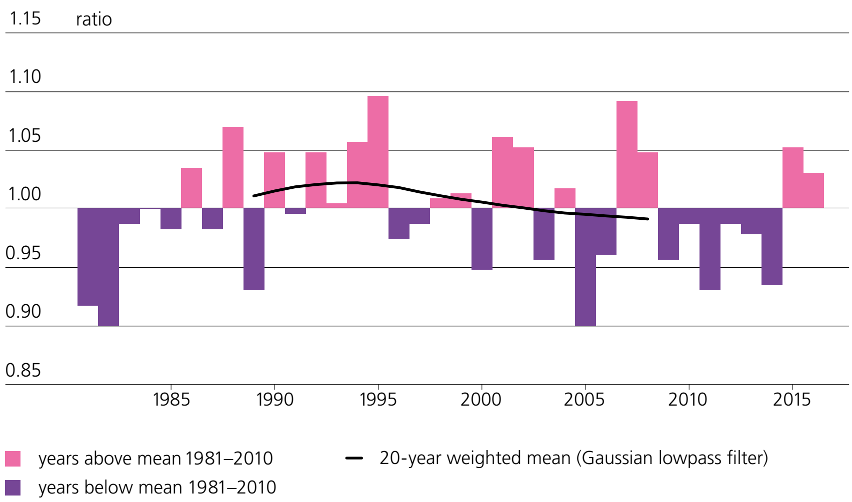
As well as meeting climatological needs, the MeteoSwiss stations provide services for other user groups, e. g. warnings, aviation weather and data for civil protection. The network of stations is continually reviewed on the basis of analyses of requirements, and the distribution of stations across the country and various altitudes has been optimised. At each automatic SwissMetNet station, values are recorded every 10 minutes and transmitted to the central database in Zurich. Quality-control procedures are run automatically on 10-minute values and are performed manually in addition. The wind observations are used to calculate hourly, daily, monthly and annual means. Additional to the SwissMetNet stations, wind velocity is derived from the radiosonde started at one place in Switzerland (Payerne), from radar wind profilers located near the three power plants for atmospheric monitoring and from the precipitation radar stations (only during favourable meteorological conditions).

Long time series and their importance

Systematic observations of wind speed and direction in Switzerland began in December 1863, when Switzerland's nationwide meteorological observation network came into operation. However, wind was only recorded three times a day observing the "Wildsche Windfahne" and using the Beaufort scale for velocity and an eight-piece classification for direction. These measurements are of reduced usefulness for most applications in climatological research. From the end of the 19th century onwards, at some selected locations, registration devices were used which made it possible to record wind data in higher time resolution and accuracy. However, they were the exception until the ANETZ came into operation in 1978. Accordingly, only a few long-term series of measurements with a higher temporal resolution and accuracy are available in Switzerland.

Annual wind speed – Zürich Fluntern 1981–2016

ratio to the mean 1981–2010



Ratio of the annual wind speed for Zurich to the multi-year average (normal values 1981–2010) from 1981 to 2016. Years above the mean are pink, years below the mean violet. The black line shows a 20-year weighted mean.

International integration

Within the GCOS Surface Network (GSN), wind speed and direction are measured at around 990 stations worldwide and transmitted on a monthly basis to the GSN Monitoring Centre.

Resources required

Operation of the NBCN stations is assured under the legal mandate of MeteoSwiss. However, in the case of station renewals, it has been shown that budgets do not always cover the parallel measurements required for a 3-year period to meet GSN standards.

MeteoSwiss – Climate normals

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.3 Humidity

Air humidity is a key characteristic of the atmosphere. Its distribution and variations determine the large-scale transport of water in the atmosphere and the evaporation/transpiration of water from the soil/plants, open waters, snow and ice. It also influences human comfort and health. As a result, air humidity is an important variable for studying climate impact on agriculture, ecology, hydrology and human well-being.

Measurements in Switzerland

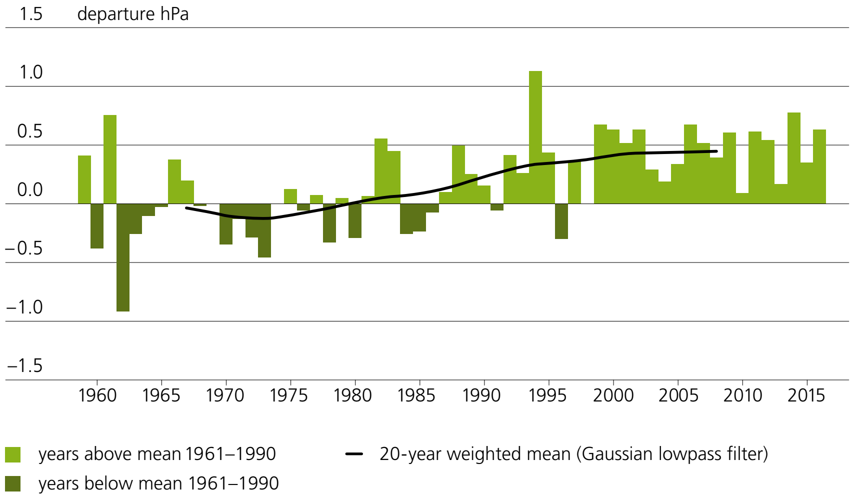
Humidity at ground level is now measured by the Federal Office of Meteorology and Climatology MeteoSwiss at almost 150 stations. In some cases, these systematic measurements extend as far back as December 1863, when Switzerland's first nationwide meteorological observation network came into operation. Since 1980, about 70 stations have been automated (ANETZ). All of these stations together with the conventional climate stations and the complementary automated meteorological monitoring network (ENET) stations have been integrated into the unified automatic SwissMetNet network since 2015 (about 160 sites in total). In addition to the MeteoSwiss stations, humidity is also measured at numerous other weather stations by cantonal and communal authorities and private operators. As well as meeting climatological needs, the MeteoSwiss stations provide services for other user groups, e.g. warnings, aviation weather and data for civil protection, agriculture and tourism. The network of stations is continually reviewed on the basis of analyses of requirements, and the distribution of stations across the country and at various altitudes has been optimised. At each automatic MeteoSwiss station values of relative humidity are recorded every 10 minutes and transmitted to the central database in Zurich. Quality-control procedures are run automatically on 10-minute values and are performed manually in addition. The relative humidity observations are used to calculate hourly, daily, monthly and annual means. In addition, several derived variables such as vapour pressure, dew point, specific humidity, etc. are calculated. In order to understand changes in atmospheric humidity conditions, soundings are carried out in addition to ground-based monitoring. Increasingly, these vertical humidity profiles are supplemented by ground- and satellite-based remote sensing measurements and in-situ sensors mounted on commercial aircraft (→ 2.9 Upper-air water vapor).

Stations of the Swiss NBCN (black, red and brown) with measurements of relative humidity. Two stations belong to the GSN (red) and eight to the RBCN (red and black).

Long time series and their importance

The stations of the Swiss National Basic Climatological Network (Swiss NBCN; → 2.1 Air temperature) also provide the most important long time series of humidity measurements, The Swiss NBCN stations cover the different climate regions of Switzerland and most of them have recorded relative humidity data continuously since 1863. Within MeteoSwiss the derived vapour pressure series of the NBCN stations were homogenised back to 1959. At the moment there are no plans to homogenize any series further back into the past.

Vapour pressure in Zurich 1959–2016



Deviation of the annual mean vapour pressure in Zurich from the 1961–1990 average between 1959 and 2016. The trend correlates with that observed for air temperature, indicating the strong relationship between the two variables.

International integration

Within the GCOS Surface Network (GSN), humidity is measured at around 990 stations worldwide and transmitted on a monthly basis to the GSN Monitoring Centres. In Switzerland, two NBCN stations (Säntis, Grd. St. Bernard) belong to the GSN.

Resources required

Operation of the NBCN stations is assured under the legal mandate of MeteoSwiss. However, in the case of station renewals, it has been shown that budgets do not always cover the parallel measurements required for a 3-year period to meet GSN standards.

MeteoSwiss – Climate normals

Legal basis

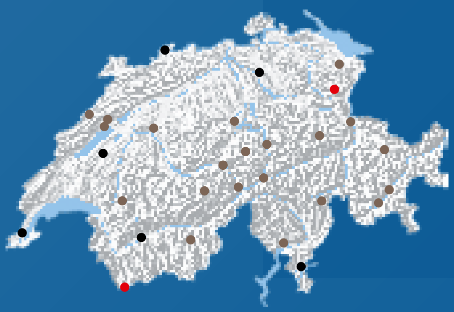
Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.4 Air pressure

Air pressure is an important component of the climate system, characterizing both local and large-scale atmospheric circulation. It is one of the key variables for the backward modelling of long-term global meteorological datasets. Long-term observation of air pressure permits conclusions concerning, for example, variations in meteorological conditions.

Measurements in Switzerland

Surface pressure is now measured by the Federal Office of Meteorology and Climatology MeteoSwiss at about 135 stations. In some cases, these systematic measurements extend as far back as December 1863, when Switzerland's first nationwide meteorological observation network came into operation. Early records for individual sites such as Basel or Geneva go back to the 18th century. Historically, air pressure was measured with mercury barometers. Since the monitoring network was automated, new methods of measurement have increasingly been used. At the automatic stations, air pressure is measured using digital pressure measuring devices which stand out by virtue of their high level of stability and precision. The device is delivered with three redundant sensors which guarantee high-quality measurements and reliability. The introduction of a new type of instrument caused less significant inhomogeneities in the data series than the associated station relocations. As air pressure decreases with increasing elevation, measurements are strongly dependent on the altitude of the station. To allow measurements from different stations to be compared, the readings are converted to sea level pressure. At the automatic stations, air pressure is measured every 10 minutes, and these values are used to calculate hourly, daily, monthly and annual means. Quality-control procedures are run automatically on 10-minute values and are performed manually in addition. These data are essential for climate observation, for description of the current state of the atmosphere, for weather forecasting and for modelling. In addition to the MeteoSwiss stations, air pressure is also measured at a number of other weather stations by cantonal and communal authorities and private operators. Surface pressure is one of the climate variables that cannot yet be measured operationally by satellites. The problem is primarily one of accuracy since the daily fluctuations to be measured are much smaller than the average air pressure values.

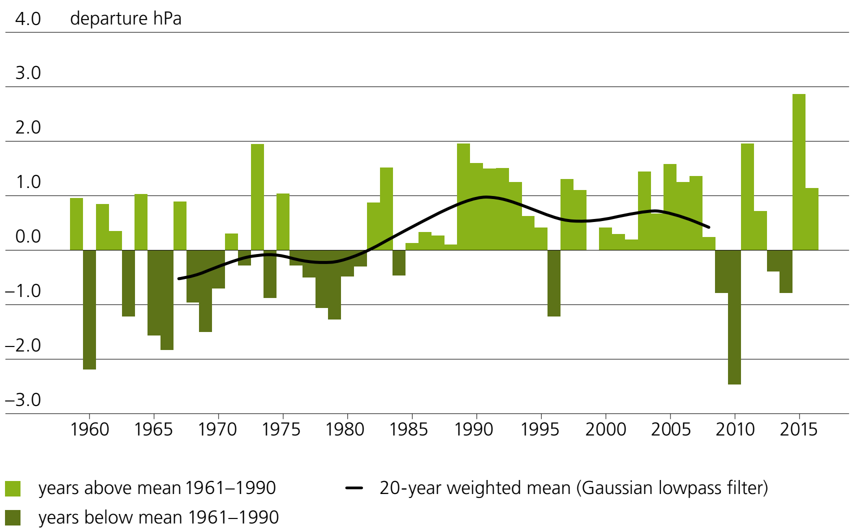


Stations of the Swiss NBCN (black, red and brown) with air-pressure measurements. Two stations belong to the GSN (red) and eight to the RBCN (red and black).

Long time series and their importance

From within the Swiss meteorological network developed since 1863 the stations of the greatest climatological importance were designated as the Swiss National Basic Climatological Network (Swiss NBCN). These NBCN stations also provide the most important long series of air pressure measurements, as most of the stations have recorded air pressure data continuously since the beginning. It is not planned to homogenise all of the time series since air pressure shows strong regional correlations and the processing of a selection of NBCN series is thus sufficient to describe long-term trends in Switzerland.

Air pressure in Zurich 1959–2016



Deviation of the annual mean air pressure in Zurich from the 1961–1990 average between 1959 and 2016. The trend correlates with that observed for air temperature, indicating the relationship between the frequencies of atmospheric circulation patterns and regional climate variability. Long-term air pressure series are valuable for the description of long-term variations in the frequency of atmospheric circulation patterns. In addition, they are the key input variable for the global and regional re-analyses used in the validation of climate models.

International integration

Eight Swiss NBCN stations (Säntis, Grand St. Bernard, Geneva, Sion, Basel, Zurich, Payerne and Lugano) belong to the Regional Basic Climatological Network (RBCN) of the World Meteorological Organization (WMO), which comprises about 2850 surface stations worldwide. Two of these stations (Säntis, Grand St. Bernard) also belong to the GCOS Surface Network (GSN), which includes 990 stations worldwide. Air pressure measurement is not one of the minimum requirements (mean temperatures, precipitation) of the GSN. Measurement of this variable is, however, a target requirement. At the WMO, the International Surface Pressure Databank (ISPD) has been assembled under the auspices of the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of GCOS and the World Climate Research Program (WCRP) (see Cram et al., 2015).

Resources required

Operation of the NBCN stations is assured under the legal mandate of MeteoSwiss. However, in the case of station renewals, it has been shown that budgets do not always cover the parallel measurements required for a 3-year period to meet GSN standards.

MeteoSwiss – Climate normals

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.5 Precipitation

Precipitation is a key indicator of changes in the climate. As long time series are available for precipitation in Switzerland, dating back to the mid-19th century, long-term analyses can be performed. These are particularly valuable for assessing the effects of climate change on the water cycle and water balance.

Measurements in Switzerland

Precipitation is now measured by the Federal Office of Meteorology and Climatology MeteoSwiss at more than 450 stations, some of which have been in operation since December 1863. In a number of cases, the measurements go back to the 18th century, although there are considerable gaps in some of the time series. Since 1980, about 70 stations have been automated (ANETZ). All of these stations together with the conventional climate stations and ENET stations have been integrated into the unified automatic SwissMetNet network since 2015 (about 160 sites in total). In addition, about 100 stations of the manual precipitation network (NIME) were also automated while the remaining precipitation stations (NIME: ~200, totalizers: ~50) are not to be automated at present. At each automatic MeteoSwiss station, precipitation is collected and measured at 10-minute intervals. Quality-control procedures are run automatically on 10-minute values and are performed manually in addition. These measurements are used to calculate total precipitation on an hourly, daily, monthly and yearly basis. At the NIME stations, the amount of precipitation is recorded once a day by the station operator and records are sent daily by SMS. To measure precipitation in mountainous areas a so-called totalizer is used which measures precipitation for the water year (October 1 to September 30). In addition to in-situ measurements, precipitation is also calculated indirectly on the basis of radar reflectivity with five precipitation radars. These stations have been in operation since 1961 (La Dôle, Albis), 1993 (Monte Lema), 2014 (Point de la Plaine Morte) and 2016 (Weissfluhgipfel) and the data have been systematically archived in digital form since 1991. The precipitation radar data thus represent potential long time series for future analyses. Due to its potential for damage, hail was determined as an important variable for climatological purposes. In the years to come a national hail climatology will be established using existing time series of radar and ground truth.

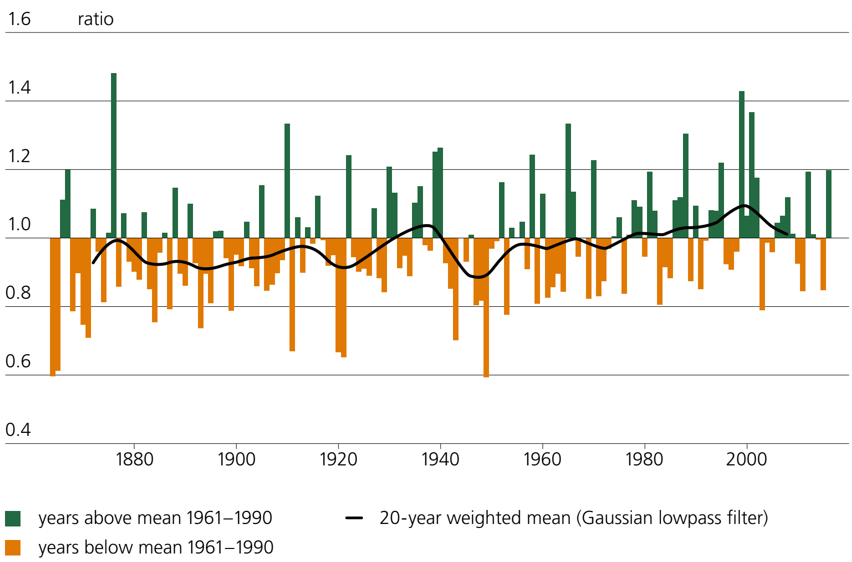
Black: Stations of the Swiss NBCN with precipitation measurements (weather stations); orange: precipitation sites; red: MeteoSwiss precipitation radars; brown: eight totalizers of greatest climatological significance.

The combination of the quantitative accuracy of automatic surface rain-gauge measurements with the high spatial resolution of a radar composite is a primary input for spatially comprehensive precipitation analysis over Switzerland. Such a gridded precipitation analysis is available on an hourly basis (Sideris et al. 2014). Another spatially comprehensive analysis at a daily time resolution is produced by statistical analysis of all the rain-gauge measurements in Switzerland (Frei et al. 2006, Isotta et al. 2014).

Long time series and their importance

Systematic recording of precipitation in Switzerland began in 1863 with the operation of, initially, about 70 weather stations equipped with a precipitation gauge. The total number of stations subsequently rose sharply, and by around 1900 precipitation was being measured daily at more than 300 locations. At many of the sites originally selected stations remain in operation today. The sites of greatest climatological importance were designated as the Swiss National Basic Climatological Network (Swiss NBCN, (Begert, 2008)). The Swiss NBCN for precipitation consists of selected weather stations and additional specific precipitation stations covering the different climate regions of Switzerland. In mountainous areas the totalizer data represent important additional precipitation series with a low temporal resolution. From a climatological perspective, 8 of the totalizers are to be protected with priority 1 and another 27 with priority 2. In-situ precipitation measurements are extensively used for a regular monitoring of the evolution of precipitation in Switzerland and for informing the general public about recent anomalies in comparison to the long-term measurement history.

Precipitation in Zurich 1864–2016



Ratio of the annual total precipitation for Zurich to the multi-year average (normal values 1961–1990) from 1864 to 2016. The data series shows a significant linear trend, with an increase of 8.5 % over 100 years. In particular, winter precipitation has increased. Long series provide a basis for understanding the broader context and permit conclusions concerning trends and recurrence intervals for extreme events (heavy rainfall and dry periods). Indirectly, they are valuable for planning flood protection measures and developing regional climate scenarios.

International integration

Precipitation data from the GCOS surface network (GSN) stations Säntis and Grd. St. Bernard are transmitted to the GSN monitoring centre at DWD, and WMO receives data from the Regional Basic Climatological Network (RBCN) stations Säntis, Grd. St. Bernard, Geneva, Sion, Basel, Zurich, Payerne and Lugano. The precipitation data from all MeteoSwiss stations are also transmitted to the GSN monitoring centre for precipitation in Offenbach. Precipitation radar networks in Europe are coordinated by the EUMETNET Operational Programme for the Exchange of weather RAdar information (OPERA). All five Swiss precipitation radars are integrated into the OPERA programme. In addition, nearby radars are improving precipitation radar coverage in the border regions with Italy and France respectively.

Resources required

Operation of the NBCN and NIME stations is assured under the legal mandate of MeteoSwiss. However, budgets do not always cover the parallel measurements required for a 3-year period to meet GSN standards. The totalizers of greatest climatological significance are only guaranteed in the short term, as about half of the stations are funded by third parties; in addition, the commercial importance of the totalizer network is declining.

MeteoSwiss – Climate trends in Switzerland

Legal basis

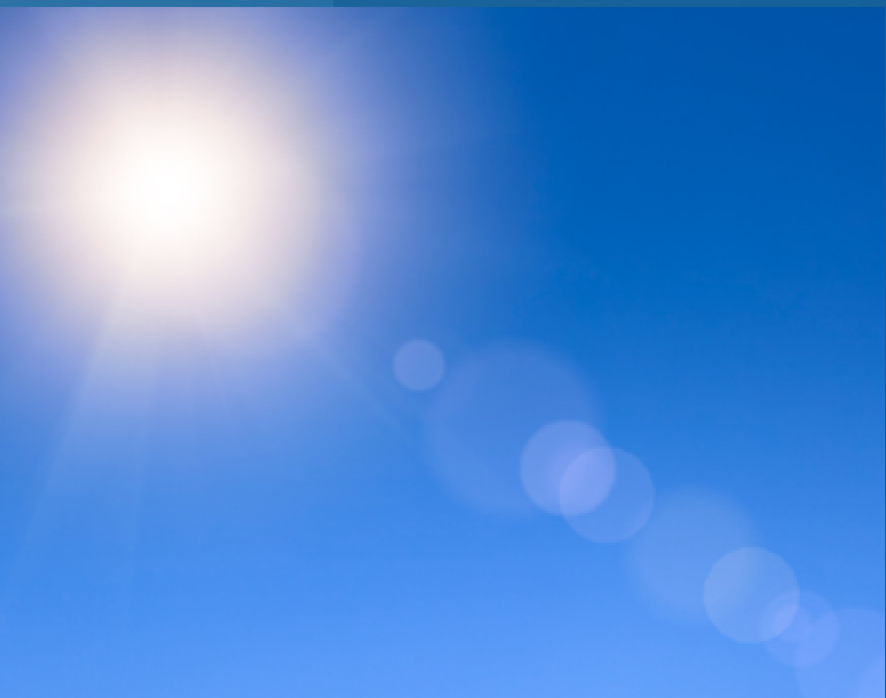
Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.6 Radiation

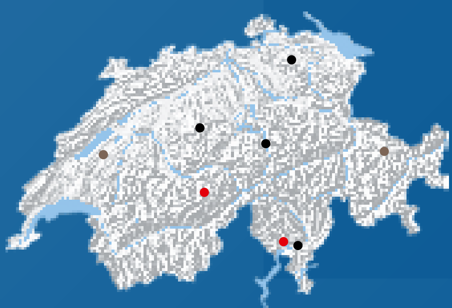
Radiation is the main factor in the climate system, accounting for seasonal and regional differences in climate. The effects of greenhouse gases and anthropogenic aerosols on the climate are directly manifested as changes in the radiation budget. These changes are measurable and allow a detailed study of changes in the climate.

Measurements in Switzerland – Surface radiation budget

Measurements of the four surface radiation budget components – both downward and upward fluxes of the solar (also called shortwave) and infrared thermal (also called longwave) radiation – are relatively recent in Switzerland. The first location where these were all measured is Payerne, starting in 1992. More recently, a few stations of the Swiss Meteorological Network (SwissMetNet, → 2.1 Air temperature) have been equipped for measuring all four components (Altdorf since 2008, Magadino since 2012 and Tänikon since 2013), or in a couple of cases three components (Davos since 2006 and Napf since 2007) – excluding longwave upward radiation. Previously, long-term monitoring of radiation at the SwissMetNet (and its precursor ANETZ) was limited to downward solar irradiance (the ANETZ stations started between 1977 and 1984). Studying the surface radiation budget using only downward solar irradiance, however, relies on proxies for estimating the other three components. These proxies are the surface albedo (→ 3.9 Albedo) for upward shortwave irradiance, parameterisations of longwave downward irradiance using surface temperature (→ 2.1 Air temperature) and humidity (→ 2.3 Humidity), as well as land surface temperature (→ 3.14 Land surface temperature) for longwave upward irradiance.



In addition to SwissMetNet, the Federal Office of Meteorology and Climatology MeteoSwiss operates the SACRaM network (Swiss Alpine Climate Radiation Monitoring) consisting of four stations dedicated to measuring radiation fluxes from the ultraviolet, over the visible to the infrared portion of the electromagnetic spectrum. The Payerne station is on the Central Plateau and Locarno-Monti lies south of the Alps, while two stations (Davos and Jungfraujoch) are located in the Alps, providing synergies with aerosol (→ 2.14 Aerosols) and cloud observations (→ 2.10 Cloud properties). At Payerne upward shortwave (reflected solar) and longwave (thermal from the Earth's surface) radiation are additionally recorded. Individual spectral radiation fluxes are also measured with high precision and temporal resolution in order to determine the aerosol optical depth and water vapor content of the atmosphere. The SACRaM measurements are used for climate studies, validation of satellite products, and studies related to solar energy. During the last years ground-based solar irradiance measurements have been complemented by satellite-derived estimates (1983 to present), namely by MeteoSwiss in the framework of the EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) Satellite Application Facility on Climate Monitoring (CM SAF) (→ 3.9 Albedo; → 8.0 Trends in climate observations).

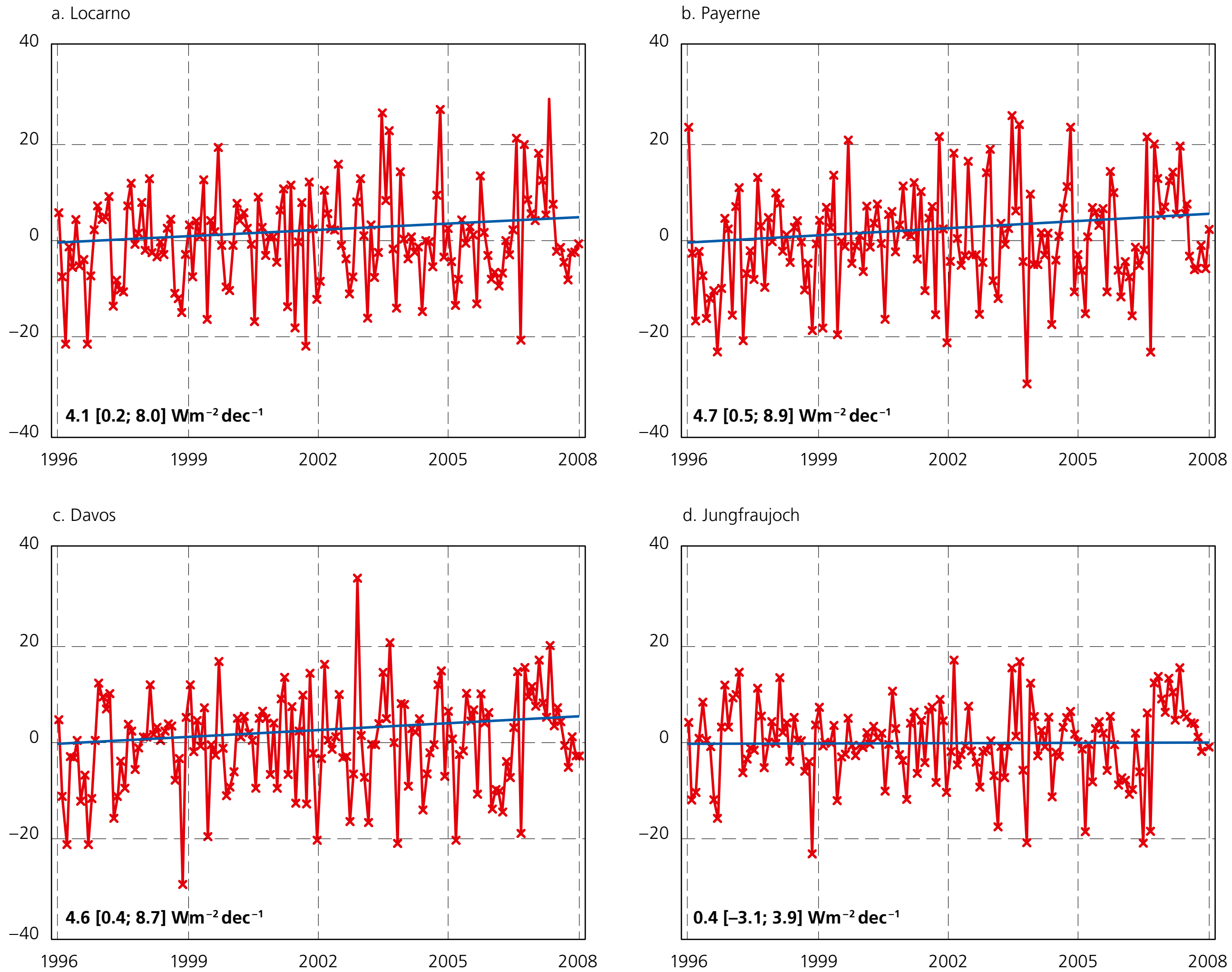


The stations of the SACRaM (red and brown) and SwissMetNet (black) monitor individual components of the surface radiation budget.

Long time series and their importance – Surface radiation budget

Monitoring of the four components of the surface radiation budget at the SwissMetNet is recent. On the other hand, radiation measurements currently under the SACRaM programme were initiated at Davos in 1991 and at the Payerne station in 1992. The Jungfraujoch and Locarno-Monti sites were established in 1996 and 2001 respectively. The SACRaM network is designed for long-term monitoring and provides reliable radiation data, making it possible to study trends in the radiation budget specifically for the Alps. The four SACRaM stations Payerne, Davos, Jungfraujoch and Locarno are located at SwissMetNet sites, permitting comparison with other variables. UV radiation has been measured at SACRaM stations since 1995 (→ 2.13 Ozone). Outgoing radiation components are recorded at the Payerne station. In addition, radiation measurements were carried out at ten ASRB stations between 1995 and 2010. Since long time series of the upward components of the shortwave and longwave radiation fluxes are only available at Payerne, proxies are necessary to estimate these at the other stations, typically surface albedo and temperature.

Downwelling long-wave radiation residual



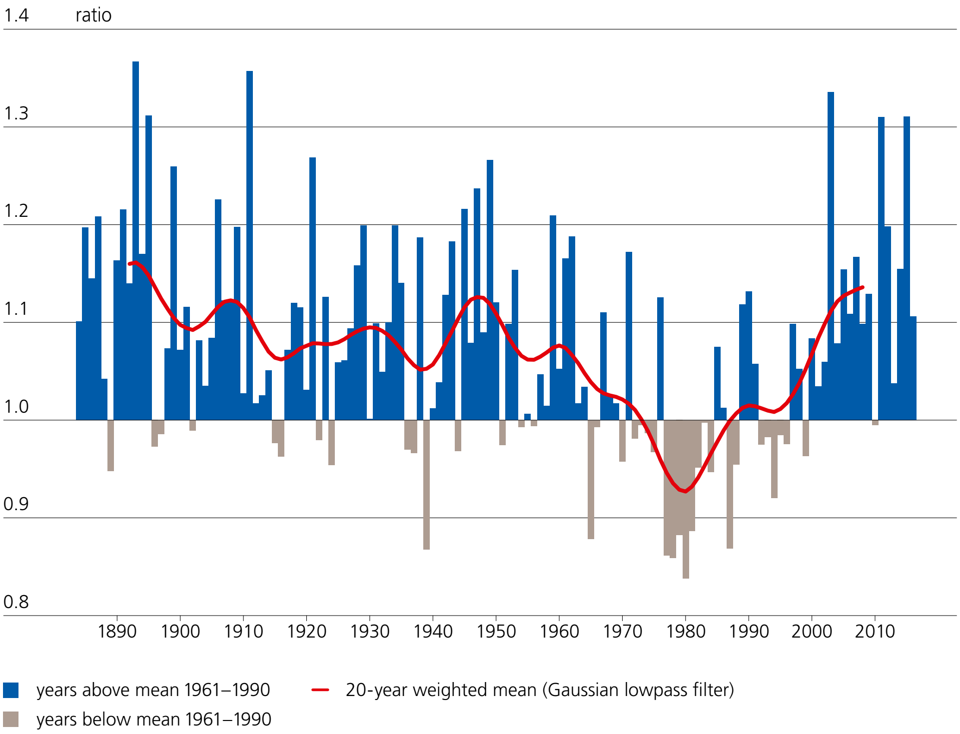
Downwelling long-wave radiation residual: longwave radiation measurements at the Locarno (a), Payerne (b), Davos (c), and Jungfraujoch (d) stations allow studying trends. The longwave radiation is anticipated to be the surface radiation budget component most affected by climate change. The residuals time series of the monthly mean cloud-free downward longwave radiation and its corresponding linear trends (blue) are shown. The least squares slope estimate and the corresponding lower and upper bounds of the 90 % confidence interval are indicated. Trends are significant at the 90 % confidence level except at Jungfraujoch (Wacker et al., 2011).

Measurements in Switzerland – Sunshine duration

The sunshine duration is defined as the total of the duration during which the direct sun beam is above a certain threshold. Sunshine duration is now measured by MeteoSwiss at 100 stations at 10-minute intervals and summed up to hourly, daily, monthly and yearly values. Systematic measurements began around 1880 when the Schweizerische Meteorologische Zentralanstalt was established and took over the nationwide observation network from the Schweizerische Naturforschende Gesellschaft. Historically, sunshine duration was measured with Campbell-Stokes recorders using a glass sphere to focus the rays from the sun and burn a trace onto a card mounted at the back. From the length of the burned trace the daily sunshine duration was derived. Automation of the network was initiated around 1980, and the last Campbell-Stokes recordings were discontinued in 1995. Changes in automated instrumentation occurred as part of the network renewal between 2005 and 2010. The automated instruments measure direct and diffuse solar radiation and calculate sunshine duration from their difference exceeding a certain threshold. Because of historical reasons and contrary to the actual recommendations of the WMO (World Meteorological Organization) the devices operated in Switzerland have always used an exceedance threshold of 200 W/m² (instead of 120 W/m²). Due to decreasing opacity of the glass spheres of the first Campbell-Stokes recorders, the different instruments in operation and the changing horizon in connection with site relocations the records of sunshine duration suffer from significant inhomogeneities. They need to be carefully homogenised before an interpretation of the long-term evolution is possible. In addition to the ground-based sunshine duration measurements, satellite-based cloud observations are used as input for the spatial interpolation algorithms of sunshine duration at MeteoSwiss. There is also potential for calculating sunshine duration directly from satellite -based solar irradiance datasets.

Stations of the Swiss NBCN measuring sunshine duration. Stations with long-term records of more than 100 years are depicted in red.

Sunshine duration in Zurich 1884–2016



Ratio of the homogenized annual total sunshine duration in Zurich to the multiyear average (1961–1990) for the period 1884 to 2016. The data series shows a more or less stable state during the first 60 years, a remarkable decrease of sunshine duration from 1950 to 1980 and an increase of the same order from 1980 to 2010. Values of the last 15 years returned to the level of pre-1950 values.

Long time series and their importance – Sunshine duration

In 1884 the first measurements of sunshine duration in Switzerland were established in Zurich. Some additional stations came into operation within the following years. However, a significant increase of the number of stations only occurred in the course of the 20th century. For all stations of the Swiss National Basic Climatological Network (NBCN) (→ 2.1 Air temperature) the available sunshine duration measurements have recently been digitised. After homogenisation, which has not been completed yet, 12 long-term records of more than 100 years of the following stations will be available: Altdorf, Basel, Bern, Davos, Genève, La Chaux-de-Fonds, Lugano, Neuchâtel, Samedan, Säntis, Sion, Zurich. As the sunshine duration can be used as a proxy to determine the influence of cloud on incoming radiation, these long-term records extend instrumental knowledge on radiation flux back to the 19th century and complete our understanding of the climate variability and change in Switzerland over the last 130 years.

International integration

SACRaM is associated to the WMO GAW (Global Atmosphere Watch) programme and the Payerne station belongs to the Baseline Surface Radiation Network (BSRN), which studies the global surface radiation budget. To this end, shortwave (direct, diffuse and global) and longwave radiation fluxes are measured in accordance with BSRN and GAW guidelines. Data are supplied to the GAW World Radiation Data Centre (WRDC) in St. Petersburg, and to the World Radiation Monitoring Centre (WRMC) of the BSRN. The BSRN is the global baseline network for surface radiation within GCOS. Previously, the BSRN WRMC and its data archive was hosted in Switzerland at the ETH Zurich. Since 2008, it has been hosted by the Alfred Wegener Institute in Germany. The Payerne BSRN station is also an official station for routine validation of EUMETSAT CM SAF products. The CM SAF is a joint project involving several European meteorological services, aiming at monitoring climate variables using satellite data. Of the Swiss NBCN stations, Basel, Genève, Grand St. Bernard, Lugano, Säntis and Zurich belong to the Regional Basic Climatological Network (RBCN) of WMO. Sunshine duration measurements of Swiss stations are included in several international data bases such as the European Climate Assessment and Dataset (ECA & D) or the Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP).

Resources required

The SACRaM network is integrated into the MeteoSwiss-run SwissMetNet. Its operation is assured both under the legal mandate of MeteoSwiss and through GAW-CH. Operation of the Swiss NBCN stations is assured under the legal mandate of MeteoSwiss. However, in case of station renewal and change of instrument type, it has been shown that budgets do not always cover the required 3-year parallel measurements. In order to allocate the limited funding for radiation monitoring most efficiently, monitoring at the previous ASRB stations that were not collocated with SACRaM stations (previously CHARM) was discontinued.

MeteoSwiss – Radiation monitoring network

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They must also participate in the recording, exchange and analysis of international meteorological and climatological data and are responsible for the provision of climatological information. In addition, they are to support theoretical meteorology and climatology and to conduct applied research projects. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks. In addition, Switzerland is a member of the WMO (SR 0.429.01) and participates in the WMO GAW programme in accordance with the Federal Council Decree of 25 November 1994.

2.7 Upper-air air temperature

Vertically resolved upper-air temperature profile measurements are of crucial importance for climate monitoring. The troposphere and the stratosphere have cooled for some time after global observations began with radiosondes in the late 1950s. From the 1970s on the troposphere started to warm up and in recent years lower stratospheric temperature has been increasing.

Measurements in Switzerland

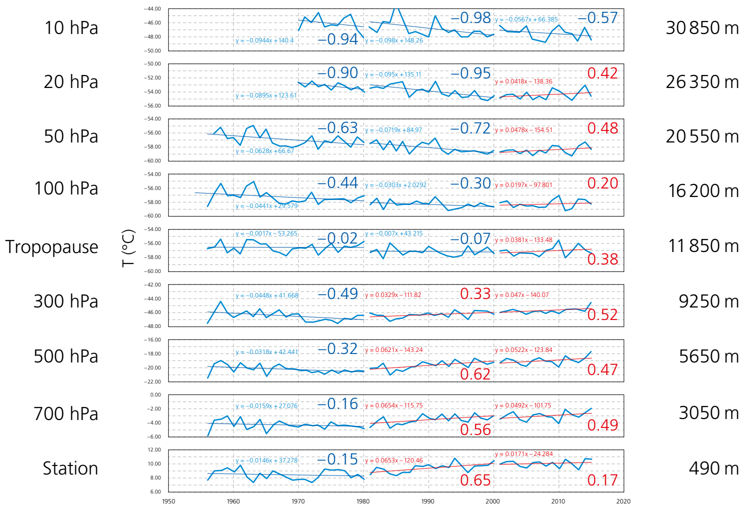
In Switzerland operational upper-air measurements started in 1942 at the only Federal Office of Meteorology and Climatology MeteoSwiss aerological station, Payerne. Operational daily soundings with two ascents per day have been available since 1954. Mechanical radiosondes were replaced by fully electronic instruments in 1991. In the old mechanical radiosondes upper-air temperature was measured with bi-metal sensors, whereas in the new electronic radiosondes thermocouples are used for very accurate temperature measurements. Thermocouples are made of very thin 0.05 mm copper and constantan wires. The temperature sensor is therefore very small and has the advantage of risking only minor exposure to perturbing solar and thermal radiation. Since the very beginning MeteoSwiss has always used Swiss-made radiosondes for their upper-air measurements, of which the newest model is presently in operation. Starting in Spring 2018, part of Payerne operational radiosoundings will be carried out using an automatic launcher. Vertical temperature profiles are recorded at Payerne twice a day at UTC 00:00 and 12:00. The weather balloon with the 190 g radiosonde ascends with a vertical speed of about 5 m/s and after a 2 hour flight bursts at an altitude of about 35 km. The radiosonde then descends with a parachute to the ground. During sounding, once the radiosonde reaches the altitude of 16 km, a first bulletin with the recorded data is sent to the users over the global telecommunication system (GTS). A final bulletin is sent out after balloon burst, hence, upper-air records are available worldwide for weather forecasts and numerical model assimilation about two to three hours after the start of the sounding. One of the goals of MeteoSwiss is that at least 80 % of their soundings reach 10 hPa (about 31 km). Another issue is the annual availability of soundings (16 km altitude reached), which is above 99 %. The uncertainty of temperature records is lower during nighttime (0.2 – 0.3 °C) than during daytime (0.2 – 0.5 °C) flights.

Upper-air air temperature measurement station in Payerne.

Long time series and their importance

The long and high-quality radio-sounding time series of Payerne provides a valuable foundation for describing vertical temperature conditions in the atmosphere. Homogenised upper-air temperature records have been available since 1954 at a given number of standard (fixed) and significant (change in profile behavior observed) pressure levels. Different climatological trend analyses have been made. Tropospheric warming has been observed since the mid-1970s and this apparently continues with similar trends of about 0.5 °C / decade in the 21st century. The stratosphere on the other hand was cooling over several decades but temperature trends have now switched to warming. The reason for the switch from cooling to warming seems to be twofold: on the one hand the ozone recovery produces a warming of the lower stratosphere, and on the other hand greenhouse warming enhances lower stratospheric warming by the warming troposphere.

Payerne radiosounding 1956 – 2015



Temperature evolution and trends at the surface and eight standard pressure levels: At Payerne, temperature evolution over the last 60 years at the surface and at eight standard pressure levels from 700 to 10 hPa shows an overall temperature decrease in the troposphere and in the stratosphere from 1966 to about 1980. From 1981 on the temperature increases in the troposphere and continues to increase with a rather large trend up to 2015. The stratosphere still shows a strong decrease from 1981 to 2000 but in the new century the lower stratospheric temperature is now also increasing at least up to a pressure level of 20 hPa.

International integration

Payerne is one of the Regional Basic Climatological Network (RBCN) stations that transmit data from radiosoundings on a daily basis to the WMO. About 170 of the approximately 800 WMO aerological stations worldwide are part of the GCOS Upper-Air Network (GUAN), meeting higher quality requirements for long-term monitoring of the climate. Payerne is part of the GUAN network and transmits the radiosonde data to the GUAN Monitoring Centres at the ECMWF in Reading (UK) and the Hadley Centre in Exeter (UK). The data are archived at the Integrated Global Radiosonde Archive (IGRA) of the National Climate Data Center (NCDC) Asheville (US). Since 2008 Payerne has also been part of the GCOS Reference Upper-Air Network (GRUAN), which is a network of selected GUAN stations that operate a broader range of reference upper-air instruments. GRUAN requests metadata and elevation-resolved uncertainty estimates of all their measured data. GRUAN upper-air data are sent to the lead center at Lindenberg.

Resources required

Operation of the Payerne aerological station can be regarded as assured under the legal mandate of MeteoSwiss.

MeteoSwiss – Radiosoundings

National Centers for Environmental Information

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.8 Upper-air wind speed and direction

Wind is a fundamental state variable for weather and climate models used to make forecasts and climate projections. The motion of the atmosphere is also a basic to the working of the climate system through transport of water vapor and trace constituents.

Measurements in Switzerland

With respect to measurements of upper-air wind speed and direction in Switzerland, the atmosphere can roughly be divided into two different layers: troposphere to lower-stratosphere and upper stratosphere to mesosphere. Concerning the troposphere/lower stratosphere, radiosonde wind profiles have been regularly performed since the 1950s at the permanent station of Payerne of the Federal Office of Meteorology and Climatology MeteoSwiss. In 2011 MeteoSwiss decided to switch from four to two launches per day measuring wind associated with the classical meteorological parameters (pressure, temperature and humidity). In the context of the meteorological surveillance of nuclear power plants, ground-based remote sensing techniques for wind profiling using radar wind profilers started to be operationally implemented in Switzerland (Payerne, Grenchen and Schaffhausen) in the early 2000s. The Aircraft Meteorological Data Relay programme (AMDAR) was launched in 1991 by the WMO. It comprises a network for the collection of meteorological data (temperature, wind speed and direction, and humidity) by aircraft. Airplanes from specific companies taking off and landing at the two main Swiss airports (Zurich and Geneva) participate in this programme.

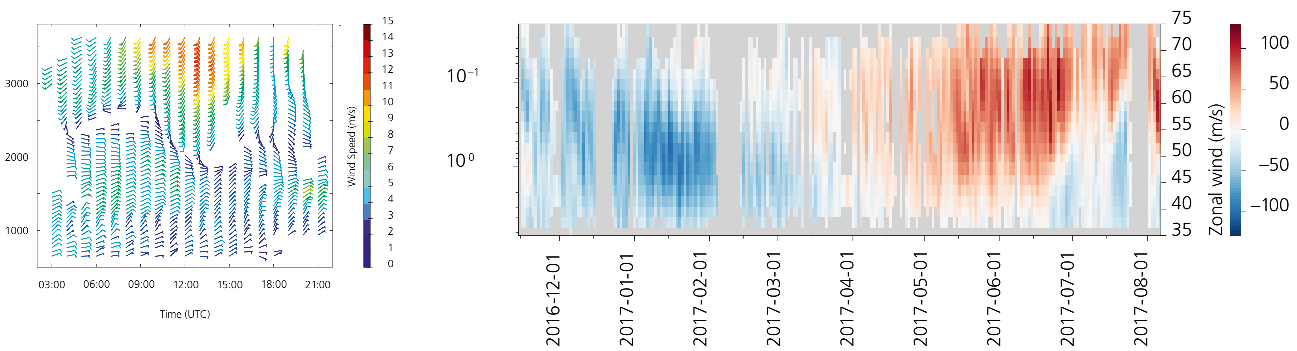
Wind measurements in the upper stratosphere and mesosphere are extremely rare. To date the only approach providing direct measurements of zonal and meridional wind profiles on a continuous basis is the recently developed technique of ground-based Doppler microwave radiometry by the Institute of Applied Physics, University of Bern. By now three mobile instruments exist that are operated worldwide (La Réunion, Svalbard and Andoya). Microwave wind radiometers are only marginally affected by weather conditions and their operation can be highly automated, which makes it possible to provide uninterrupted time series of middle-atmospheric zonal and meridional wind on a routine basis. An example of an extended wind data set is given in the figure on the opposite page.

Upper-air wind speed and direction measurement station in Payerne.

Long time series and their importance

No specific climatology of free atmosphere winds above Switzerland has been performed up to now. The main purpose of wind profile information is the assimilation into numerical weather forecasting models as well as a product for weather and air pollution forecasters. Meanwhile a very interesting dataset of more than 60 years is available to climatologists for analyzing long-term evolution of wind speed and direction in the vertical component over Switzerland. Since September 2014 the GRUAN Payerne radiosounding station data are operationally transmitted to the GRUAN Lead Centre.

Examples of automated wind profile time series



Example of radar wind profiler time series measured at Payerne (left panel) and zonal wind profiles from a microwave radiometer on La Réunion measuring Doppler shifted emission lines of ozone (right panel).

International integration

Payerne is one of the Regional Basic Climatological Network (RBCN) stations that transmit data from radiosoundings on a daily basis to the WMO. About 170 of the more or less 800 WMO aerological stations worldwide are part of the GCOS Upper-Air Network (GUAN), meeting higher quality requirements for long-term monitoring of the climate. Payerne is part of the GUAN network and transmits the radiosonde data to the GUAN Monitoring Centres at the ECMWF in Reading (UK) and the Hadley Centre in Exeter (UK). The data are archived at the Integrated Global Radiosonde Archive (IGRA) of the National Climate Data Center (NCDC) Asheville (US). Since 2008 Payerne is also part of the GCOS Reference Upper-Air Network (GRUAN), which is a network of selected GUAN stations that operate a broader range of reference upper-air instruments. GRUAN requests metadata and elevation-resolved uncertainty estimates of all their measured data. GRUAN upper-air data are sent to the Lead Centre at Lindenberg.

Resources required

Operation of the Payerne aerological station is to be regarded as assured under the legal mandate of MeteoSwiss.

MeteoSwiss – Atmosphere

Institute of Applied Physics – University of Bern

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.9 Upper-air water vapor

Water vapor is the most important natural greenhouse gas and has a large impact on the radiative budget and the chemistry of the atmosphere. Upper tropospheric water vapor is particularly important due to its strong radiative forcing. Therefore long-term measurements of water vapor at all vertical levels are essential to understand and quantify climate change.

Measurements in Switzerland

Payerne (MeteoSwiss), Bern/Zimmerwald (University of Bern) and the Jungfraujoch (University of Liège) form a super site for upper-air water vapor measurements. Besides the operational radiosoundings of temperature, water vapor and wind, which started in 1954, the Federal Office of Meteorology and Climatology MeteoSwiss has performed regular radiosoundings with a high-quality chilled mirror frost/dew point hygrometer since 2001. Good quality measurements are available up to the lower stratosphere (approx. 12 km). The MeteoSwiss regional center at Payerne was complemented with a Raman water vapor lidar in 2007 for continuous operation. With a data availability of more than 50 % on average over 10 years and a temporal resolution of 1 minute the Raman lidar record is one of the most extensive water vapor data sets to address water vapor change and variability on all temporal and spatial scales from the surface up to the lower stratosphere. Integrated water vapor has been measured at Bern with a two channel radiometer since 1994 at 2 s temporal resolution. Stratospheric and mesospheric water vapor profiles have been measured at Zimmerwald with a multi-channel microwave radiometer since 2001 with a temporal resolution of a few minutes. At the Jungfraujoch a variety of trace gases, including carbon dioxide, methane and water vapor, are measured with Fourier transform spectrometers. The data record is limited to sunny conditions and reaches back to 1950, however, regular measurements only started in 1984. Integrated water vapor is also derived from GPS (Global Positioning System) satellite data using the signal delay introduced by atmospheric water vapor. The Automated GNSS (Global Navigation Satellite System) Network of Switzerland (AGNES) counts 31 stations and allows for investigations of the spatial behavior of water vapor. GPS data is becoming more and more important to drive numerical weather prediction and climate models.

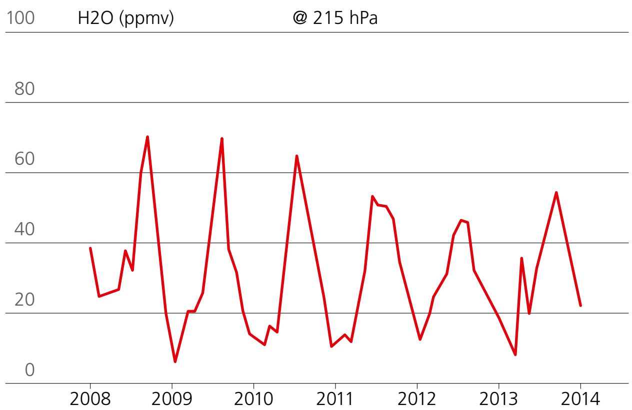
Upper-air water vapor measurement stations in Payerne (red) and Bern and Zimmerwald (black) and Jungfraujoch (brown).

Long time series and their importance

The University of Liège water vapor record from Jungfraujoch extends back to 1950. However, the record is inhomogeneous since the measuring device has changed over time. A homogenised data set has been available since 1996. Still, there is potential to generate a climatologically useful data set back to 1984, when regular measurements started, and maybe even back to 1950 with corresponding efforts. The Bern time series of integrated water vapor starting in 1994 is well maintained and continues growing every day.

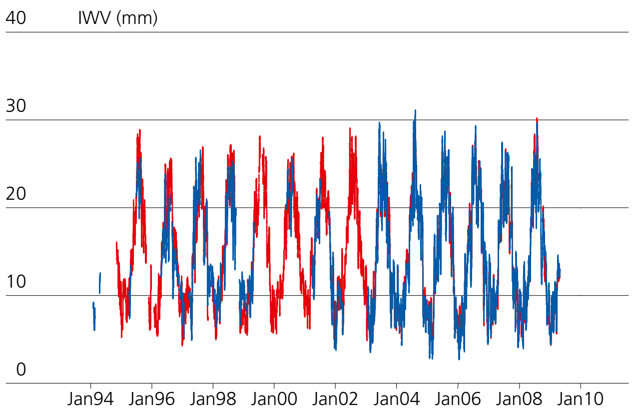
The data set has been homogenised and forms an important observational basis for climate change assessments in Switzerland. The stratospheric and mesospheric water vapor measurements carried out at Zimmerwald have been published in various publications by the University of Bern. The frost/dew point hygrometer and Raman lidar measurements from Payerne have been validated and published. Efforts to homogenise these data sets are under way.

Time series of monthly mean water vapor mixing ratio at 215 hPa, Payerne, 2008–2014



Time series of monthly mean water vapor volume mixing ratio at 215 hPa (approximately 11 km) measured by the Raman lidar at the regional center of Payerne. Only nighttime measurements taken under cloud-free conditions are considered. A distinct annual cycle is visible with a more humid tropopause region in summer.

Time series of integrated water vapor, Bern, 1994–2009



— GROMOS model 4 — TROWARA

16-year time series of integrated water vapor above Bern measured by two microwave radiometers. Figure from Hocke et al., 2011.

International integration

Payerne, Bern/Zimmerwald and Jungfraujoch are NDACC sites (Network for the Detection of Atmospheric Composition Change) and all data are uploaded to the NDACC data base on regular intervals. Furthermore, in 2015, Payerne was recognized as a station of the GCOS Reference Upper-Air Network (GRUAN) which aims at providing long-term, highly accurate measurements of the atmospheric profile. As such, the Payerne station is among the first 9 certified GRUAN sites worldwide. Radiosonde and Raman lidar data are submitted to the GRUAN data center.

MeteoSwiss – Atmosphere (Radiosonde, GPS, LIDAR)

University of Bern

Resources required

Operation of the radiosoundings and the Raman lidar at the regional center of Payerne can be regarded as assured under the legal mandate of MeteoSwiss as part of its commitment to GRUAN. Continuation of the time series by the University of Bern is assured until 2018. NDACC does not provide any funding and hence the network operates according to best efforts and relies on the commitment of the contributing parties and on national funding. The activities at Jungfraujoch by the University of Liège are partly supported through the GAW-CH (Global Atmosphere Watch Switzerland) programme.

University of Liège

NDACC

GRUAN

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. They are also to participate in the recording, exchange and analysis of international meteorological and climatological data. In addition, they are responsible for the provision of climatological information and for the implementation of measures contributing to the long-term preservation of an intact environment. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks.

2.10 Cloud properties

Clouds play a dominant role in the energy and water cycle of our planet. Since the interaction between radiation and clouds is one of the major sources of uncertainty in climate models, measurement of the spatial distribution and microphysical properties of clouds are a key requirement. For this purpose, soundings, ground-based remote sensing and satellite measurements would ideally be combined in a complementary manner.

Measurements in Switzerland

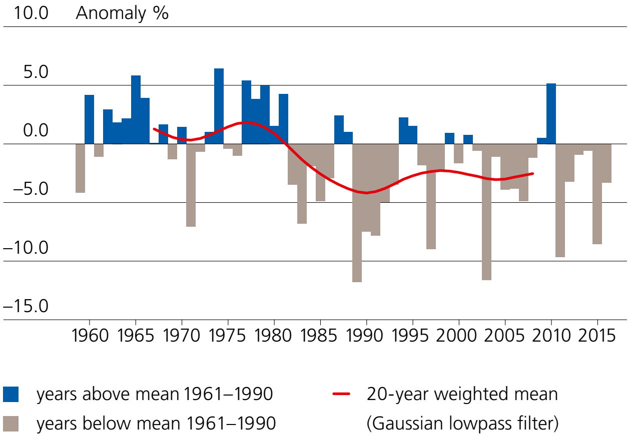
At the 26 stations of the Federal Office of Meteorology and Climatology MeteoSwiss Manual Observation Network (OBS) cloud variables are estimated by observers at regular intervals. The variables recorded include cloud cover, cloud type, cloud height and visibility. Observations are made at least three times a day. At the airports, since 2016 in addition to human observers, Present Weather Sensors (PWS) are used to measure a number of cloud variables (e. g. ceilometer for cloud-base height) and visibility (transmissometer). In-situ observations of cloud microphysical properties and aerosol-cloud interactions at the Jungfraujoch research station have been done on a campaign basis by the Paul Scherrer Institute (PSI), the ETH Zurich and collaboration partners since 2000 (PSI) and 2009 (ETH Zurich). Efforts to improve the quality and comparability of different types of in-situ cloud observations are currently undertaken within the framework of the European Research Infrastructure for the observation of Aerosol, Clouds, and Trace gases (ACTRIS). Comprehensive recording of the spatial extent and high temporal variability of clouds, including their microphysical properties, has only been possible since the 1980s by use of multi-spectral satellite sensors. Decadal stability is however still not suitable for climate change analysis as inter-sensor differences due to shifting overpass times, sensor spectral differences and methodological uncertainties are large as demonstrated by the MeteoSwiss contribution to the ESA (European Space Agency) Cloud Climate Change Initiative (CCI) project. For regional and local applications over Switzerland and when considering a period of more than 25 years, two satellite-based data records are available. Firstly, the AVHRR-based (Advanced Very High Resolution Radiometer) local area coverage cloud cover estimates provided by the University of Bern is available at 1 km spatial and daily temporal resolution but is subject to changing observation times related to the drifts in AVHRR overpasses. Secondly there exists a Meteosat-based (MVIRI + SEVIRI) Cloud Fractional Cover (CFC) estimate of MeteoSwiss as part of the EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) CM SAF (Satellite Application Facility on Climate Monitoring) at only 5 km spatial but 30 minute temporal resolution, thus resolving the full diurnal cycle.

Black: Stations with cloud observations; red: Jungfraujoch measurement location by PSI and ETH Zurich.

Long time series and their importance

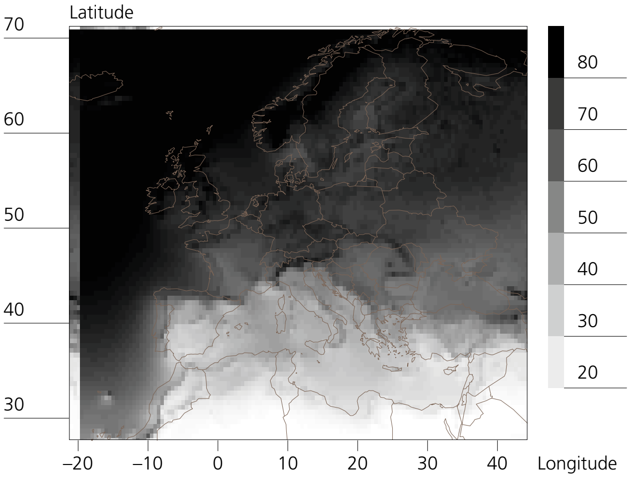
Manual cloud observations at 17 of the 26 stations of the OBS go back to the 19th century. They complete and extend information about long-term fluctuations in the anti-correlated sunshine duration time series back to 1864 (→ 2.6 Radiation). At the time of the last inventory in 2007, 63 stations were still operating. This decrease is documented in the MeteoSwiss "Messkonzept 2010/07 II" and is based on financial constraints. It is partially alleviated by a replacement of manual observations with cameras. However, cameras cannot be used for quantitative cloud observations which are needed to fulfill GCOS ECV requirements. With upcoming retirements of available human observers there is a risk of a gap in the climate data record until automated cloud observation methods become available. Manual cloud observation data for 5 OBS stations have been homogenised back to 1959 (figure below left) with inhomogeneities being removed resulting from different observers, changing observation times or station relocations.

Ground-based Cloud Observations



Homogenised 57-year-long time series of yearly cloud amount anomalies (%) with reference to the mean 1961–1990 at Meiringen, which anti-correlates well with corresponding sunshine duration time series.

Satellite-based Cloud Observations



Mean Cloud Amount (%) over Europe for 1982–2014 from the ESA CCI on Clouds project.

International integration

Long-term manual cloud observations of Switzerland are utilised together with regional and global SYNOP (Surface Synoptic Observations) archives for climate model evaluation and for building better satellite retrieval algorithms. MeteoSwiss has been part of the ESA CCI on Clouds project. It has exercised the AVHRR-based CC4CL (Community Cloud retrieval for Climate) dataset with ground-based cloud measurements over the complex Alpine terrain in Switzerland and over Europe (figure above right). As part of its engagement in the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) MeteoSwiss has developed its own cloud fractional cover climate data record from long-term Meteosat observations. The retrieval algorithm called "GEOSATCLIM" is now extended to other geostationary satellite sensors.

Resources required

The continuation of visual cloud observations of MeteoSwiss is only partly assured. The manual observation network decreased from 63 sites in 2007 to 26 sites in 2017 with no replacement available and only 17 reaching back to the 19th century. Continuation of Payerne and Säntis is threatened by staffing problems. Four additional sites will be closed in a few years. If and where a spatially-resolved and temporally-continuous climate data record of cloud cover and related cloud properties is demanded, financial resources and substantial scientific and technical development and innovation are required to transfer research-grade algorithms for automated ground- and satellite-based cloud measurement systems into an operational climate monitoring. The project-based measurements of aerosol-cloud interactions at the Jungfraujoch are funded through GAW-CH.

MeteoSwiss:
- **Manual observation network**
- **ESA CCI**
- **CM SAF**

ETH Zurich – Lab and Field Group

PSI – Aerosol Physics Group

PSI – CLACE GAW Plus

HFSJG – Jungfraujoch

ACTRIS

Legal basis

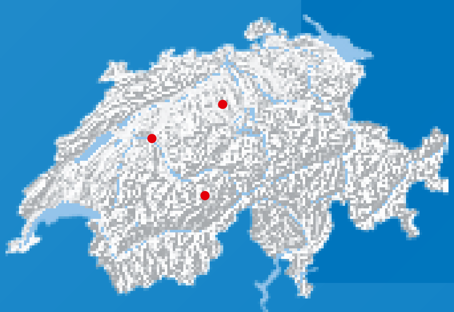
Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. This includes records of clouds in the atmosphere and the radiation balance at the top of the atmosphere. The federal authorities are also to participate in the recording, exchange and analysis of international meteorological and climatological data. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss is responsible for these tasks. Switzerland is a member of EUMETSAT (SR 0.425.43).

2.11 Carbon dioxide

Anthropogenic greenhouse gases are the main driver of climate change. Concentrations of greenhouse gases in the atmosphere have risen markedly since the industrial revolution. Levels of carbon dioxide (CO_2) – the most important greenhouse gas apart from water vapor – are now more than 40 % higher than in the preindustrial era.

Measurements in Switzerland

The national implementation of the emission reduction obligations under the international agreements is primarily covered by the CO_2 Act. While the first CO_2 Act, which entered into force in 2000, covered only CO_2 emissions, the revised CO_2 Act is addressing all greenhouse gas emissions (see chapter 4.2) regulated by the Kyoto Protocol. Nevertheless, CO_2 emissions from fossil fuel use contribute to approximately 75 % of the national total emissions. The Federal Office for the Environment (FOEN) calculates the CO_2 emissions from fossil fuel use based on the national energy statistics and the carbon content of the fuels (i. e. the CO_2 emission factors). In Switzerland, atmospheric concentrations of CO_2 have been measured by the Bern University Physics Institute on the Jungfraujoch since the end of 2000 and in Bern since October 2003. At the Jungfraujoch site, air samples are collected once per week in glass flasks between 06:30 and 07:30. This guarantees measurement of carbon dioxide concentrations in background air, avoiding contamination of samples with more heavily polluted lower layers of air through vertical advection. In addition to measurements of the CO_2 mole fraction, the ^{13}C and ^{18}O fractions ($\delta^{13}C$, $\delta^{18}O$) as well as the oxygen/nitrogen (O_2/N_2) ratio of the samples is determined. Since the end of 2004, continuous CO_2 and O_2 measurements have been made at Jungfraujoch. The accuracy of the CO_2 measurements is better than the World Meteorological Organization (WMO) target value of ± 0.1 parts per million (ppm). Since December 2008, these measurements have been complemented by continuous CO_2 isotope observations. Jungfraujoch CO_2 measurements act as terrestrial background since they represent mainly free tropospheric air concentrations originating from all over Europe. In addition, the tall tower in Beromünster was equipped with instrumentation for CO_2 sampling from five different height levels in November 2012.

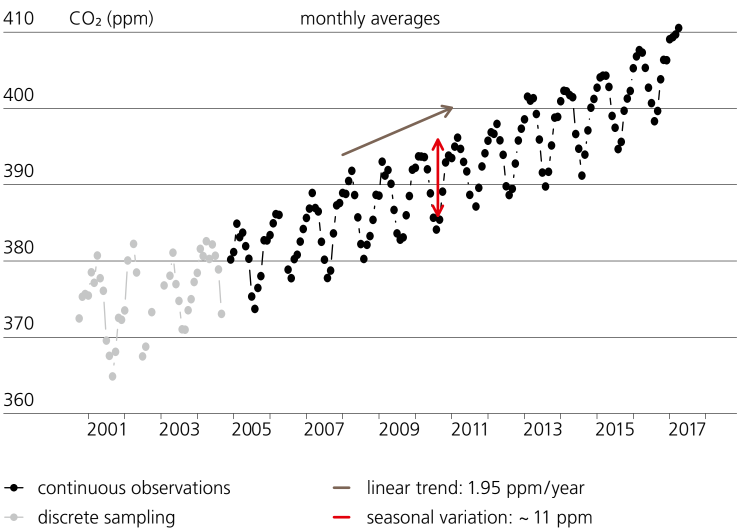


Locations of long-term carbon dioxide measurements in Switzerland (Jungfraujoch, Bern, and Beromünster).

Long time series and their importance

The increase in atmospheric carbon dioxide levels is a result of the rise in anthropogenic emissions from the burning of fossil fuels and changes in land use. The mixing ratio of CO_2 in the atmosphere is determined by the balance between emissions and uptake by the terrestrial biosphere and the oceans. Today, slightly more than half of the emissions are absorbed by the oceans and terrestrial ecosystems. The quantification of ocean and terrestrial sinks and their temporal variability is important for an improved understanding where the emitted carbon is distributed to. Carbon fluxes to and from the terrestrial biosphere and the oceans can be determined by combined measurements of O_2 (or O_2/N_2) and CO_2 as well as CO_2 isotopes. The comprehensive measurement programme at Jungfraujoch, which was initiated in 2000, is thus of major importance for GCOS.

Carbon dioxide measurements Jungfraujoch



Carbon dioxide concentrations measured at the Jungfraujoch station. Seasonal variation was found to be approximately 11 ppm (see red arrow). The positive CO_2 trend amounts to nearly 2 ppm per year (see brown line) over the past 15 years (2001–2016) and is identical to the trend observed from column-integrated CO_2 determinations (Schibig et al., 2016). An international flask intercomparison programme showed good agreement for CO_2 (van der Laan-Luijkx et al., 2013). Continuous collocated measurements performed by the University of Bern and Empa have been available since 2010. A comprehensive analysis of the first four years of parallel CO_2 measurements showed an excellent agreement (Schibig et al., 2015).

International integration

The Pan European Research Infrastructure Integrated Carbon Observation System (ICOS RI) was established in 2015. This infrastructure aims at providing harmonised and high-precision data on the carbon cycle and greenhouse gas budgets and perturbations. Long-term observations of the greenhouse gas emissions and their regional dynamics provided by ICOS RI will enable the evaluation of the mitigation activities against climate change. ICOS RI observes primarily carbon dioxide, methane and nitrous oxide. ICOS data will be openly available at the Carbon Portal (www.icos-cp.eu/).

Resources required

The funding of carbon dioxide measurements at the Jungfraujoch station is assured through the National Air Pollution Monitoring Network (NABEL) run by FOEN and the Swiss Federal Laboratories for Materials Science and Technology (Empa). In order to link in-situ with satellite retrievals, vertical profile data are needed for which there is currently no funding. The funding of carbon dioxide measurements at the Beromünster station was assured until 2015 through the Swiss National Science Foundation (SNSF) Sinergia CarboCount-CH. Funding for long-term monitoring is currently not available.

WMO World Data Centre for Greenhouse Gases

Legal basis

Switzerland ratified the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and its Doha Amendment, and the Paris Agreement. Under these international agreements, Switzerland has to report its national greenhouse gas emissions since 1990. FOEN is responsible for the annual compilation of the greenhouse gas inventory compliant with the reporting guidelines provided by the UNFCCC. At the national level, the legal basis for compiling greenhouse gas emissions is provided by the Federal Act on the Reduction of CO_2 Emissions (CO_2 Act; SR 641.71).

2.12 Other long-lived greenhouse gases

Besides carbon dioxide, methane, nitrous oxide and synthetic, fluorinated gases act as greenhouse gases. The concentration of these gases is constantly on the increase, which accentuates global warming. Their long-term monitoring is therefore crucial for national and international climate research and legislation.

Measurements in Switzerland

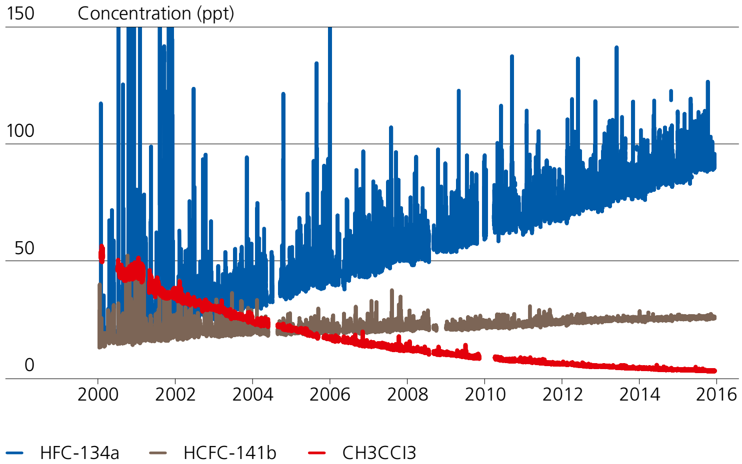
Within the framework of the National Air Pollution Monitoring Network (NABEL), the Swiss Federal Laboratories for Materials Science and Technology (Empa) and the Federal Office for the Environment (FOEN) have been measuring the atmospheric concentrations of the greenhouse gases methane (CH_4), nitrous oxide (N_2O) and sulfur hexafluoride (SF_6) in Switzerland at the Jungfraujoch station since 2005. Moreover, halogenated greenhouse gases such as chlorofluorocarbons (CFCs), and perfluorocarbons (PFCs) have been analysed under the project HALCLIM (Empa/FOEN). Together with the carbon dioxide (CO_2) measurements (→ 2.11 Carbon dioxide), these continuous, globally networked measurements record the trends for these substances. The readings can also be used in combination with atmospheric transport models to estimate Swiss and European emissions. This independently supports the emission estimates recorded by the individual countries within the scope of the Kyoto Protocol. Moreover, the CFCs and the hydrachlorofluoro-carbons (HCFCs) that are responsible for the stratospheric ozone depletion and affect the climate are also measured on the Jungfraujoch. Here, the measurements are used to identify remaining fugitive emissions of these substances, which are forbidden in the Montreal Protocol. Furthermore, the halogenated greenhouse gases CFCs, HCFCs and hydrofluorocarbons (HFCs) are measured during campaigns in Dübendorf every few years to track the development of local and regional emissions. The measurements at this upstream location can then be compared with those on the Jungfraujoch.

Stations with long-term monitoring of other greenhouse gases (besides CO_2). Red: GAW-station, Jungfraujoch; black: NABEL station, Dübendorf.

Long time series and their importance

Thanks to its high-alpine and central location at the heart of a heavily industrialised Europe and the low local pollution levels, the Jungfraujoch station is just the ticket for researching pollutant emissions. Due to the Jungfraujoch's unique location, the CH_4, N_2O and synthetic gas measurements recorded there are a key series for GCOS.

Selected synthetic greenhouse gases on the Jungfraujoch 2000 – 2016



Concentration of three synthetic greenhouse gases on the Jungfraujoch. The decrease in the solvent 1,1,1-trichloroethane (CH3CCl3, red), forbidden in the Montreal Protocol, is a clear indication of the ban's success (Reimann et al., 2005). The foaming agent HCFC-141b (brown), which has been banned since 2003, also reveals declining peak concentrations on the Jungfraujoch (Derwent et al., 2007). Emissions outside Europe, however, are causing a continued increase. HFC-134a (blue), which primarily enters the atmosphere through losses when used as a coolant, displays a steep increase (Carpenter and Reimann, 2014).

International integration

The Jungfraujoch station plays a key role in monitoring the atmospheric composition. The data is regularly communicated to the World Data Center for Greenhouse Gases (WDCGG) in Japan. Moreover, the station is part of the renowned Advanced Global Atmospheric Gases Experiment (AGAGE) measuring network. The measurements in AGAGE are based on the same calibration scale and measuring technique, which enables comparable, precise measurements with high temporal resolution.

Resources required

Measurements of atmospheric concentrations of the greenhouse gases methane and nitrous oxide at Jungfraujoch station are currently supported by FOEN and the European infrastructure project ICOS. Measurements of halogenated greenhouse gas are currently funded under the Swiss HALCLIM project. The goal is to acquire long-term funding.

Empa – Climate Gases

Legal basis

Switzerland ratified the United Nations Framework Conference on Climate Change (UNFCCC), the Kyoto Protocol and its Doha Amendment, and the Paris Agreement. Switzerland has therefore made a commitment to report national CO_2, CH_4, N_2O and long-lived fluorinated substance emissions. The FOEN compiles the greenhouse gas inventory according to the UNFCCC guidelines using the Federal Act on the Reduction of CO_2 Emissions (CO_2 Act; SR 641.71) as the legal basis. In addition, the Montreal Protocol governs halogenated substances, which, besides their impact as greenhouse gases, also contribute towards the depletion of the ozone layer (SR 0.814.021). The handling of these substances is regulated in the Chemical Risk Reduction Ordinance (ChemRRV, SR 814.81).

2.13 Ozone

The ozone layer in the stratosphere filters out a large proportion of the sun's harmful ultraviolet rays. Monitoring of stratospheric ozone is therefore extremely important, especially in view of the ozone layer depletion at the end of the 20th century. Understanding the impact of a changing climate on the ozone layer and vice versa also has a high priority.

Measurements in Switzerland

The Federal Office of Meteorology and Climatology MeteoSwiss uses a variety of instruments to monitor ozone concentrations in the atmosphere over Switzerland. At the Light Climatic Observatory (LKO) in Arosa, total ozone has been measured continuously since 1926 using Dobson and Brewer spectrophotometers. These instruments measure the total ozone column above Arosa. The three Dobson instruments were automated in recent years. However, no changes were made to the optics of the instruments to prevent any break in the long-term measurements series.

Additionally, ozone profiles are derived using various measurement techniques. At Arosa, the Umkehr method has been used since 1956 to obtain a coarse ozone profile (6–9 vertical layers) from 15 to 50 km. At Payerne, radio soundings have been used since 1966 to record in situ ozone profiles with a high vertical resolution (approx. 150 m) up to an altitude of about 33 km. Ozone sondes are attached to the aerological balloons (→ 2.9 Upper-air water vapor) three times a week and record the ozone partial pressure during the ascent.

Since November 1994, the Institute of Applied Physics (IAP) at the University of Bern has operated a Ground-Based Millimeter Wave Ozone Spectrometer (GROMOS) to measure stratospheric and mesospheric ozone at altitudes ranging from 20 to 70 km. A second-generation instrument – the Stratospheric Ozone Monitoring Radiometer (SOMORA) – has been used operationally at Payerne by MeteoSwiss since 2002. Their data acquisition system has been upgraded recently to improve the data quality.

Presently, satellite measurements play an important role in recording the global distribution of ozone in the high atmosphere. The extensive ozone monitoring program in Switzerland makes a decisive contribution to the validation of satellite-based products. As an example, data of Swiss ozone sondes was used to create a database of back/forward trajectories to improve the coincidence between ground-based and satellite measurements in support of the European Space Agency Climate Change Initiative (ESA CCI) "Ozone" project. Similarly, the Swiss ozone data allow to calibrate and validate simulation results of climate models.

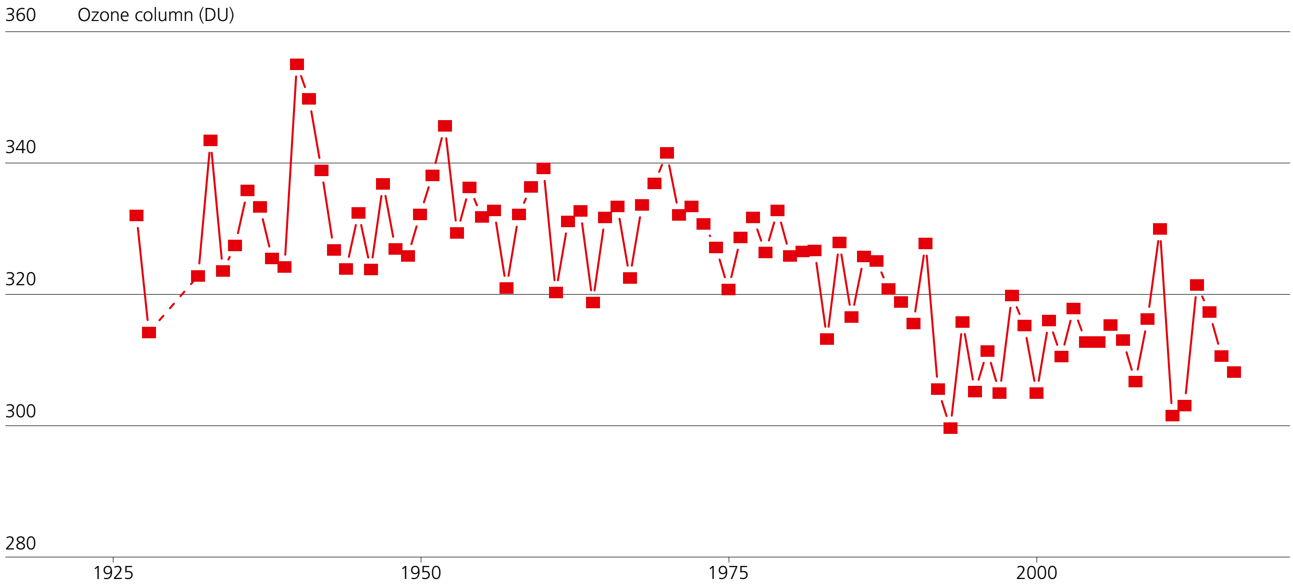
Total ozone measurements and ozone profiles active sites: at Payerne and Arosa by MeteoSwiss (red), at Davos by PMOD/WRC (brown) and at the University of Bern by IAP (black).

Long time series and their importance – Total ozone

Switzerland has a long history of ozone monitoring, going back to the first measurements at Arosa in 1926. The ozone column has been determined on virtually every sunny day without interruption until now. Almost from the beginning of the time series, measurements have been carried out using the same type of instrument (Dobson). The global network for the monitoring of the ozone layer is still partly based on Dobson instruments. In the 1980s, a second type of instrument (Brewer) was developed in Canada. MeteoSwiss used its first Brewer instrument at Arosa in 1988. In subsequent years, two more Brewer instruments were installed. The ozone column over Arosa is currently measured by three Dobson and three Brewer spectrophotometers.

To date, the global networks of Dobson and Brewer instruments have maintained independent calibration procedures. The former is based on the US reference instrument D083 and the latter on the reference triad in Toronto. Both networks produce similar results with differences between 1% and 3 % depending on the season and the station latitude. Recent accurate ozone cross-section measurements and the use of real stratospheric temperature have significantly decreased these systematic differences to less than 1%.

Total ozone above Arosa for the period 1925–2016



Dobson spectrophotometers have been used to measure the ozone column above Arosa for 90 years. The time series are mainly based on the three successive Dobson models D2, D15 and D101, and also on the redundant devices D7 and D62. The homogenised time series shown here was carefully derived using data from the various Dobson instruments (Staehelin et al., 1998; Zanis et al., 2006; MeteoSwiss, 2007). This is the world's longest time series based on Dobson instruments. It makes it possible to study the state of the ozone layer before and after the beginning of anthropogenic influences, as well as interactions between ozone and the climate.

Long time series and their importance – Ozone profile 0–33 km

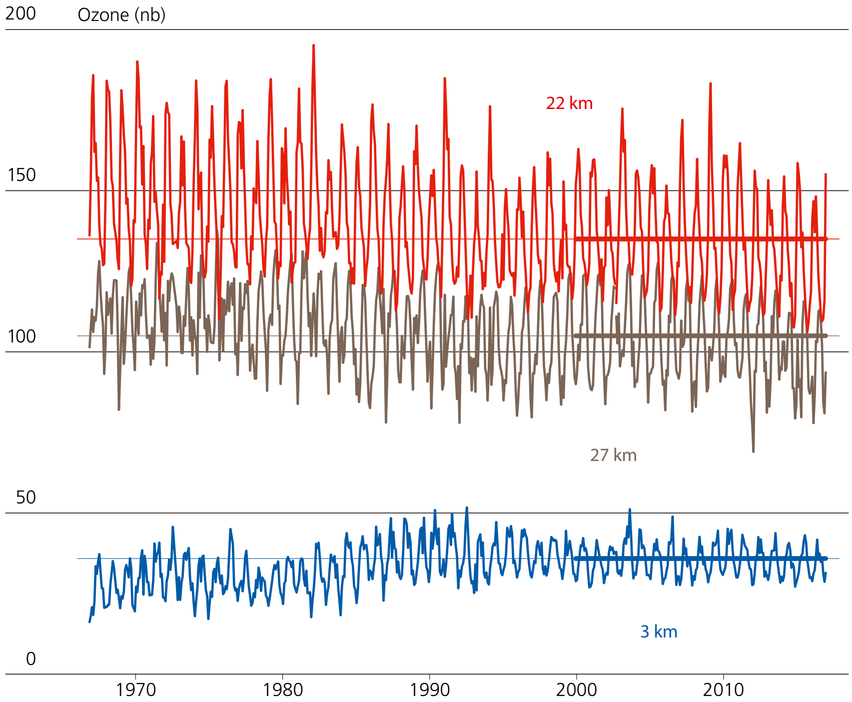
Information on the vertical distribution of ozone is important since the processes of ozone production and destruction differ markedly in the troposphere and the stratosphere.

The first estimates of the ozone profile in the atmosphere were obtained by means of special Dobson measurements in the 1930s. The so-called Umkehr measurements have to be performed as the sun rises (sets) up to (from) 30° above the horizon. This method of measurement yields only 6–9 layers, at altitudes between approx. 5 and 50 km. In addition, a rather complex mathematical processing is required. For this reason, measurements could not be carried out on an operational basis until the 1950s. At Arosa, the Umkehr ozone profile series was initiated with the Dobson D15 instrument. In 1980, the automated D51 instrument came into operation.

The Arosa Umkehr measurement series are the world's longest and at the same time one of the few sources of information on vertical ozone distribution in the years 1956–1970, before the start of satellite observations. Since 1988, the fully automatic Brewer B40 instrument has similarly produced Umkehr ozone profiles. Major efforts are currently under way to homogenise these multiyear parallel measurement series.

In the late 1960s, in situ ozone profiles started to be measured using small ozone sondes. These measurements were first performed for two years at Thalwil (1966/67), and since 1968, the ozone sondes have been associated three times a week (Monday, Wednesday, Friday) to the meteorological radiosonde at Payerne. The in situ recorded ozone profiles have a high vertical resolution (currently about 150 m) between the Earth's surface and an altitude of 30–35 km.

Mean ozone concentrations at three altitudes for the period 1967–2016

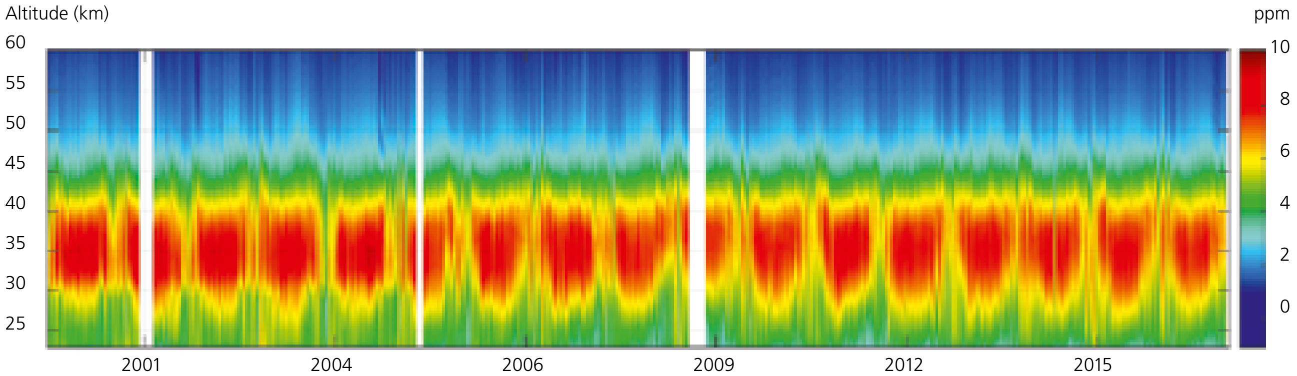


Time series of mean monthly ozone concentrations at three altitudes for the period 1967–2016 measured by ozone sondes. Similar series based on Umkehr measurements at Arosa extend as far back as 1956, and series recorded by microwave radiometers at Bern and Payerne go back to 1995. The complementarity of these independent series is unique, allowing cross-comparisons to be made so as to assure the best possible quality of these ground-based climate-relevant measurement series. Accordingly, these Swiss ozone series mentioned above are analyzed in scientific publications worldwide, especially for the Scientific Assessment of Ozone Depletion reports published every four years by the WMO/UN Environment.

Long time series and their importance – Ozone profile 20–70 km

In the early 1990s, a microwave radiometer known as the GROMOS was developed at the Bern University IAP. Since 1995, it has been used to determine the ozone profile about every 30 minutes. The second-generation SOMORA was tested in parallel to the GROMOS instrument at Bern from January 2000, and it has been used operationally by MeteoSwiss at Payerne since 2002. Covering an altitude range of 20–70 km and with a high temporal resolution, this more than 20 years long time series extends the ozone sounding information up to the upper stratosphere. New phenomena like the ozone daily cycle at high altitude (> 40 km) can be studied and compared to model simulations. The results are important to improve the satellite data validations at those high altitudes.

Ozone profile (20–60 km) measured over the Payerne region for the period 2000–2016



Homogenised time series of ozone profiles determined by the SOMORA microwave radiometer at Bern (2000-2002) and Payerne (since 2002), part of the NDACC (Network for the Detection of Atmospheric Composition Change) network. The volume mixing ratio (VMR) of the trace gas ozone reaches its peak at an altitude of around 35km during the summer season, with values of approx. 8 parts per million (ppm). The ozone profiles also vary on daily to monthly timescales as a result of atmospheric transport processes. The annual cycle is clearly apparent in the distribution.

International integration

Ozone measurements from Arosa (Dobson and Brewer) and Payerne (ozone sondes) are regularly uploaded to the World Ozone and UV Radiation Data Center (WOUDC) in Toronto, as well as to the European Brewer Network (EUBREWNET) database (developed within the COST action 1207). These data together with data from the two microwave radiometers (GROMOS and SOMORA) are also fed into the Network for the Detection of Atmospheric Composition Change (NDACC). All the time series described above will be of major importance for future ozone monitoring. Internationally, the ozone measurements are increasingly integrated into models for use in the Integrated Global Atmospheric Chemistry Observation (IGACO) Strategy of the Global Atmosphere Watch (GAW) programme.

Under the joint EU/ESA environmental monitoring initiative – Copernicus Atmosphere Monitoring Service (CAMS) – global and regional ozone maps are generated daily by the European Centre of Medium-Range Weather Forecasts (ECMWF) on an operational basis.

Resources required

Ozone monitoring operations at Payerne and Arosa are assured under the legal mandate of MeteoSwiss and through Switzerland's participation in the World Meteorological Organization (WMO) GAW programme.

MeteoSwiss – Ozone measurements

Institute of Applied Physics – University of Bern

World Calibration Center – Ultraviolet Section (WCC-UV)

Legal basis

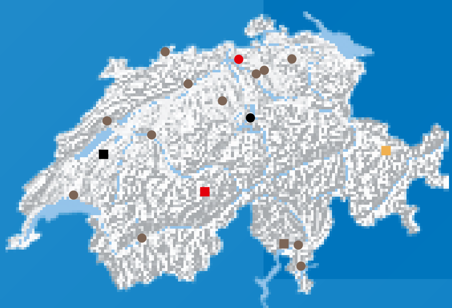
Since 1985, the thinning of the ozone layer by ozone-depleting substances such as chlorofluorocarbons has been closely monitored under the Vienna Convention for the Protection of the Ozone Layer (Vienna Convention, SR 0.814.02) and the Montreal Protocol (SR 0.814.021). Worldwide, ozone measurements are coordinated by the GAW programme of the WMO. Switzerland is a member of the WMO (SR 0.429.01) and participates to the GAW programme in accordance with the Federal Council Decree of 25 November 1994. As the lead agency vis-à-vis the WMO, MeteoSwiss is responsible for Switzerland's contribution to the GAW programme.

2.14 Aerosols

Aerosols influence climate directly through aerosol-radiation interactions and indirectly through aerosol-cloud interactions. Overall, these effects cause a cooling. However, limited understanding of the aerosol effects remains the largest source of uncertainty in radiative forcing estimates. Besides, aerosols are known to cause adverse health effects.

Measurements in Switzerland

As part of Switzerland's contribution to the Global Atmosphere Watch (GAW) programme, continuous aerosol measurements are carried out by the Paul Scherrer Institute (PSI), on behalf of the Federal Office of Meteorology and Climatology MeteoSwiss, at the High Altitude Research Station Jungfraujoch (HFSJG). The variables measured include optical properties, total number and size distribution, cloud condensation nuclei and chemical composition. Measurements of aerosol mass concentration (PM10 and PM2.5), elemental and organic carbon (EC and OC) in PM2.5 and particle number concentration are carried out at several sites within the NABEL programme (→ 2.15 Ozone and aerosol precursors). In addition, at the 4 SACRaM stations (→ 2.6 Radiation) aerosol optical depth (AOD) is measured by spectrophotometers. A further category consists of the AErosol RObotic NETwork (AERONET) programme coordinating a network of approx. 400 ground-based aerosol remote sensing stations worldwide, two of which are located in Switzerland, at Lägeren (since 2003; run by the University of Bern) and Davos (since 2005; run by the PMOD/WRC, who also hosts the World Optical Depth Research and Calibration Center (WORCC); (→ 6.3 Other centres). The Payerne Ralmo Lidar is part of the European Aerosol Research Lidar Network (EARLINET), which belongs, together with the in-situ aerosol and trace gas measurements, to the ACTRIS research infrastructure. Valuable additional aerosol data (e.g. AOD) are provided by passive satellite measurements from SEVIRI, MODIS and MISR, as well as the latest active satellite measurements from CALIPSO and CLOUDSAT.

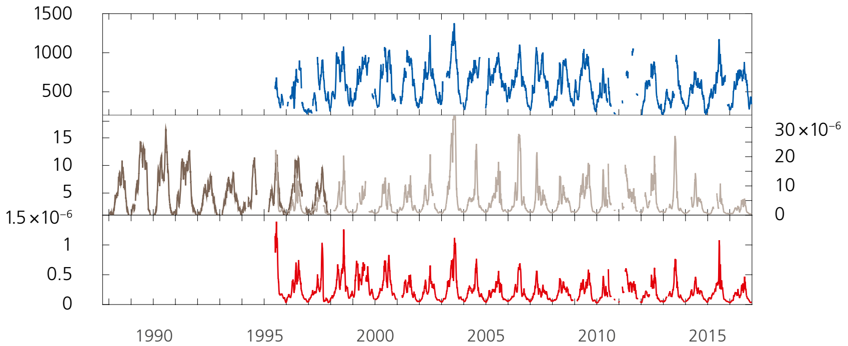


Aerosol monitoring stations: Jungfraujoch (red square), Payerne (black square), Locarno-Monti (light yellow square), Davos (orange square) are all SACRam stations. Lägeren (orange triangle) and Davos are AERONET stations. Jungfraujoch, Payerne and Rigi-Seebodenalp (black dot) are GAW stations, Payerne and Rigi-Seebodenalp are also EMEP stations. NABEL stations are represented by brown dots, including Jungfraujoch, Payerne, Davos, and Rigi-Seebodenalp.

Long time series and their importance

From 1973, total suspended particle mass concentrations have been measured at three sites including Jungfraujoch within a programme preceding NABEL, followed by PM10 and PM2.5 measurements in 1997 and 1998. Measurements of particle number concentrations and elemental and organic carbon in PM2.5 started in 2004 as well as aerosol light absorption measurements in 2007. The PSI has carried out continuous measurements of aerosol variables at the Jungfraujoch site since 1988. The first variable measured by the PSI was the surface concentration of aerosol particles. In 1995, PSI monitoring was integrated into the GAW programme and expanded to cover the most relevant optical variables, followed by further parameters at later stages. Monitoring of aerosol optical depth (AOD) at multiple wavelengths has been carried out since over two decades within the SACRaM network. At all stations, GAW Precision Filter Radiometers have been installed since the early 2000s providing AOD at 9 wavelengths between 368 nm and 1024 nm. At Davos and Payerne, earlier sun-photometer versions have provided AOD since the early 1990s. The Raman lidar at Payerne has provided vertical profiles of the optical properties of aerosols since the end of 2007. This constitutes one of the most extensive datasets of vertical profiles of aerosol properties.

Time series of aerosol concentration and optical properties at the JFJ



Among all long-term aerosol monitoring sites existing worldwide, the JFJ belongs to the small number of sites where both free tropospheric (FT) conditions and influences from planetary boundary layer injections can be observed. The temporal evolution of various aerosol parameters continuously measured for at least 20 years shows that FT air masses dominate during winter while vertical transport of more polluted air from the PBL often occurs during spring and summer. This data set is also useful for the detection of recurring or singular aerosol transport events such as Saharan dust events, forest fires or volcanic aerosol plume (Bukowiecki et al., 2016).

International integration

Since 2006, the Jungfraujoch site has been one of the 25 global GAW stations worldwide delivering data to the World Data Center for Aerosol (WDCA) and the EBAS hosted by NILU. It frequently hosts international experiments focusing on aerosol-cloud interactions involving e.g. the INUIT consortium. The Jungfraujoch aerosol research platform and the Raman Lidar at Payerne are also part of the ACTRIS network, which is now in the preparatory phase to become a European research infrastructure, thereby integrating the previous EU infrastructure projects EUSAAR, EARLINET and CLOUDNET. The NABEL network is embedded in the European Monitoring and Evaluation Programme (EMEP) and shares data with the European Environmental Agency (EEA). Since 2000 PMOD/WRC has been responsible for the GAW-PFR network with 12 main and 17 associate stations worldwide. The GAW-PFR (Global Atmosphere Watch – Precision Filter Radiometers) network is advised by the WMO-SAG (World Meteorological Organization – Scientific Advisory Group for aerosols). The Raman lidar of MeteoSwiss is part of the European Aerosol Research Lidar Network, EARLINET, within ACTRIS, and contributes to the Network for the Detection of Atmospheric Composition Change, NDACC.

Resources required

The funding of the aerosol monitoring at Jungfraujoch is assured through the Swiss GAW programme. ACTRIS provides additional financial resources for the international integration and collaborative research. Once ACTRIS is European Research Infrastructure, this contribution will need to be replaced by a national research infrastructure. AERONET measurements at the Lägeren site and in Davos are funded by the University of Bern and the PMOD/WRC respectively. Funding of the NABEL is assured through contributions from the Federal Office for the Environment (FOEN) and Empa. Operation of the Raman lidar at the regional center of Payerne is to be regarded as assured under the legal mandate of MeteoSwiss as part of its legal mandate and its commitment to GRUAN.

WMO – GAW Aerosol Research

ACTRIS:
- **Home**
- **Data Policy**

EBAS

Empa – NABEL

WDCA

EARLINET

NASA Goddard Space Flight Center

Legal basis

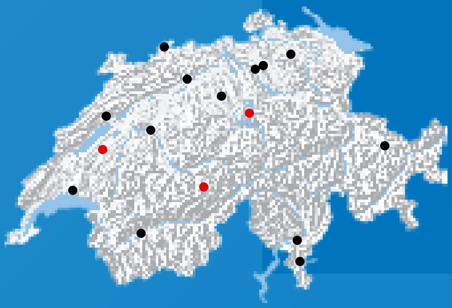
Switzerland is a member of the World Meteorological Organization (SR 0.429.01) and participates in the WMO GAW programme in accordance with the Federal Council Decree of 25 November 1994. As the lead agency vis-à-vis the WMO, MeteoSwiss is responsible for the GAW programme in Switzerland. Limits for mass concentration of aerosols are specified in the Ordinance on Air Pollution Control (OAPC, SR 814.318.142.1). The FOEN and the cantons are responsible for the monitoring of air quality at national and regional scales (→ 2.15 Ozone and aerosol precursors).

2.15 Ozone and aerosol precursors

Reactive trace gases with indirect effects on climate – such as carbon monoxide (CO), nitrogen oxides (NO_x) and Volatile Organic Compounds (VOCs excluding methane) – do no directly affect the Earth's radiative budget but they act as precursors of radiatively active species such as ozone and aerosols. Furthermore, through their influence on hydroxyl radical (OH) concentrations, the most important oxidant of the atmosphere, they affect the lifetime of several greenhouse gases such as methane.

Measurements in Switzerland

The National Air Pollution Monitoring Network (NABEL), a joint project of the Federal Office for the Environment (FOEN) and the Swiss Federal Laboratories for Materials Science and Technology (Empa), is an important element of air pollution control in Switzerland. Within the NABEL network air pollution is measured at 16 sites, representing the whole range of typical air pollution situations from urban environments to the locally unpolluted regime of high-alpine areas. The NABEL monitoring programme covers gaseous pollutants (ozone (O_3), nitrogen monoxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), CO, VOCs, ammonia (NH_3)), Particulate Matter (PM10, PM2.5, particle number, particle size distribution, carbonaceous particle fraction and other key constituents), as well as dust deposition and constituents in precipitation. The measurement programme is continually adapted to meet new requirements and to include new variables and measurement technologies. The long-term, precise and internationally comparable time series allow the assessment of air quality trends and the evaluation of the effectiveness of air pollution control measures. The time series can be used for estimation of the impacts of gaseous air pollutants and aerosol particles on human health and the environment. NABEL thus provides essential information for policymakers. From the data collected, knowledge of sources, sinks and atmospheric chemical processes can be obtained. Particularly, the combination of measurements and modelling is highly valuable as it allows capturing the spatiotemporal variation of air pollutants on regional and urban scales.



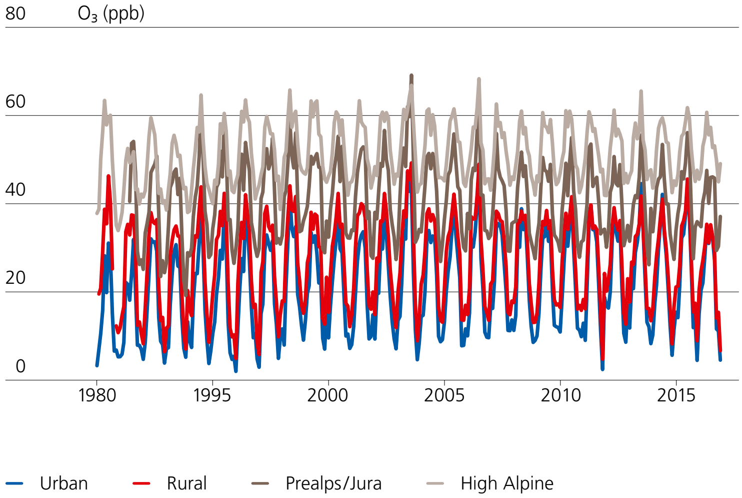
Black: Location of NABEL stations. Red: NABEL stations participating in the GAW programme and/or the EMEP.

Today, in-situ measurements still form the backbone of our monitoring of the ECV precursors CO, NO_x and VOCs. Satellite observations are still suffering from limited spatial resolution and from the inability to take observations under cloudy conditions. Nevertheless, the importance of satellite observations will continue to increase especially with the planned new sensors Sentinel-5P, Sentinel-4 and Sentinel-5 of the European Copernicus programme. These satellites will provide measurements with significantly enhanced spatial resolution (approx. 7 × 7 km) and, in case of the geostationary satellite Sentinel-4, with nearly continuous coverage during daytime.

Long time series and their importance

In 1969, monitoring of air pollutants was initiated by Empa at three stations in Switzerland (Dübendorf, Payerne, Locarno-Monti) under a joint international programme involving 11 countries. In subsequent years, measurements were also started at the Jungfraujoch station. The NABEL network came into operation in stages from 1979 onwards. From 1989 to 1991, the network was modernised and expanded from 8 to 16 stations. The longest ongoing time series is that for SO_2 at Payerne (since 1969). Other long series include those for suspended particulates at the stations Dübendorf and Payerne (since 1973), and for SO_2 and suspended particulates at the high-altitude Jungfraujoch station (since 1973).

Ground-level ozone in the northern part of Switzerland 1990–2016 for different environments



Ozone is an important anthropogenic greenhouse gas. The figure shows how ozone concentrations in the air have developed since 1990 (monthly means). For all four station types, the mean values increased in the 1990s and started to level off or to decrease since then. In the urban areas, the increase of O_3 is mainly due to reductions in nitrogen oxide emissions. The rise in ozone concentrations at the elevated rural (Prealps/Jura) and high-alpine stations suggests an increase in background levels of ozone from anthropogenic sources in the northern hemisphere. Peak ozone concentrations have declined since 1990 at all station types except urban roadside and high-alpine (not shown).

International integration

The NABEL network exchanges data with several international monitoring programmes. The rural stations Payerne and Rigi are part of the European Monitoring and Evaluation Programme (EMEP), under the United Nations Economic Commission for Europe (UNECE) Convention on long-range transboundary air pollution. The NABEL measurements also contribute to the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) programme: the Jungfraujoch site is a global, and the Rigi site is a regional GAW station. Furthermore, Jungfraujoch is a class 1 station of the Integrated Carbon Observation System (ICOS). The NABEL network also supplies data to the European Environment Information and Observation Network (Eionet). Eionet was established by the European Environment Agency (EEA) and includes in particular stations in urban and suburban areas across Europe. Measurements from the NABEL stations are also used for air quality forecasting and data assimilation purposes, e. g. within the Copernicus Atmosphere Monitoring Service (CAMS).

Resources required

Funding of the NABEL network is assured in the long term the long term through contributions from the FOEN and Empa.

Federal Office for the Environment FOEN – Topic Air

Empa – NABEL

Legal basis

Switzerland's air pollution control policy is based on the Federal Act on the Protection of the Environment (EPA, SR 814.01), which requires the federal and cantonal authorities to monitor environmental impacts and review the effectiveness of measures taken under this legislation. Under the Ordinance on Air Pollution Control (OAPC, SR 814.318.142.1), FOEN is responsible for determining the current state and development of air pollution on a nationwide basis. Swiss air pollution control policy thus complies with international accords (UNECE Geneva Convention LRTAP, SR 0.814.32) and subsequent protocols. Although indirectly relevant for climate, emissions of these precursors are not regulated under any climate treaties.

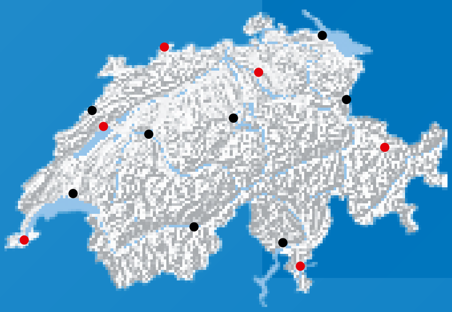
2.16 Pollen

Pollen production, release and dispersal are mainly controlled by meteorological conditions. Some 20% of the Swiss population suffer from allergy to pollen. Moreover, airborne pollen is an important indicator of climate change impact. Changes in pollen levels may affect allergy sensitisation and spectrum, and reveal the spread of new allergenic plant species.

Measurements in Switzerland

In Switzerland, from the late 1960s, airborne pollen has been analysed at a few sites on a private basis. From 1982, pollen monitoring was coordinated by the Swiss Working Group on Aerobiology (now Swiss Society of Aerobiology). Since 1993, the Federal Office of Meteorology and Climatology MeteoSwiss has been responsible responsible for operating the National Pollen Monitoring Network. This network comprises 14 stations, most of them located near built-up areas, and stations for ragweed monitoring. Most of the stations are operated during the vegetation period, some all year round. Every station is equipped with a 7-day recording volumetric pollen trap. Each week, 47 pollen taxa are manually identified under the microscope at the MeteoSwiss laboratory in Payerne, and daily pollen concentrations reported (number of pollen grains per m³ air). Data are used for informing the public, the health care professionals and as input for climatology, forecasts and models. In Switzerland, the pollen types responsible for the major pollen allergies are from the following plant families: birch family (hazel and alder, flowering in late winter; birch and hornbeam in spring), olive family (ash in spring), beech family (beech and oak), grasses in late spring and summer, and aster family (mugwort, ragweed) in late summer. In the late 1990s, the spread of ragweed was detected at an early stage thanks to the pollen monitoring. Effective plant control measures could then be taken. Pollen concentrations vary according to the phenology of the emitting plants and the meteorological conditions, and from one region to another, according to the local and regional vegetation. Pollen can be transported by wind over very long distances and cause allergies far away from its source.

Recent research has shown that automatic pollen taxa detection providing real time data at high temporal resolution will be possible with air flow cytometers. This is the basis for the automation of measurements (Crouzy et al. 2016).

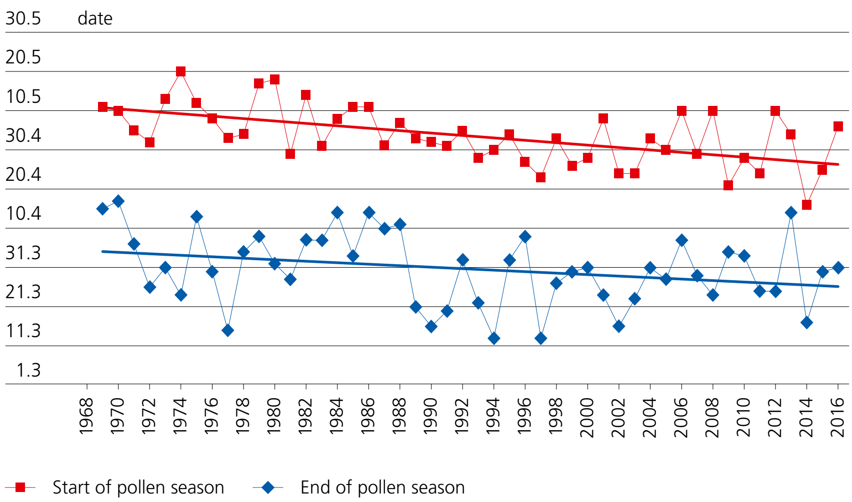


The Swiss National Pollen Monitoring Network comprises 14 stations (black and red). The selection of 6 (red) of the 14 sites shows the longest data series in various climate and vegetation regions.

Long time series and their importance

Switzerland's first pollen analyses were carried out in Basel in 1969. Since the 1980s other pollen monitoring stations have successively started measurements: Neuchâtel and Genève (1979), Zurich (1981), Davos (1983) and Lugano (1985), at which more than 40 pollen types are determined. This selection of stations with the longest datasets provides coverage of some important climate and vegetation regions: northern foot of Jura Mountains (Basel), North-East (Zurich), Plateau (Neuchâtel), South-West (Genève), Alps (Davos) and South of the Alps (Lugano). The distribution of the stations in the different bio-climatic regions is important for the detection of future changes in pollen occurrence and possible spread of invasives (main routes are from South, South-West and North-West).

Birch pollen in Basel 1969–2016



The beginning of the birch pollen season depends on temperature levels in February and March. The higher the air temperature, the earlier the onset of birch flowering. Rising temperatures have brought birch flowering forward by a significant amount (10 days) since 1969. Over the same period, the end of flowering has been brought forward by 15 days. The intensity and duration of the pollen season are highly dependent on environmental factors, meteorological and climatological conditions being among the most important.

International integration

In Europe, there is at least one pollen monitoring network in each country. The European Aerobiology Society (EAS) was created in 2008 to serve as information and exchange platform. In addition, the EAS provides an interface with the European Institutions. MeteoSwiss collaborators were among the EAS founding members and are still active contributors. The world umbrella association is the International Association for Aerobiology.

Resources required

The continuation of pollen monitoring is assured under the legal mandate of MeteoSwiss. Automation of the measurement network is planned for the coming years.

MeteoSwiss – Pollen monitoring network

aha! Allergiezentrum Schweiz

Ambrosia

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the authorities are required to record meteorological and climatological data continuously throughout Switzerland. They are also responsible for measures contributing to the long-term preservation of an intact and safe environment. Pollen concentrations are made available by the responsible agency, MeteoSwiss. The Federal Office of Public Health also provides information on the spread of ragweed (Ambrosia artemisiifolia). The Federal Office of Agriculture, the Federal Office for the Environment and the cantons are involved in control of this plant producing highly allergenic pollen.

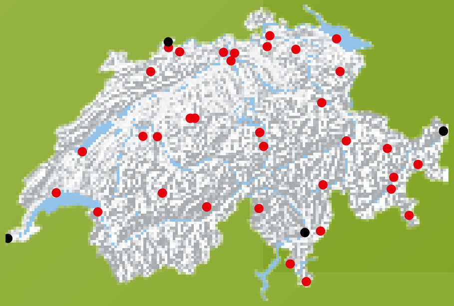
3.1 Rivers

Changes in climate affect the water cycle in various ways. In turn, possible shifts in hydrological variables, including river discharge, lake and river water levels and water temperature in rivers, have consequences for water management sectors such as water resource use, water protection, and flood control.

Measurements in Switzerland – River Discharge

The Swiss river discharge monitoring networks currently consist of around 200 federal stations, about 300 cantonal stations on smaller surface waters and a number of privately operated stations. The Federal Office for the Environment (FOEN) monitors water flows and – in cooperation with the Swiss Federal Institute of Aquatic Science and Technology (Eawag) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) – water quality in Swiss waterbodies. Data collection takes the form of continuous measurements at permanent hydrometric stations and individual measurements at temporary sites. Surface water measurements fall into the following categories: the basic monitoring network, the National River Monitoring and Survey Programme (NADUF), the National Surface Water Quality Monitoring Programme (NAWA), water temperature, and sediment transport.

The basic monitoring network, which records water levels and discharge, goes back to the mid-nineteenth century. The status and trend of water quality in Swiss rivers is surveyed by the FOEN under the NADUF at 17 monitoring sites and jointly with the cantons under the NAWA at 111 monitoring sites. In addition to monitoring changes in water constituents (e.g. nutrients and micropollutants), the surveys are intended to evaluate the effectiveness of water protection measures. The water quality analyses therefore focus on longer-term changes rather than seasonal fluctuations. In the 1950s, Hydrological Study Areas (HUG) were first designated in Switzerland; over the years, further catchment areas have been added. The approximately 40 gauging stations in these areas are part of the basic monitoring network. The aim of the HUG studies is to observe long-term changes in the water regime in near-natural catchment areas across the country's various climatic regions.



The selection of Switzerland's most important discharge series comprises various monitoring networks (red), including border stations (black).

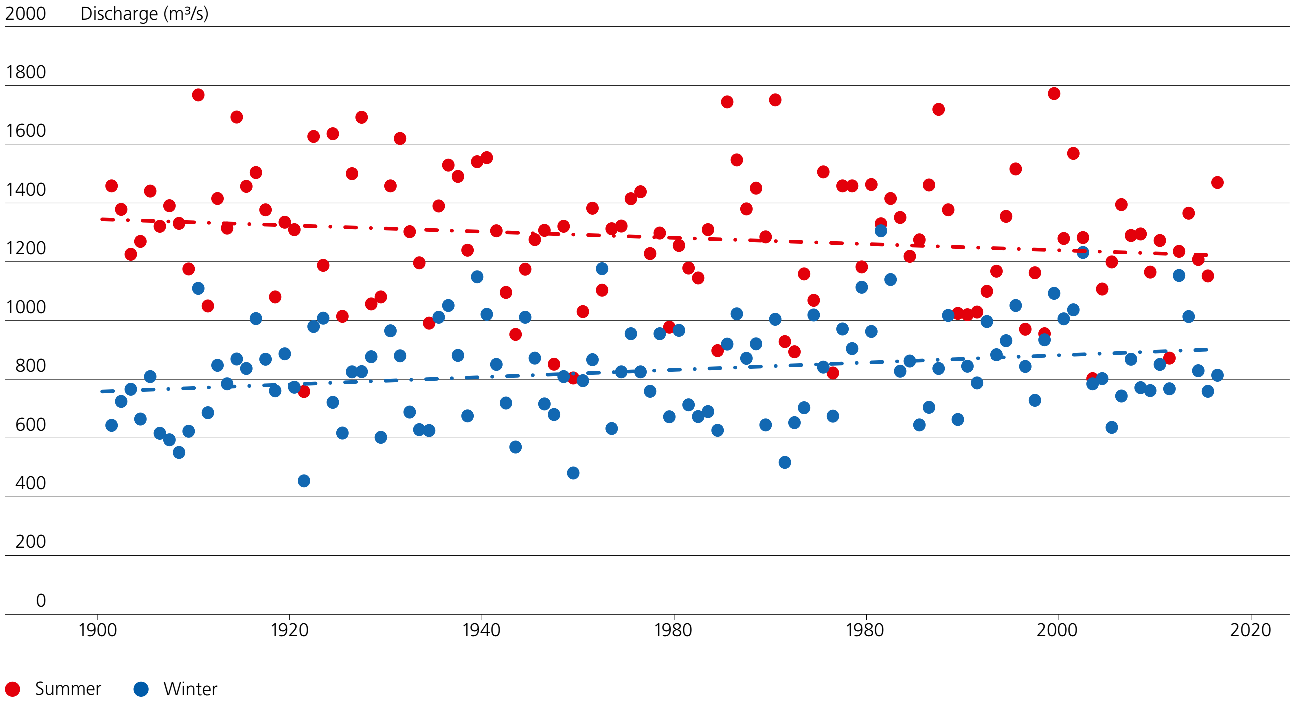
abbr.

Long time series and their importance – River Discharge

Data (including discharge) from all the gauging stations operated by the FOEN has been published online. The longest continuous daily discharge series come from stations on the Rhine (1891 Basel), the Thur (1904 Andelfingen) and the Birs (1917 Münchenstein). Among the oldest gauging stations are four border stations (Rhein-Basel, Rhône-Chancy, Ticino-Bellinzona, Inn-Martina), which record discharge from Switzerland and, in some cases, belong to the NADUF programme. The HUG gauging stations belonging to the basic monitoring network have an average time series length of almost 50 years. The HUG areas were selected with a view to covering all types of hydrological regime in Switzerland.

Mean seasonal discharge for the station Rhein-Basel

Annual discharge is subject to very wide variations



No clear trends are apparent from a study of the 20th century. If the two halves of the year are compared, it is apparent that mean discharge tends to rise in winter and fall in summer. Runoff reacts sensitively to climate change: the rise in air temperatures observed since the 19th century promotes glacier melt and increases evaporation. Winter discharge increases because in an increasingly warm climate more precipitation falls as rain in the winter and less is temporarily stored as snow or ice. This means that some of the water which fills the reservoirs in summer as the snow and ice melt is lost, and summer discharge tends to decline.

Measurements in Switzerland – River Temperature

The river temperature monitoring network in Switzerland currently comprises 79 federal stations and more than 500 cantonal stations. Along large rivers, most of the federal stations are evenly distributed. Two stations are in operation with the Federal Republic of Germany (Rhein-Basel) and with the Principality of Liechtenstein (Rhein-Ruggel).

Since the 1960s, the Swiss Confederation has been operating a monitoring system to measure water temperature in the river network. In the beginning, the intention was to monitor the water temperature in large streams in anticipation of the planned expansion of nuclear power plants and their influence on river temperature due to their cooling water systems. Later, in the 1990s, aspects of the aquatic ecosystems became more important and stations along smaller rivers were included in the federal network. Currently the water temperature network has three main additional observation challenges: climate change, thermic water use and knowledge improvement of drivers-interaction in the water temperature system.

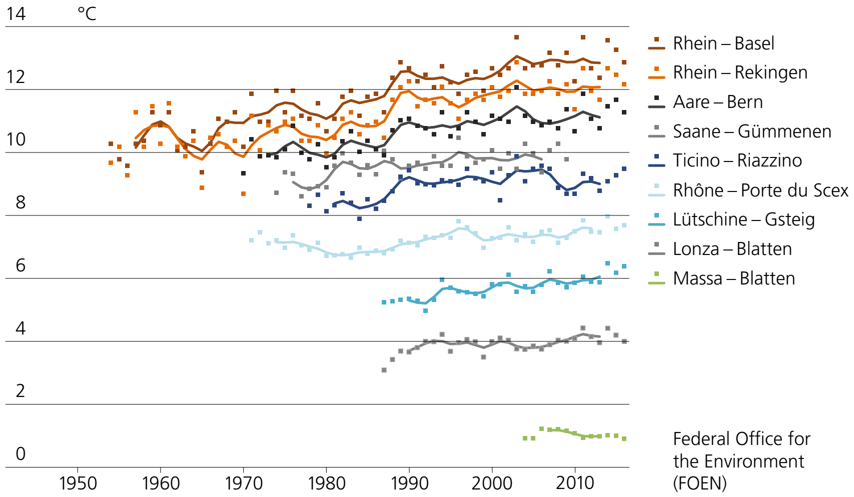
Water temperature stations in Switzerland.

Long time series and their importance – River Temperature

For most of the stations the monitoring results of the water temperature indicate slight temperature increases during the last decades caused by climate change. Especially climatological observation needs a high-quality database in order to draw conclusions on developments such as average long-term behaviour, trends or range of variation. Thanks to the well-established and long-term water temperature measurements in Switzerland, it is possible to analyse the frequency or trends of unexpected incidents in river temperature. Besides, this also enables the provision of specific information about water-temperature regimes of selected catchment areas.

Water temperature in the rivers of Switzerland 1954–2016

Results of nine selected water temperature stations



Federal Office for the Environment (FOEN)

In the last decades, the water temperature has increased by a maximum of ~0.04° per year (Rhein-Basel). Only one station (Massa-Blatten) indicates a slight decline of the hydrograph. It is very closely located to the Aletsch Glacier.

International integration

A selection of stations (12) with long discharge series participate in the Global Runoff Data Centre (GRDC). Daily river discharge data from a total of 27 Swiss stations is supplied to the GRDC, representing an important contribution to international data exchange. The GRDC is part of the Global Terrestrial Network for Hydrology (GTN-H), which is supported by GCOS, Global Terrestrial Observing System (GTOS) and the World Meteorological Organization (WMO) Hydrology and Water Resources programme. The European Terrestrial Network for River Discharge (ETN-R) is a GRDC contribution to the European Flood Alert System (EFAS), facilitating medium- to long-term flood forecasts.

Resources required

Measurements of discharge and continuous monitoring of surface waters will be continued in the framework of the long-term observation programmes jointly supported by the FOEN, the Eawag and the WSL. These programmes are fundamental to flood control, climate changes and water protection efforts.

Federal Office for the Environment FOEN:
- **Topic Water**
- **Hydrological data and forecasts**
- **Watercourse temperatures**

Legal basis

Under the Federal Act on the Protection of Waters (GschG, SR 814.20), the federal authorities are required to carry out surveys of national interest on hydrological conditions. The FOEN is responsible for these tasks.

3.2 Groundwater

More than 80% of Switzerland's drinking and industrial water is sourced from groundwater. Groundwater recharge is influenced not only by precipitation and dry periods but also by human activities. Monitoring of groundwater quality and quantity is therefore required nationwide to ensure the long-term preservation of these resources.

Measurements in Switzerland

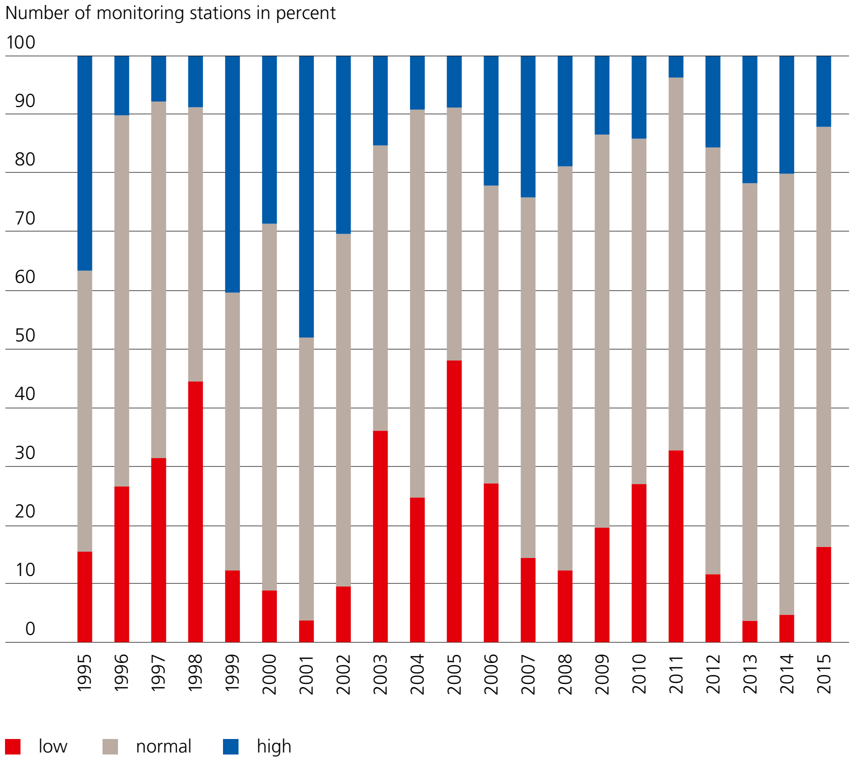
The National Groundwater Monitoring (NAQUA) operated by the Federal Office for the Environment (FOEN) is designed to provide a representative picture of state and evolution of Swiss groundwater resources in terms of both quality and quantity. Groundwater quality and quantity is also monitored at numerous sites by various other institutions (cantons, water utilities, universities). NAQUA facilitates (a) the protection, long-term preservation and sustainable use of natural groundwater resources and thus (b) the protection of the public against excessive pollution (harmful substances and organisms in drinking water). NAQUA consists of 4 modules: TREND for tracking the long-term evolution of anthropogenic and geogenic groundwater quality (50 monitoring sites), SPEZ for the specific monitoring of pollutants (500 sites), QUANT for observing groundwater quantity and temperature (100 sites), and ISOT for observing isotopes in the water cycle (22 sites) (➞ 3.4 Isotopes). Within the framework of NAQUA, groundwater level measurements are generally carried out automatically in abstraction wells or piezometers. Spring discharge is measured as close as possible to the spring using a natural cross-section or with the aid of an artificial overflow. The actual data logger devices are being replaced between 2017 and 2018 by a standard Programmable Logic Controller (PLC). The data of groundwater level or spring discharge, of water temperature, electrical conductivity and, at selected springs, also turbidity are observed at 5-minute intervals and are automatically transferred onto a server. Grab samples for water quality analysis are collected from different types of monitoring sites such as abstraction wells, springs and piezometers. Inorganic and organic substances such as major ions and nitrate, plant protection products, volatile organic compounds and pharmaceuticals are analysed 1–4 times a year depending on the exposure of the monitoring station. Long-term observations are available for groundwater level (m a.s.l.), wellhead level (m a.s.l.), spring discharge (l/min, m^3/s), temperature (°C) and water quality.

Switzerland's NAQUA National Groundwater Monitoring: selected stations from TREND (brown) and QUANT (black) modules, and stations belonging to both modules (red).

Long time series and their importance

To better assess the possible consequences of anthropogenic impacts, e. g. directly by urban heat emissions or indirectly by climate change, NAQUA pursues an integrated approach, aimed at increasingly recording groundwater quality and quantity at the same stations over time. Under the NAQUA programme, the FOEN is therefore collaborating closely with the cantons. The longest groundwater level data series in Switzerland (from around 1900 to the present) are available from water utility pumping wells. Since the end of the 1970s, groundwater levels have been continuously monitored nationwide, e. g. in the Rhine (Maienfeld, since 1975), Arve (Soral, since 1975) and Vedeggio basin (Lamone, since 1980). The discharge of the Areuse spring at St-Sulpice has been measured continuously since 1959, representing one of Switzerland's longest spring discharge time series. Groundwater temperature represents a) natural (groundwater recharge, aquifer conditions, thermal flow) and b) anthropogenic conditions (climate change, urban heat emissions).

Evolution of groundwater quantity 1995–2015



Long-term weather patterns (temperature and precipitation) in Switzerland are often correlated with periods of relatively low or high groundwater levels lasting for several years. Within this general pattern, significant regional differences are the norm. Over recent years, the drought periods of 2003–2005, 2010/2011 and the hot summer of 2015 led to unusually low groundwater levels. On the other hand, above-average precipitation in 1999–2002, 2006/2007, 2012/2013 resulted in high groundwater quantities. The impacts of climate change on groundwater can only be reliably estimated with sufficiently long time series on groundwater quality and quantity. Results of different NRP61 projects underline the importance of groundwater/river water exchange particularly during drought periods.

International integration

Groundwater observations are coordinated internationally by numerous networks. The International Groundwater Resources Assessment Centre (IGRAC), a joint United Nations Educational, Scientific and Cultural Organization/World Meteorological Organization (UNESCO/WMO) initiative for the Global Groundwater Information System (GGIS), belongs to the Global Terrestrial Network Hydrology (GTN-H). The data and information network responsible at the European level is EUROWATERNET, which is operated by the European Environment Agency (EEA).

Resources required

The operation of monitoring stations under the NAQUA programme can be regarded as assured, at least in the medium term. However, especially in connection with the instrumentation of springs, the technical and financial resources required for station equipment and data transmission have proved to be substantial.

Federal Office for the Environment FOEN – State of groundwater

Legal basis

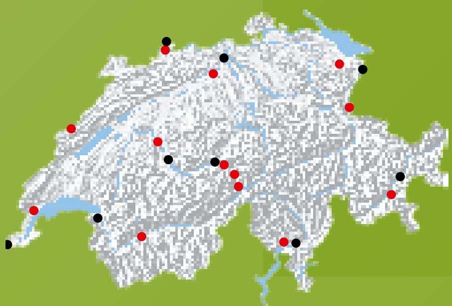
Under the Federal Act on the Protection of Waters (GSchG, SR 814.20), the federal authorities are required to carry out surveys of national interest on hydrological conditions and on water quality in surface water and groundwater. The FOEN is responsible for these tasks.

3.3 Isotopes

Serving as natural tracers, isotopes of oxygen and hydrogen leave a "fingerprint" in numerous components of the climate system. Accordingly, in addition to their use in groundwater management and protection, long-term isotope data series provide necessary reference values for climatological studies.

Measurements in Switzerland

The signature left by isotopes in the water cycle is mainly due to isotope fractionation during the formation of precipitation. Most naturally occurring elements have stable isotopes; other isotopes are radioactive (unstable) and decay over time. The stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H) and the radioactive hydrogen isotope tritium (^{3}H) are constituents of the water molecule. They are measured by various institutions in Switzerland in water samples from precipitation, rivers, lakes, glaciers, snow and groundwater. In 1992, as part of the National Groundwater Monitoring (NAQUA), a new module was established for the observation of the water isotopes (module ISOT). The ISOT network currently consists of 22 monitoring sites distributed throughout Switzerland: 13 precipitation and 9 surface water sites. At these sites, the Federal Office for the Environment (FOEN) measures isotope ratios of oxygen-18, deuterium and, until 2010, also tritium. The ISOT precipitation sites are spread across the various climatic regions of Switzerland (the Jura Mountains, the Plateau, the Alps, the Southern side of the Alps). Monthly composite samples from a precipitation gauge emptied daily are used for isotope measurement. Sites belonging to the discharge monitoring network (basic monitoring network) or the National River Monitoring and Survey Programme (NADUF) were selected as ISOT surface water sites. At these sites, composite samples are collected automatically every 4 weeks or spot samples are taken manually. During a test period 2002 – 2010, spot samples were collected and analysed at 3 groundwater sites.



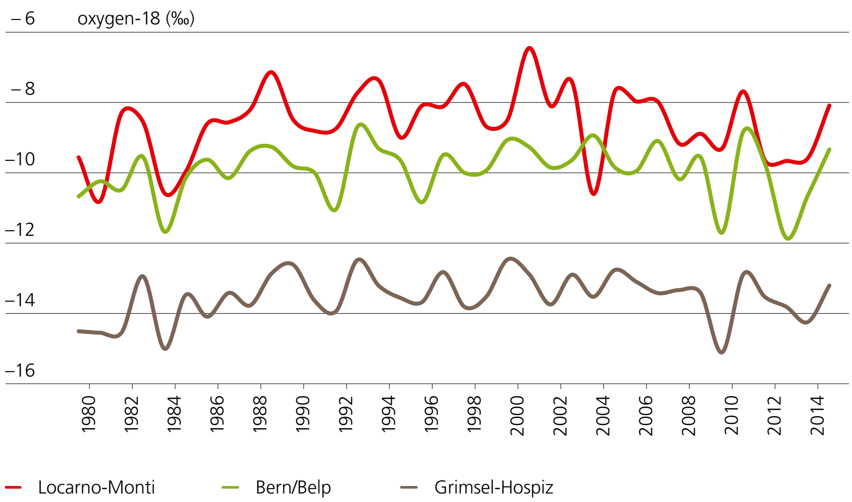
The isotope observation network (NAQUA ISOT) measures the ratios of oxygen-18 and deuterium in precipitation (red) and in surface water (black).

Long time series and their importance

At the monitoring sites in Belp/Bern, Grimsel-Hospiz and Locarno-Monti, the water isotopes have been analysed in monthly composites of daily precipitation samples since the early 1970s. Time series from these three sites are the longest available in Switzerland and together form a North-West/South-East profile through the Alps from Bern (541 m a. s. l.) across the Grimsel Pass (1950 m a. s. l.) to Locarno (379 m a. s. l.). Most of the ISOT precipitation stations are located close to climatological stations operated by MeteoSwiss, where additional variables, such as air temperature and relative humidity, are measured. Isotope observation in rivers dates back to the mid-1980s (Rhine at Diepoldsau, Rhône at Porte du Scex and Inn at S-chanf). These measurements thus cover Switzerland's major rivers.

Oxygen-18 isotope in precipitation 1980–2015

Yearly averages in per mille at three ISOT sites



The yearly averages of the oxygen-18 isotope in precipitation, 1980–2015, reveal the climate trend over the past three decades, which is also apparent from the discharge of large Swiss rivers. The signature left by isotopes in the water molecule is due to the hydrometeorological conditions prevailing during the formation of precipitation – from the original source of humidity to the final rainfall at the collection point (Spreafico and Weingartner, 2005).

International integration

Since 1992, data from selected ISOT sites have been transmitted to the database of the Global Network of Isotopes in Precipitation (GNIP), and since 1996 to the Global Network of Isotopes in Rivers (GNIR) operated by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO). The ISOT network thus makes an important contribution to internationally coordinated isotope programmes, with data being used in research as reference values or for calibration purposes. Together with Germany and Austria, Switzerland has a dense monitoring network with long time series, as compared with other countries. This makes the ISOT series particularly valuable, e. g. for international research programmes.

Resources required

Operation of the ISOT sites is integrated into the NAQUA National Groundwater Monitoring. As the tritium content of water samples is continuously declining, the costly tritium analyses were abandoned in 2010.

Federal Office for the Environment FOEN – State of groundwater

Legal basis

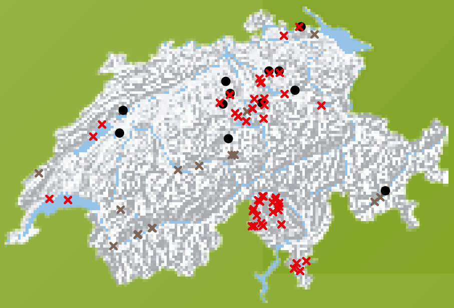
Under the Federal Act on the Protection of Waters (GSchG, SR 814.20), the federal authorities are required to carry out surveys of national interest on hydrological conditions and on water quality in surface water and groundwater. The FOEN is responsible for these tasks.

3.4 Lakes

Lakes function as sentinels of climate change, depending on the type and size of the waterbody concerned. Thermal variation in lakes are a crucial key for responses like vertical mixing, stratification, nutrient and oxygen dynamics, as well as spread and geographical expansion of biota. Historical records of freeze and thaw dates for lakes permit valuable inferences about past regional climatic conditions.

Measurements in Switzerland

Since the first lake-level measurements were taken at Lake Geneva (1780), the Swiss Confederation has expanded a hydrometric network for lake-level monitoring as well as for the runoff/discharge at the outflow of the lakes. In contrast, water temperature observations at federal level are limited to measurements at lake outflow stations (e.g. Aare-Brügg since 1962) and vertical or horizontal temperature conditions in the lakes have not been observed to this day. Nevertheless, more or less regular measurements of water temperature are undertaken during water quality observation by cantonal water departments, international commissions (e.g. monitoring of Lake Constance), Eawag (Swiss Federal Institute of Aquatic Science and Technology), and ETH Zurich, EPFL (École polytechnique fédérale de Lausanne) or University of Bern. Thereby, sensors are lowered from a boat, enabling a high resolution of measurements in the depth, from the surface down to the deepest point in the lake. Thanks to these efforts, long time series on water temperature with measurements starting in the nineteenth century are available. As these data often have been collected on a project basis the time series are, however, very heterogeneous regarding their temporal resolution and may have been discontinued after a few years. Complementing in-situ observations, time series on lake water temperature can also be derived from remote sensing data, as e.g. done by the University of Bern with satellite data (NOAA AVHRR). Overall, long time series and data with higher temporal resolution will be required for further interpretation or reasonable predictions of water temperatures.



Freeze and thaw dates for more than 100 years (black dot). Water temperature time-series longer than 10 years (red cross) or less than 10 years (brown cross). The database is still incomplete and will be updated as new information becomes available.

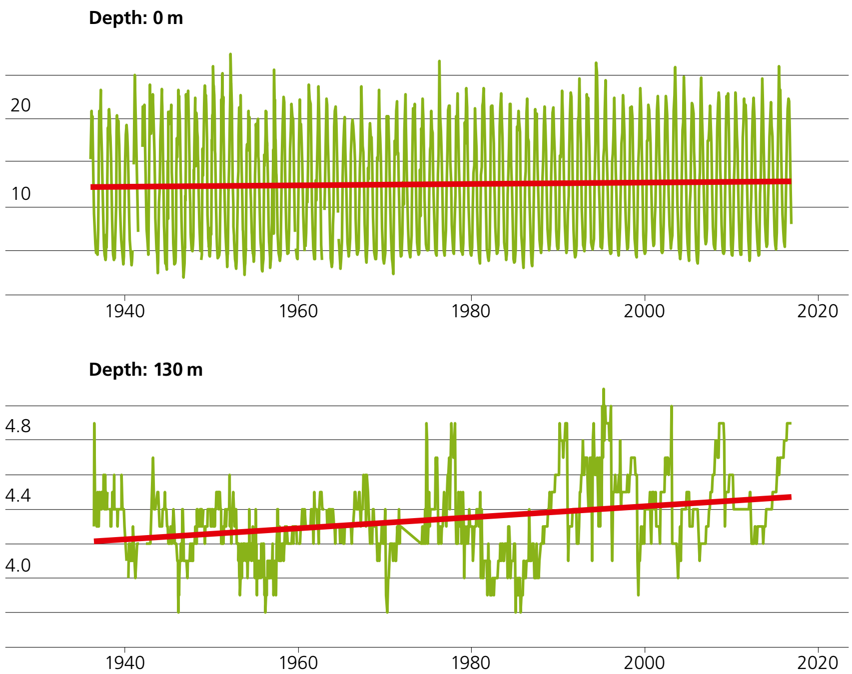
The combination of in-situ data, satellite data, and modelling plays a key role in better understanding lake dynamics. That in mind, the Federal Office for the Environment (FOEN) is currently assessing the different monitoring networks for lake water temperature with the aim of streamlining the efforts by all different actors and of closing gaps in the observation network, as appropriate.

Long time series and their importance

Long time series of water temperatures include the observations recorded by the Zurich water utility at the Thalwil site on Lake Zurich (since 1936). Other measurements have been carried out on Lake Zug (since 1950), Lake Greifen (since 1956), Lake Geneva (since 1957), Lake Neuchâtel (since 1963) and other lakes. As the measurements have been carried out differently over the decades, homogenisation for future studies will be very important. Historical records of freeze and thaw dates for lakes permit additional valuable inferences concerning the past regional climate and provide information on winter temperature patterns. These observations are not carried out systematically across Switzerland and come from various sources (including newspapers and personal records).The longest time series available in Switzerland is for Lake St. Moritz; starting in 1832. This dataset is unique for Central Europe.

Water temperatures at Lake Zurich 1936–2016

Temperature (C°)



Long-term measurements with monthly collected data of water temperature at Lake Zurich started in 1936. Here, time series for different depths (0 and 130 m) are shown. Additional measurements exist in 1897 and 1902. (Data obtained from AWEL, The Cantonal Department of Waste, Water, Energy and Clean Air of Zurich , Switzerland)

International integration

Switzerland's contribution to the Global Terrestrial Network for Lakes (GTN-L) includes the periodical submission of lake water level measurements at Swiss lakes. Additionally, the freeze and thaw dates for alpine lakes are transmitted to the Global Lake and River Ice Phenology Database at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. It archives observations from Lakes St. Moritz, Silvaplana and Sils, whereby observations are no longer being updated for the two last-named lakes.

Resources required

Lake vertical temperature measurements are carried out by various institutions across Switzerland in an uncoordinated manner. Likewise, freeze and thaw dates are not systematically observed. As no legal basis exists for long-term observations of lake ice, these time series are not guaranteed.

Meteolakes – Hydrodynamic

Die 3 Seen

CIPAIS

CIPEL

igkb

NSIDC

eawag – Department Surface Waters

Legal basis

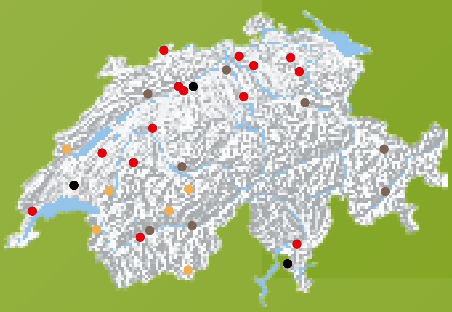
The goals and requirements for the observation of lake variables are specified in the Federal Water Protection Ordinance (WPO, SR 814.201) accompanying the Water Protection Act (WPA, SR 814.20). With regard to water temperature, one of the requirements specified for standing waters is that natural temperature regimes are not to be detrimentally altered as a result of human interventions. Other relevant provisions are to be found in the federal legislation on Environmental Protection (EPA, SR 814.01), Nature and Cultural Heritage protection (NCHA, SR 451) and the exploitation of hydroelectric power (WRG, SR 721.80).

3.5 Soil moisture

Soil moisture influences the exchange of water and energy between soil, vegetation and the atmosphere, and thus affects temperature, precipitation and the boundary layer stability. An increased risk of aridity is expected as a result of climate change in Southern and Central Europe, with potential negative consequences on the environment as well as economic impacts on the agricultural, forestry and water management sectors.

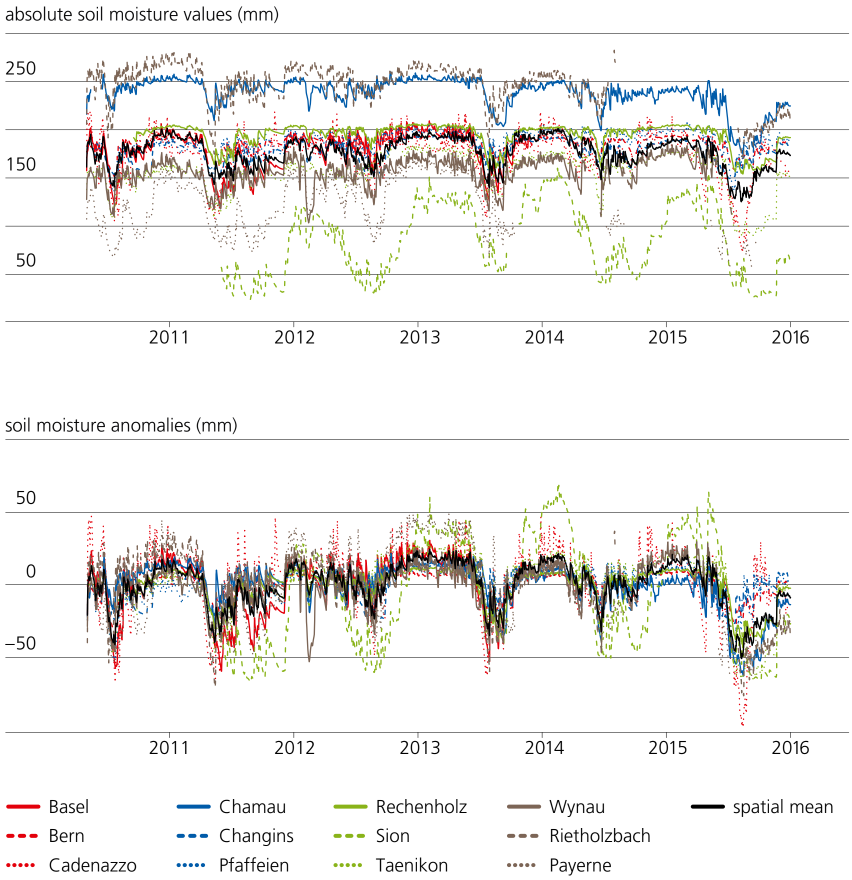
Measurements in Switzerland

Soil moisture (soil water content) is a measure of the volumetric or gravimetric water content in soil. Soil moisture measurements in the root zone are essential for evaluating the water and energy balances in weather, climate and ecosystems, whereby dry as well as moist soil conditions, including the extreme ends of the spectrum, are relevant. The only nationwide soil moisture monitoring programme currently in place is the Swiss Soil Moisture Experiment (SwissSMEX). This programme was initiated by ETH Zurich, MeteoSwiss and Agroscope Reckenholz-Tänikon as part of the SwissSMEX project of the Swiss National Science Foundation (SNSF), and was subsequently extended to involve the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). The network consists of 19 monitoring stations at 17 different sites, and covers a wide area in central Switzerland as well as parts of Ticino and Valais. Soil moisture and soil temperature are measured every ten minutes at depths of 5, 10, 30, 50, 80 and 120 cm, as local conditions permit. Most of the measuring sites are installed either at the SwissMetNet stations of MeteoSwiss (automatic monitoring network), at stations associated with WSL's Long-term Forest Ecosystem Research Programme (LWF), or at Swiss Fluxnet stations. The LWF measures soil moisture at depths of 15, 50 and 80 cm at eleven forest sites. Six further stations are operated by the University of Fribourg within the Soil Moisture in Mountainous Terrain (SOMOMOUNT) research monitoring network at medium and high altitudes. The latter installations follow the same design as that of the SwissSMEX stations, and measurements are taken at depths of 10, 30 and 50 cm. There are also a few individual monitoring stations that are operated in connection with the research and observation projects of various institutions. Thanks to the spatial heterogeneity of Switzerland, soil moisture measurements offer an attractive basis for validating remote sensing data, which provide long-term series of measurements across a large geographical area. For instance, the SwissSMEX measurements are considered for validating data in the European Space Agency (ESA) Climate Change Initiative soil moisture project.



Climate-relevant soil moisture monitoring sites of the various institutions. SwissSMEX grassland and forest (red), LWF (brown), SwissSMEX and LWF (black), and SOMOMOUNT (orange).

Soil moisture variability at grassland sites 2010–2015



Soil moisture time series at SwissSMEX grassland sites. The diagram shows the absolute value of soil moisture integrated over the top 50 cm of soil (above). Large variations of the individual sites from the spatial mean can be seen. In contrast, the temporal anomalies of soil moisture (deviation from the temporal mean, below) show essential fewer differences from the spatial mean. Whilst the differences in absolute soil moisture values are predominantly characterised by the site-specific soil textures, those of the temporal anomalies are mainly influenced by the dynamic meteorological conditions and reflect a signal on the regional scale. Diagram adapted from Mittelbach and Seneviratne (2012).

Long time series and their importance

The SwissSMEX monitoring network gathers long-term measurements over a large part of Switzerland in shallow as well as deeper levels of soil over varied climatic conditions (in both space and time). The resulting time series range over a wide spectrum of moisture levels, including potential values at the extreme ends, and thus provide a basis for estimating the spatial and temporal variability of soil moisture as well as for evaluating weather and climate models. The monitoring network covers a variety of land-use regimes. Data at the grassland sites are available predominantly for the period of 2009 onwards, and have been available for forest locations since the summer of 2010. The soil moisture measurements in the LWF programme have been available for all stations since 2008 while the majority of data from the SOMOMOUNT stations have been available since 2013.

International integration

SwissSMEX is one of the first soil moisture monitoring networks in the world that measures soil moisture long-term and large-scale, based on a uniform installation. The data are useful, for example, for evaluating weather and climate models and for gaining a better understanding of the processes underlying land-atmosphere interactions. They also enable the validation of remote sensing data. With its LWF programme, Switzerland is participating in the ICP Forests Programme (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) that is run under the auspices of the United Nations Economic Commission for Europe (UNECE) agreement on Long-range Transboundary Air Pollution. Four of the existing SOMOMOUNT stations form an integral part of the Swiss Permafrost Monitoring Network (PERMOS, → 3.8 Permafrost).

Resources required

The SwissSMEX monitoring network has continued to collect data since the project ended in 2011, although ongoing funding for the long-term maintenance of the network has not yet been secured. The same applies for the SOMOMOUNT network, where SNSF funding ended in 2016. The continuation of soil moisture monitoring activities within the LWF programme (forest sites) is secured in the medium term, as the LWF is anchored in the Swiss Forest Ordinance, however, this only concerns 8 of the 34 stations.

ESA

WLS – Long-term Forest Ecosystem Research (LWF)

ETH Zurich – Swiss FluxNet

ETH Zurich – SwissSMEX

Legal basis

To date, there has been no comprehensive legal framework in place for the long-term monitoring of soil moisture. The need for soil moisture measurements has been acknowledged in the Swiss Federal Council's report on "Dealing with local water shortages in Switzerland", in response to Postulate 10.353. The report highlights that there is a lack of standardised and generally accessible data around the issues of aridity and water shortage in Switzerland. In this context, it is recognised that the existing knowledge and data related to these topics must be expanded, and that the catalogue of measures needs to include improvement of the base data.

3.6 Snow

Besides playing a key role in the climate system, snow cover is a vital economic factor in sectors such as tourism, water management, hydropower, agriculture and transport. With long time series for snow variables, conclusions can be drawn concerning past and future developments.

Measurements in Switzerland – Snow depth and new snow

The most important observations for snow climatology are snow depth, new snow height, and Snow Water Equivalent (SWE) of the total snow cover.

Snow depth and new snow height are recorded by measurement networks mainly operated by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) Institute for Snow and Avalanche Research (SLF) and the Federal Office of Meteorology and Climatology MeteoSwiss. These networks comprise both automatic and conventional (manual) stations. Automatic stations can only provide automatic snow depth measurements. Conventional stations provide daily measurements of snow depth and new snow height. The roughly 80 SLF conventional stations are located between 1000 and 2000 m a. s. l., whereas the roughly 100 automatic stations are operating between 2000 and 3000 m a. s. l. By contrast, the 27 automatic (SwissMetNet) and 230 conventional snow measurement stations operated by MeteoSwiss are evenly distributed across Switzerland, also covering elevations below 1000 m a. s. l.

In 2010, 71 stations with climatologically important snow measurements in Switzerland were identified (NBCN-S, Wüthrich et al. 2010). Out of these, 17 stations with special importance from a global perspective were determined as GCOS snow stations. The choice was based on long-term parallel new snow and snow depth measurement reaching back to at least 1950, on data quality and on completeness. Meanwhile, the list of GCOS snow stations includes 22 stations to also reflect the importance of long-term SWE measurements. Half of these stations measure all three snow variables.

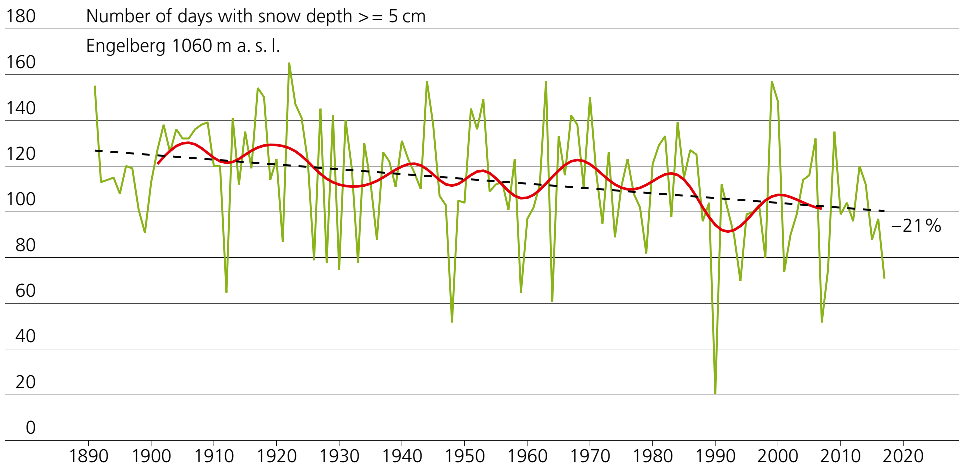
Satellite data are being used operationally to determine snow covered areas, e. g. from the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) (by the University of Bern) and Meteosat Second Generation (by MeteoSwiss). Data is also used to generate long time-series to monitor the spatial distribution of snow extent and its variability based on the data archive compiled and maintained by the University of Bern.

71 stations with climatologically important snow measurements in Switzerland (NBCN-S)

Long time series and their importance – Snow depth

Compared with the automatic measurement networks, the advantage offered by the conventional stations is that the available time series are sufficiently long for climatological purposes (> 50 years). In most cases, the most important measurement series for total snow depth are shorter than for new snow depth. This may be associated with the early initiation of precipitation measurements (→ 2.5 Precipitation). Data on snow depth were only recorded more or less regularly following the introduction of measurement instructions from 1893 onwards. In many cases, the data collected before 1930 are only available in the original analogue form and therefore require additional processing and digitisation if they are to be used in analyses. The longest total snow depth series go back to the 1890s – Säntis (1890), Engelberg (1891) and Davos (1896). At other stations, measurements also began around 1900, but the frequency of measurement varies widely from year to year and from station to station. At most sites, continuous observations of total snow depth began at the earliest in the 1930s (e.g. Weissfluhjoch, Montana, La Chaux-de-Fonds, Einsiedeln). Total snow depth has also been recorded regularly since the 1930s at stations in a number of Swiss towns on the Central Plateau. However, given the high degree of variability in snow depth associated with small amounts of snow at this elevation, time series from these sites are difficult to interpret.

Number of days with snow depth ≥ 5 cm in Engelberg

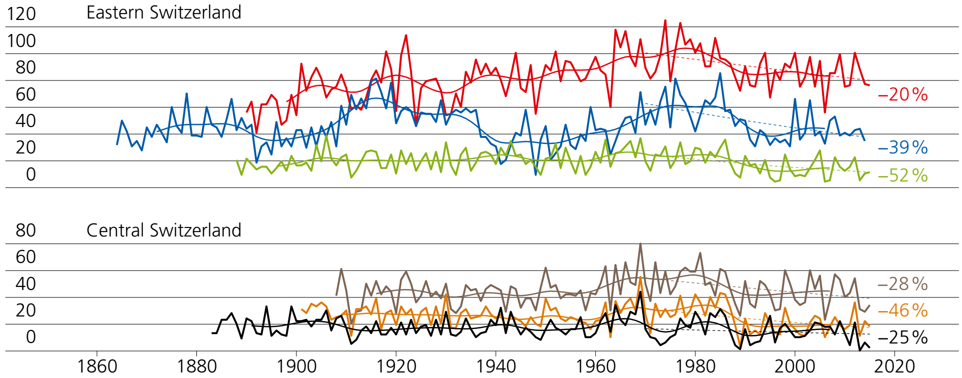


Number of days with a snow depth of at least 5 cm per snow season (Nov–Apr) for the station Engelberg in Central Switzerland (light green). The 20-year Gaussian smoothed line is shown in light blue. The long-term linear trend reveals a decrease of 21 % in the number of such snow days (black dashed line).

Long time series and their importance – New snow

Altogether 15 stations have new snow records dating back to the 19th century. Either MeteoSwiss or the SLF is responsible for these measurements nowadays. At seven stations, new snow has been recorded since around 1880 – Sils Maria (1864), Guttannen (1877), Elm (1878), Lucerne (1883), Airolo (1885), Chur (1888) and Arosa (1890). The temporal evolution is discussed in detail in Scherrer et al. (2013). The amount of new snow per day and the number of days with new snow are variables of climatological importance, making it possible to analyse the influence of warmer winter temperatures (i.e. more rain than snow) and the possible increase in more intense snowfalls. New snow height is also important for avalanche warning operations, winter tourism and snow clearance services. Some of the longest new snow height series have only recently been digitised and analysed (Scherrer et al. 2013).

Number of days with new snow/snowfall (daily new snow ≥ 1 cm) per snow year



Upper panels: Eastern Switzerland stations (Sils-Maria: blue, Elm: red, Chur: green), lower panels: Central Switzerland stations (Einsiedeln: brown, Meiringen: orange, Luzern: black). All stations show strong declines (–20 to –52 %) from 1970 onwards (dashed linear trend lines).

Measurements in Switzerland – Snow water equivalent

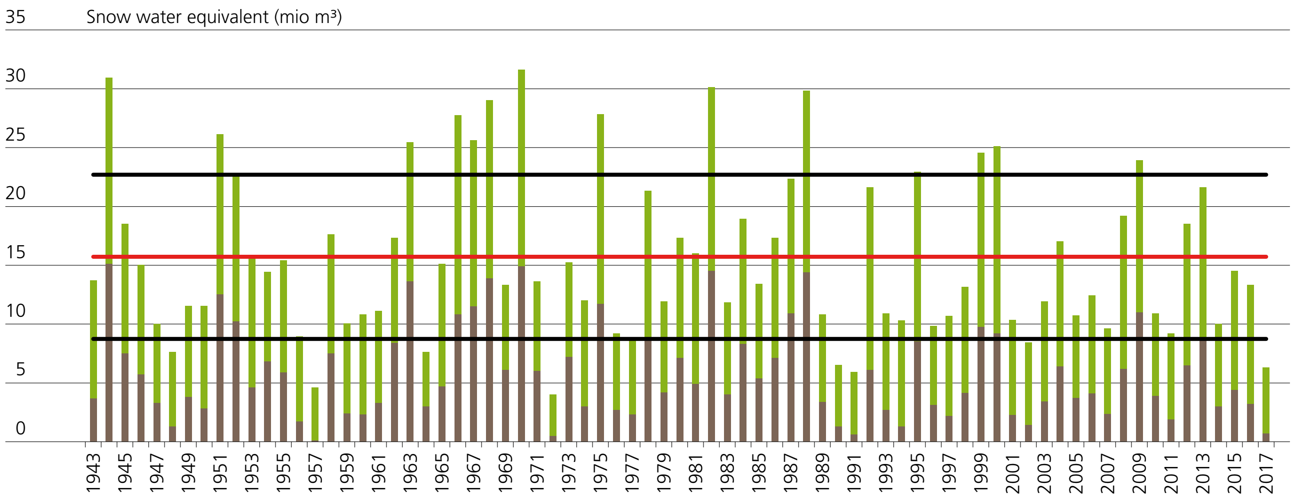
SWE is a measurement of the amount of water contained in the snow pack. It can be considered as the depth of water that would result if the whole snow pack melted instantaneously. It is therefore of interest from a hydrological perspective, but also for engineering purposes as the SWE is equivalent to the weight of the snow pack. These values are therefore used in construction standards (SIA NORM 261) for the maximum snow load on structural elements. The first regular observations of SWE within a measurement network were carried out in the 1940s by SLF on behalf of ETH Zurich (Hydrology Division of the Laboratory of Hydraulics, Hydrology and Glaciology, VAW) in cooperation with the hydropower sector. Currently regular SWE measurements are recorded by SLF and Meteodat GmbH. SLF carries out SWE measurements twice a month at roughly 40 of its observer stations. Once a year, on 1 April, Meteodat runs and maintains a catchment-focused SWE time series in the Wägital valley. The series includes 11 snow density and 28 snow depth sites, from which the total SWE of the whole catchment is estimated. All these SWE time series are based on laborious manual measurements, which are very time-consuming compared to a simple snow depth reading. Automated measurement methods (e. g. snow pillow) do not yet constitute a satisfactory solution, since they often have problems with snow bridging. Moreover, at least most of the SLF stations are manned anyway due to their daily observation programme for the avalanche warning service. Additional isolated measurements are carried out within the framework of the mass balance determination by determining the accumulated SWE in the firn snow on a few Swiss glaciers before summer melt begins (→ 3.7 Glaciers).

GCOS snow stations with snow water equivalent measurements (red), the Wägital (black), and the Alpthal valley (brown)

Long time series and their importance – Snow water equivalent

The longest time series goes back to 1937 and comes from Weissfluhjoch (2540 m), the highest SLF station with SWE measurements. The catchment-wide time series of Wägital began in the 1940s. Davos (1947), Klosters (1948) and Trübsee (1949) followed a few years later. Unfortunately, there is only one time series on the south side of the Alps (San Bernardino) starting in 1973. Furthermore, WSL has maintained SWE measurements at 14 snow courses in the Alpthal valley since 1971. The complete digitisation of most of the long-term SWE time series have only recently been finished. The completion of metadata information is still to be done. Such time series of SWE are valuable for the validation of satellite technologies, for flood forecasting purposes, for model validations, for snow load standards and as indicator to assess the changes in snow water resources in mountain areas, where measuring winter precipitation by conventional buckets is a problem due to wind under-catch.

Snow water equivalent in the Wägital 1943–2017



On the basis of point measurements at each site, the water reserves stored in the snowpack are combined into an area-averaged SWE as a function of elevation band. Variation in SWE can thus be shown for the entire catchment area. The red line shows the long-term mean on 1 April. Winter precipitation at lower and medium elevations is likely in future to increasingly take the form of rainfall rather than snowfall. Among the consequences would be an increased settlement (Rohrer et al., 1994). SWE is therefore expected to show a less pronounced negative trend with climate change than snow depth.

International integration

Two of the above mentioned GCOS snow stations (Davos and Weissfluhjoch) are part of the World Meteorological Organization's (WMO) Global Cryosphere Watch (GCW) Cryonet, which aims to provide clear and useable data, information, and analyses on the past, current and future state of the cryosphere. About half of the snow measurements are also daily transmitted to the European Centre of Medium-Range Weather Forecasts (ECMWF) within the WMO Global Telecommunication System (GTS) framework, where these data are used as part of the assimilation process for numerical weather prediction.

WSL Institute for Snow and Avalanche Research SLF

MeteoSwiss

Resources required

Continuation of the longest time series of snow depth and new snow is largely assured. Whether certain long-term SLF series will be continued is uncertain, since the climatological measurement sites have been outsourced from the avalanche warning service and the current support by the Federal Office for the Environment (FOEN) and ETH may not be guaranteed in the long run. However, continuation of SWE measurements is not assured. Since 2010, snow water equivalent measurements by Meteodat GmbH and since 2016, part of the snow water equivalent measurements by SLF have been funded through MeteoSwiss within the framework of GCOS Switzerland.

WSL

The Global Cryosphere Watch (GCW)

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data throughout Switzerland and to provide weather hazard warnings. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), the implementing agency is MeteoSwiss. Under the ETH Zurich Board Ordinance on Research Institutes of the ETH Domain (SR 414.161), the SLF ensures the Swiss avalanche warning service and informs the general public on avalanche danger.

3.7 Glaciers

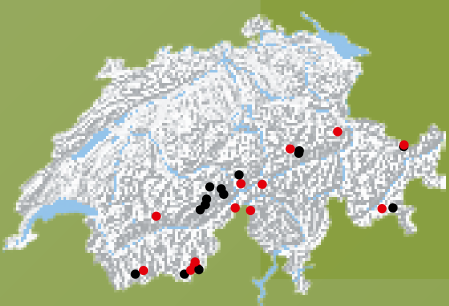
The predominantly negative mass balance of Alpine glaciers is among the clearest signals of changing climatic conditions. Long-term losses in glacier volume and length are key indicators demonstrating the effects of global warming.

Measurements in Switzerland

The investigated variables (mass balance, ice volume change, length change, glacier area (inventories), firn temperature and flow velocity) have been endorsed by the Cryospheric Commission (EKK) of the Swiss Academy of Sciences (SCNAT). The aims are to integrate existing measurements into the Global Terrestrial Network for Glaciers (GTN-G), to define future strategies with regard to relevant issues (research, public affairs) and to incorporate modern technologies (air- and space-borne data, geoinformatics, numerical models) into the monitoring programme. With regard to GCOS and the GTN-G tier system, data can be integrated as follows: mass balance in Tier 3, length change in Tier 4 and glacier inventories in Tier 5. These three variables are described in detail below.

Measurements in Switzerland – Mass balance

The mass balance of a glacier – the result of accumulation of snow and the loss of firn and ice mainly caused by melting (ablation) – is an area-averaged value based on measurements taken across the entire glacier. Mass balance is determined using the direct glaciological method; i. e. measurements are performed twice a year (April/May and September) in snow pits and at a number of stakes drilled into the ice and calibrated with repeated precision mapping. This combination of methods is currently used to determine area-averaged (seasonal) mass balances for 14 glaciers. The mass balance measurements are carried out in the frame of GLAMOS (Glacier Monitoring Switzerland) by the ETH Zurich and the Universities of Fribourg and Zurich. Results are regularly published in the Glaciological Reports (1881–2017) and are submitted to the World Glacier Monitoring Service (WGMS).



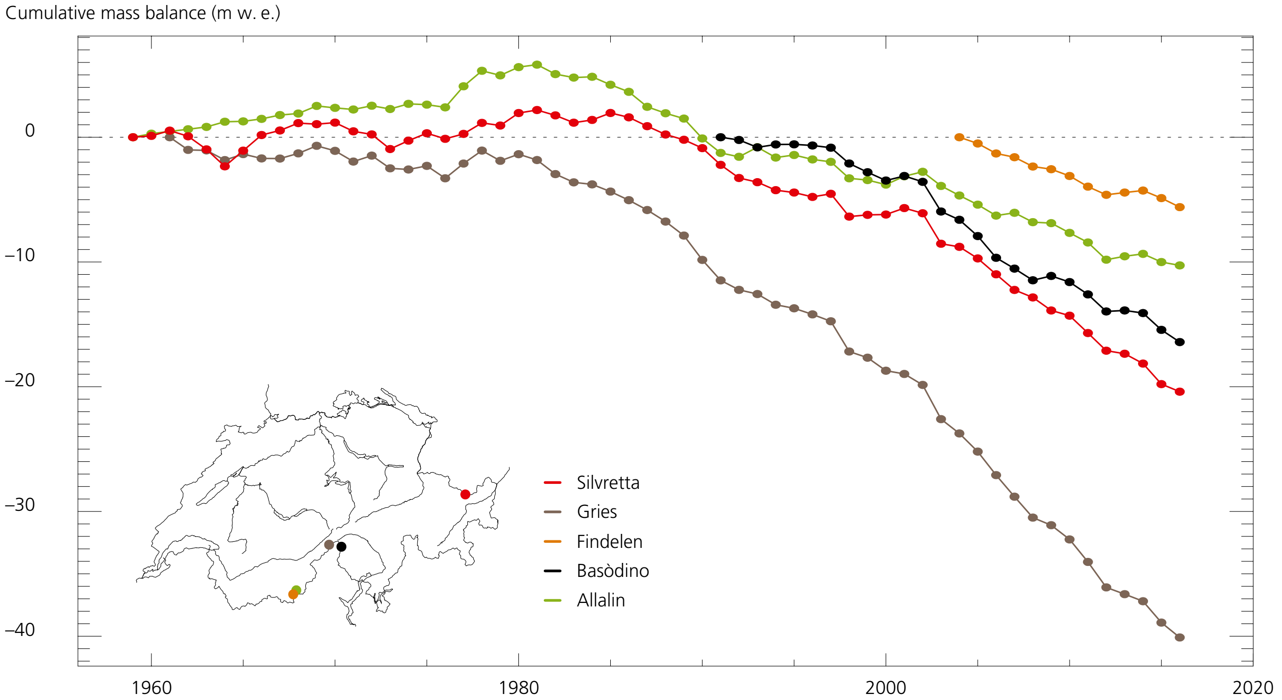
Swiss Glacier Monitoring Network. Red: glaciers with mass balance measurements; black: additional glaciers with volume change measurements.

Long time series and their importance – Mass balance

The first measurements of glacier mass balance were carried out on Rhonegletscher in 1884–1910. The longest in-situ observations of seasonal mass balance worldwide span the period 1914 (Clariden) and 1918 (Silvretta), respectively, to present, and thus cover one century. Data for these glaciers refer to two measurement sites, while monitoring with a dense observational network is carried out on Silvrettagletscher (since 1959), Griesgletscher (since 1961) and Ghiacciaio del Basòdino (since 1991). Multi-decadal mass balance series with an annual resolution and a minimal stake network are maintained on Allalin, Schwarzberg and Hohlaub (since 1955), and on Giétro (since 1967) and Corbassière (since 1997). During the last decade, the measurement network was extended to all hydrological catchments of the Swiss Alps integrating smaller glaciers. In order to be prepared for the potential loss of long-term series due to strong wastage and disintegration in the coming decades, detailed programmes were started on two large valley glaciers (Findelen, Rhone) providing data since 2004 and 2006. Measurements at an individual site have also been available for Grosser Aletschgletscher since 1918 at seasonal resolution.

In-situ mass balance observations are complemented with long-term volume changes derived from repeated Digital Elevation Models. Such data are available for about 50 glaciers, partly covering more than one century at intervals of 5–50 years. The series of ice volume change are continuously updated for 28 glaciers. This independent information on glacier mass change is used to periodically validate direct mass balance series, thus contributing to a homogenous data set that is relevant for climatic interpretation.

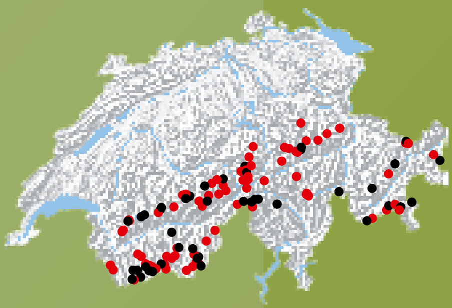
Mass balance series five selected Swiss glaciers



Cumulative glacier-wide mass balance (in m water equivalent) for Silvretta, Gries, Findelen, Basòdino (dense observational network) and Allalin (minimal stake network) based on the glaciological method. By combining in-situ measurements with decadal to multi-decadal ice volume changes all series were regularly calibrated (Huss et al., 2015).

Measurements in Switzerland – Length change and inventories

The glacier monitoring network in Switzerland includes mass balance and length change measurements for glaciers of all sizes and types, ranging from small cirque glaciers to large valley glaciers. The measurements cover all major hydrological basins of Switzerland. Length change survey are coordinated by GLAMOS and are carried out in cooperation with the cantonal forest agencies, federal offices, hydropower companies and private bodies. Changes in length are mostly determined by in-situ or remote-sensing surveys.



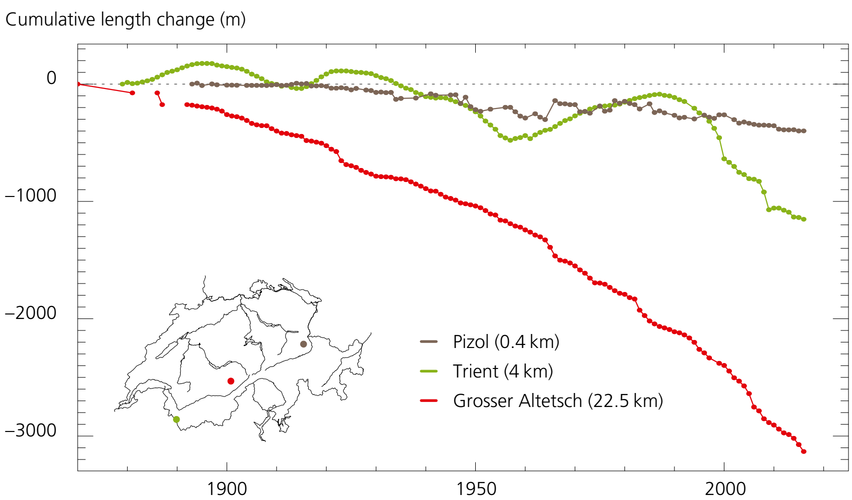
Length change measurements within the Swiss Glacier Monitoring Network. Red: priority1 glaciers; black: the rest of the surveyed glaciers.

Remote sensing systems (aerial photography and satellite imagery) are important to complement in-situ measurements. In the frame of GLAMOS remote-sensing data are used for the determination of ice volume change, length change and the establishment of glacier inventories. Vice versa, in-situ measurements will remain indispensable to calibrate and validate glacier data derived from remote-sensing products. Furthermore, seasonal mass balance (and its spatial distribution) – the most relevant glaciological variable from a climatological perspective – cannot yet be captured by remote sensors. New technologies such as the acquisition of high-resolution surface elevation models using repeated terrestrial laser scans or drone-based photogrammetry are currently being integrated in the monitoring strategy. In addition, helicopter-borne radar measurements of the snow depth have been shown to be a valuable alternative to conventional measurements of winter accumulation.

Long time series and their importance – Length change

The first regular glacier observations in the Swiss Alps began in 1880 with annual measurements of the change in frontal position. Since 1893, glacier length change data have been systematically collected, first in Switzerland and since 1894 in an internationally coordinated manner. Thanks to the continuous efforts of numerous observers, Switzerland has one of the world's most extensive monitoring networks. According to a recent evaluation, monitoring is to be continued for at least 101 of the 115 glaciers that are currently surveyed. However, as a result of the increasing disintegration of many glacier tongues in recent years, unequivocal determination of length change may be problematic in some cases, and the continuation of individual series should be critically reviewed. To address these methodological challenges, the use of new technologies such as airborne observation or terrestrial laser scanning should be considered.

Changes in length of three Swiss glaciers 1880–2016



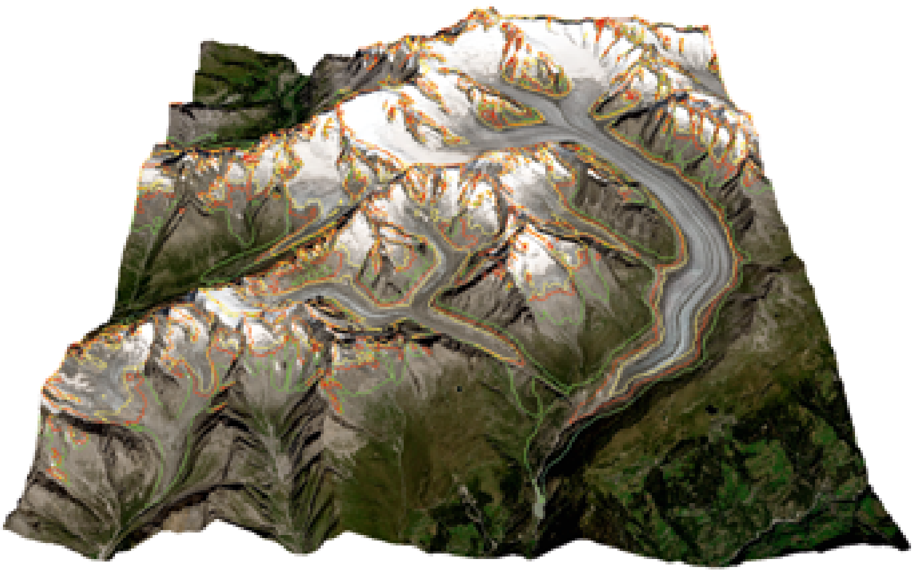
Cumulative annual measurements of length change for different glacier sizes (length in km) showing a diverging response to climate change. The figure illustrates how glacier area influences the delayed reaction of the glacier terminus. Switzerland's largest glaciers (e. g. Grosser Aletsch) have retreated continuously since observations began. In contrast, steeper mountain glaciers (e. g. Trient) show decadal variations, while small glaciers (e. g. Pizol) show low-amplitude annual to multi-annual variations (Glaciological Reports, 1881–2017).

Long time series and their importance – Inventories

Glacier inventories describe the characteristics of each glacier according to a standardised scheme. An inventory for a given point in time provides a complete set of glacier outlines and corresponding attributes such as area, length, aspect, name, hydrological catchment etc. Inventories allow individual measurements (e.g. mass balance) to be extrapolated to the regional scale and thus enable nationwide changes to be assessed.

Complete and attributed Swiss glacier inventories based on aerial photographs are available for 1973 and 2010, and supplementary inventories relying on satellite remote sensing exist for 1999 and 2003. In addition, glacier extent around 1850 was reconstructed from geomorphological evidence. All Swiss glacier inventories are freely available via the Global Land Ice Measurements from Space (GLIMS) database.

Retreat of glaciers in the Aletsch region



Comparison of the Swiss glacier inventories of 1850 (green), 1973 (red) and 2010 (yellow) for the Aletsch region (Maisch et al., 2000; Fischer et al., 2014). Glacier inventories store data for a complete sample of glaciers at a given point in time. They provide an essential basis for numerous glaciological, hydrological, climatological and geomorphological investigations. In close collaboration with swisstopo the area changes of all glaciers in the Swiss Alps are regularly inventoried in 6-year intervals with the first new inventory expected to appear in 2020. Digital terrain model: copyright Sentinel data 2015.

International integration

Swiss glacier monitoring is well integrated into international efforts of coordinated glacier monitoring. All data are being submitted to international data archives within the GTN-G network such as the WGMS, National Snow and Ice Data Center (NSIDC) or GLIMS and are available for regional or global studies of climate sensitivity, hydrology or sea-level rise. Switzerland has an active role in further developing the methodologies for a more accurate monitoring of glacier changes. Numerous approaches, such as the generation of glacier inventories from satellite data or the homogenisation of long-term mass balance series, have been adopted by the international glaciological community, and thus contribute to the excellent integration of Swiss research in this field of science.

Resources required

Owing to the lack of a legal basis, the funding of glacier measurements is not assured in the long term. However, since 2016, activities for a sustainable monitoring of the most important glaciological variables on selected Swiss glaciers with extraordinary long-term measurement series have been supported through GLAMOS. GLAMOS is jointly funded by the Federal Office for the Environment, SCNAT, swisstopo, and MeteoSwiss in the framework of GCOS Switzerland.

GLAMOS

WGMS

Cryospheric Commission

GLIMS

Legal basis

No clearly defined legal basis exists for long-term climate-related glacier monitoring. At present, national legislation provides for regular measurement of glaciers only in the Federal Department of Defence, Civil Protection and Sport Technical Ordinance on Cadastral Surveying (TVAV, SR 211.432.21). Under Art. 7b of the TVAV, the information layer "Ground cover: 6. unvegetated areas" is subdivided into the following categories: rock, glacier/firn, debris/sand, extraction/landfill and other unvegetated areas. In addition, trends derived from glacier observations are relevant as a basis for the assessment of natural hazards in mountain regions (Art. 12c of the DETEC Organizational Ordinance/OV-UVEK, SR172.217.1).

3.8 Permafrost

Permafrost reacts to changes in climate such as the rising air temperatures currently observed. Permafrost degradation can lead to a decrease in ground stability at high altitudes and may have adverse impacts on high mountain infrastructure (e.g. buildings, protective structures, cableways, hiking paths, pass roads and mountain villages).

Measurements in Switzerland

Permafrost is defined as lithosphere material with maximum temperatures of 0 °C over many years. In the Alps, permafrost occurs above the treeline in rock faces and debris slopes and underlies ca. 5 % of the area of Switzerland. Permafrost is not visible as a thermal phenomenon of the subsurface, but typical landforms such as rock glaciers can indicate its occurrence. Permafrost lies below an active layer with positive temperatures during summer.

The connection between climate and subsurface temperatures is not straightforward. Snow cover, surface and subsurface characteristics, and topography can alter or mask changes in the atmosphere when they propagate into the underground. The observation strategy of the Swiss Permafrost Monitoring Network (PERMOS) follows a «landform-based approach» (distinguishing mainly between rock walls, crests, talus slopes and rock glaciers) and includes three types of observation for a comprehensive picture of permafrost in the Swiss Alps: (1) The core of the network is ground temperature measured in boreholes, which provides direct evidence of permafrost and its changes. Changes at depth integrate and filter the signal from the surface and reflect trends delayed but more clearly. Temperature measurements near the ground surface capture the spatial variability and the influence of different surface conditions. (2) Electrical Resistivity Tomography (ERT) is performed at several borehole sites. Relative changes in subsurface ice are observed using differing electrical resistivities of frozen and unfrozen ground and changes between surveys. (3) The creep velocity of selected rock glaciers is observed with annual and aerial surveys.

PERMOS coordinates the long-term permafrost observations in the Swiss Alps since the year 2000. Six partner institutions from academia carry out the terrestrial measurements, while the PERMOS Office coordinates the monitoring activities and is responsible for the data management and reporting.

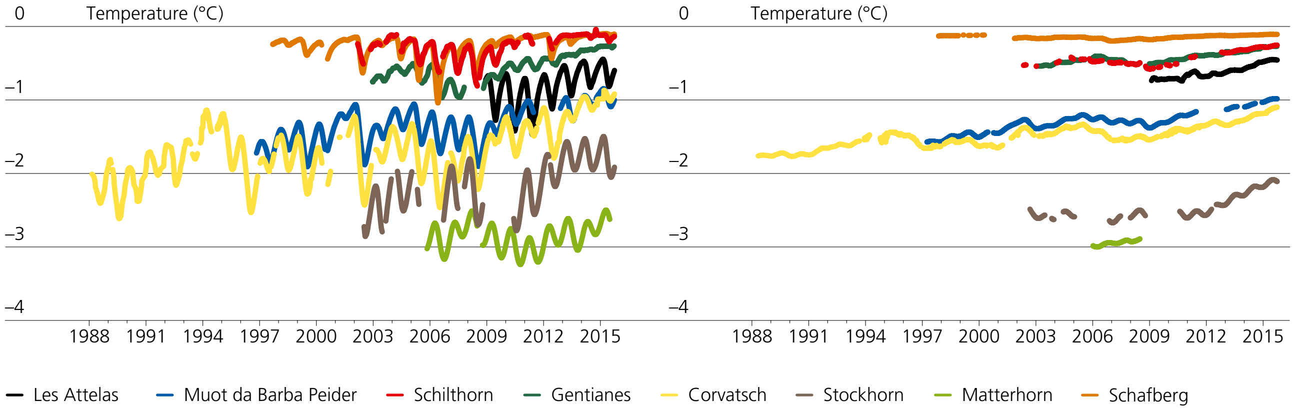
The sites of the Swiss Permafrost Monitoring Network PERMOS: temperature (red), kinematics (black), both (brown). All reference sites as crosses. As the stations were mainly initiated within research projects, their distribution is heterogeneous.

Long time series and their importance

Many of the PERMOS time series cover a significant length of time, also when compared internationally. The longest borehole temperature time series is measured in the rock glacier Murtèl on Corvatsch. It started in the year 1987 and reached the 30 years of a climate normal period in 2017. About half of the nearly 30 borehole temperature time series measured within PERMOS will reach 15 years of data in the same year (see figure below). The longest Ground Surface T (GST) series cover a period of more than 20 years and the first ERT measurements started in 1999. Most of the TGS on rock glaciers were initiated after 2000, and rock temperature measurements started in the year 2004.

The existing stations were mostly set up within the scope of research projects addressing process- related questions. A sound evaluation of their suitability for long-term monitoring was performed in 2007 and 2009, and was repeated in 2017.

Borehole temperatures 1988–2016



Ground temperatures measured in selected PERMOS boreholes. The data measured by the thermistors closest to 10 m (left) and 20 m (right) depth is plotted for each borehole. The exact depth is given in brackets in the caption.

International integration

In the context of international research and monitoring activities, PERMOS is one early component of the Global Terrestrial Network for Permafrost (GTN-P) within GCOS. Borehole temperatures and active layer thickness are the two variables currently collected by GTN-P and annually transmitted to the GTN-P database (together with metadata information). The PERMOS Office is responsible for coordination and data exchange.

PERMOS is also involved in the operational and strategical development of GTN-P as one of the first national permafrost observation networks with nearly 20 years of operational experience.

Resources required

PERMOS relies on substantial financial support by the joint partnership of the Swiss Federal Office of Meteorology and Climatology MeteoSwiss within the framework of GCOS Switzerland, the Federal Office for the Environment (FOEN), and the Swiss Academy for Sciences (SCNAT). PERMOS is run by its coordinating office, the PERMOS Office, six partner institutions, and a Steering and Scientific Committee, and it is part of the Swiss cryosphere monitoring effort. The six PERMOS partners (University Fribourg, University of Lausanne, University of Zurich, ETH Zurich, Scuola Universitaria Professionale della Svizzera Italiana (SUPSI), WSL Institute for Snow and Avalanche Research SLF carry roughly half of the data acquisition costs.

PERMOS

GTN-P

Swiss Cryosphere Portal

Legal basis

Permafrost monitoring is only provided for indirectly in national legislation, in connection with the natural hazards arising from changes in permafrost. Under Article 12c of the Federal Department of the Environment, Transport, Energy and Communications (DETEC) Organizational Ordinance (OV-UVEK, SR 172.217.1), the federal authorities are required to ensure protection against natural hazards. The FOEN is responsible for this task. Under Article 3d of the ETH Zurich Board Ordinance on Research Institutes of the ETH Domain (SR 414.161), the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) is also active in the area of permafrost.

3.9 Albedo

Land surface albedo, the fraction of the incoming irradiance that is reflected by the Earth surface, controls the amount of energy available for heat storage or energy exchange with the atmosphere. It is an important climate forcing variable and a sensitive indicator of environmental degradation.

Measurements in Switzerland

Land surface albedo can be determined from shortwave radiation measurements as the ratio of the outgoing flux of radiation over the incoming flux. Hence, quality controlled measurements of both the downward and reflected shortwave radiation from selected SwissMetNet (automatic monitoring network of the Federal Office of Meteorology and Climatology MeteoSwiss) sites can be used to characterize the land surface albedo locally. The reflected shortwave radiation components are recorded at six SwissMetNet sites in addition to the downward radiation (➞ 2.6 Radiation).

Land surface albedo is highly variable in space and time, particularly in mountain regions, as it is influenced by vegetation, snow coverage and soil moisture. Ground measurements are precise and quality controlled, but are only representative for a small area. Satellite sensors can monitor the spatial heterogeneity of land surface albedo on a regional scale. Moreover, satellite measurements provide additional information on the directional signature of the land surface albedo related to reflectance properties relevant for climate modelling.

Satellite-based land surface albedo products have been available from the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor since 2000 onwards and from Meteosat sensors since the mid-1990s with a high spatial resolution. MeteoSwiss will generate this ECV together with all other components of the surface radiation budget in the framework of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Climate Satellite Application Facility (CM SAF). The University of Bern has recently shown the feasibility of generating a land surface albedo climatology with a 1 km spatial resolution based on its own Advanced Very High Resolution Radiometer (AVHRR) satellite data archive for the years 1990 to 2014. The successful retrieval showed changes in land surface albedo for different land cover types during the last 25 years indicating the high relevance of a homogenous land surface albedo data set.

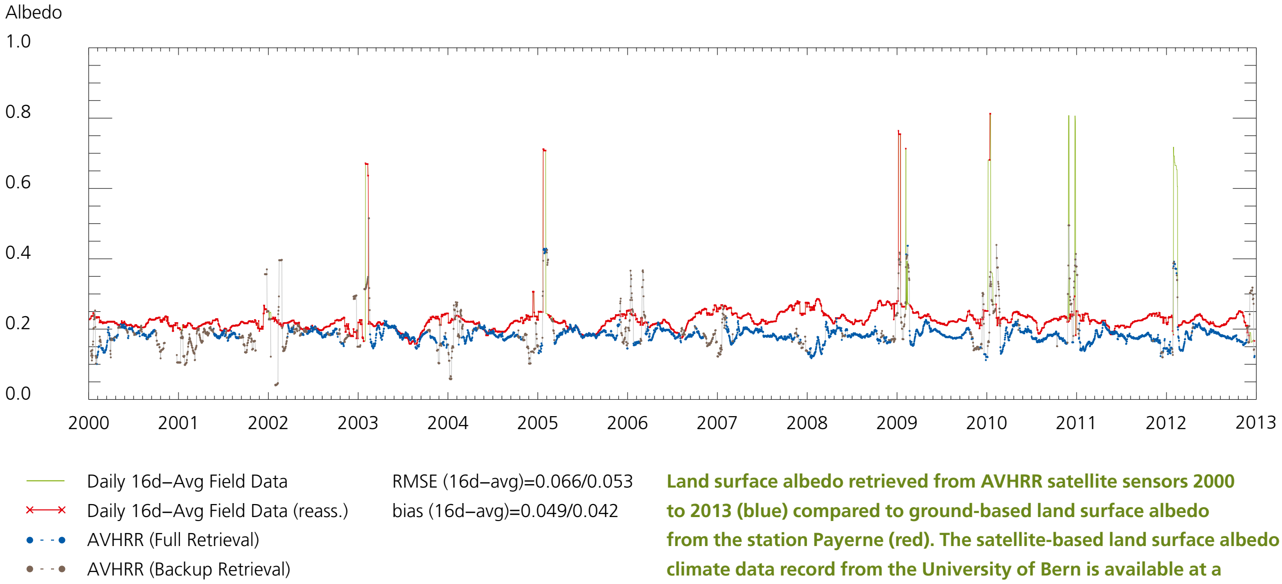
The six stations of SwissMetNet (red) monitor individual components of the surface radiation budget which can be used to characterise the land surface albedo locally.

Long time series and their importance

Ground-based measurements of the reflected radiation component in addition to the downward radiation only started recently. Reflected shortwave radiation measurements began at the SwissMetNet sites Altdorf, Davos, Magadino, Napf, Payerne and Aadorf between 2006 and 2008.

Satellite instruments have collected Albedo data since the late 1980s. Reliable Albedo information has been available from the Meteosat satellite instruments since 1995 and from AVHRR since 1990.

Land surface albedo based on AVHRR satellite data in Switzerland (Payerne):



Land surface albedo retrieved from AVHRR satellite sensors 2000 to 2013 (blue) compared to ground-based land surface albedo from the station Payerne (red). The satellite-based land surface albedo climate data record from the University of Bern is available at a 1 km spatial resolution covering the entire territory of Switzerland.

International integration

The EUMETSAT CM SAF, a joint project involving several European meteorological services, aims to monitor climate variables using satellite data. In this framework MeteoSwiss generates land surface albedo climate data from geostationary satellite data. Ground-based radiation measurements are associated to the World Meteorological Organization Global Atmosphere Watch (WMO GAW) programme (→ 2.6 Radiation).

Institute of Geography – Remote Sensing

MeteoSwiss – CM SAF

CM SAF

Resources required

The operation of the SwissMetNet radiation measurements is assured both under the legal mandate of MeteoSwiss and through GAW-CH (→ 2.6 Radiation).The CM SAF Third Continuous Development and Operations Phase and the EUMETSAT Climate Service Development Plan ensure the continuation of satellite-based Meteosat land surface albedo climate data until 2022. The AVHRR satellite archive of the University of Bern will be extended until the lifetime of National Oceanic and Atmospheric Administration/Meteorological Operational Satellites (NOAA/MetOp-satellites) expires, which is expected for 2022. Funding to continue the high resolution AVHRR land surface albedo climatology is unsecured.

Legal basis

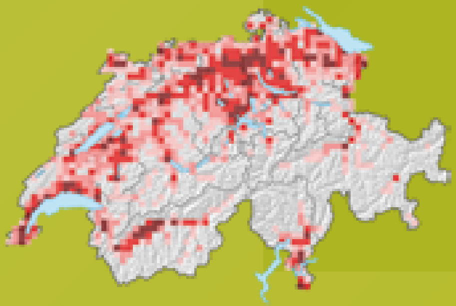
Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. The legal framework does not explicitly specify long-term monitoring of land surface albedo. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss performs surface radiation measurements (→ 2.6 Radiation), which can be used to deduce land surface albedo.

3.10 Land cover and use

Switzerland's landscape is formed by a continuous flow of natural events and human activities. This transformation influences the regional climate. Land-use and land-cover changes are associated with emissions or removals of greenhouse gases. Information on historical and current conditions is needed to determine and understand the interactions between land use and climate.

Measurements in Switzerland

The Federal Statistical Office (FSO) Land Use Statistics determine the land cover and land use of a sample point at every hectare of Switzerland, based on the interpretation of aerial photographs. To date, three surveys at the periodicity of 12 years have taken place using images from 1979–1985, 1992–1997 and 2004–2009. Starting in 2014, a fourth survey is being conducted using images from 2013–2019. Hence, the periodicity of the statistics is reduced to nine years and will be further shortened to six years from 2020 onwards. The Swiss Land Use Statistics differentiate between 46 categories of land use and 27 of land cover. These can be combined to form 72 basic categories of a hierarchical standard nomenclature offering aggregations of 27 or 17 classes or 4 main categories. By the inclusion of 74 specifications in addition to these categories, the land use information will be reported in a more detailed way and multiple uses can be identified. Annually, new regional results are published, a process which will be completed for Switzerland's entire territory in 2020. The nomenclature of the Land Use Statistics is the basis for land area representation in the Swiss Greenhouse Gas Inventory. The 46 land-use and 27 land-cover categories were aggregated to form 18 combination categories, thus implementing the main categories proposed by the Intergovernmental Panel on Climate Change (IPCC) as well as country-specific subdivisions. In addition to the Land Use Statistics, Switzerland also contribute information to the seamless European data program Coordination of Information on the Environment (CORINE) Land Cover which is updated every three years. At the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Land Use Statistics and CORINE data are compared with forest inventory data and global satellite products. In order to preserve nationally protected ecosystems, additional landscape surveys are conducted by various project partners on behalf of the Federal Office for the Environment (FOEN).

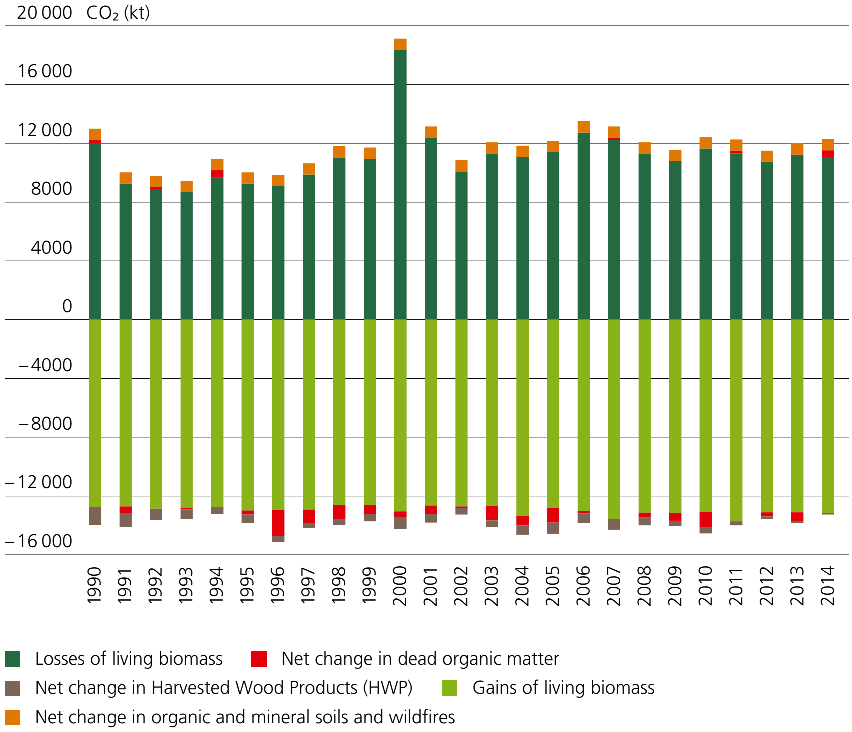


Change of settlement and urban areas, 1985–2009, in hectares
- −14–20
- 21–40
- 41–70
- 70–120
- 121–259

Long time series and their importance

Swiss land use surveys were previously carried out in 1912, 1923/24, 1952 and 1972. However, owing to inconsistencies in these surveys, changes in land use cannot be reliably determined over these periods. Since the implementation of the new land use statistics in the late 1970s, the datasets have been directly comparable with each other. They permit statistically-based conclusions on land use and land cover changes over longer periods of up to 33 years. This also provides an excellent basis for determining carbon balances for the Swiss Greenhouse Gas Inventory.

Switzerland's carbon dioxide (CO_2) emissions and removals of sector LULUCF , 1990–2014



(i) CO_2 removals due to gain (growth) of living biomass, (ii) CO_2 emissions due to loss (harvest and mortality) of living biomass, (iii) net CO_2 emissions and removals due to changes in dead organic matter, (iv) net CO_2 emissions from soils and wildfires, and (v) net CO_2 removals from harvested wood products, 1990–2014. Positive values indicate emissions, negative values indicate removals. The largest carbon fluxes occurred in forests, where growth of biomass exceeded the harvesting and mortality rate except for the year 2000 (windthrow caused by storm Lothar). On average, the LULUCF sector was a sink of –2123 kt CO_2 yr-1 between 1990 and 2014 (FOEN, 2016).

International integration

As a signatory state to the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and its Doha Amendment, and the Paris Agreement, Switzerland is required to annually submit a domestic inventory of emissions and removals of greenhouse gases. The Federal Office for the Environment (FOEN) is the single national entity with overall responsibility for the inventory. Next to the sectors Energy, Industrial Processes, Agriculture, and Waste, a greenhouse gas balance is estimated for Land Use, Land-Use Change and Forestry (LULUCF) according to the guidelines issued by the IPCC. 1990 was set as the base year. Since the first commitment period Switzerland has provided accounts for the activity "Forest management" under Article 3, paragraph 4 of the Kyoto Protocol. Therefore, special attention is paid to carbon fluxes in the forest sector. The estimates are primarily based on data from the FSO Land Use Statistics and the National Forest Inventory.

Resources required

The Swiss Land Use Statistics are part of the Multi-Annual Programme in the Swiss System of Official Statistics. Its results are made available to various users as basic geographical data. The data, broken down by region, are indispensable for LULUCF. These activities are assured under the Statistics Act.

Federal Statistical Office

Swiss climate reporting under the UNFCCC

Legal basis

Under the Federal Statistics Act (BStatG; SR 431.01), the federal authorities are required to obtain representative data, in a scientifically independent manner, on the state and development of the population, economy, society, land and environment in Switzerland. The FSO is the national responsible agency. The principles governing the collection of statistical data are specified in the Ordinance on the Conduct of Federal Statistical Surveys (SR 431.012.1).

3.11 Forest ecosystems

Forests are not only a natural resource, but they also fulfil protective and recreational functions. A changing climate affects forests not only via higher temperatures and drought but also by altering the length of the vegetation period – affecting the future distribution limits of individual tree species. With long-term observations, impacts on the forest ecosystem can be assessed.

Measurements in Switzerland

Since 1985, the state and health of the Swiss forests has been documented by the Sanasilva Inventory, which monitors tree health. These surveys are carried out in July and August, on a 16 × 16 km sampling grid (approx. 50 study sites all over Switzerland). The main tree characteristics assessed are (a) crown transparency, (b) crown discoloration and (c) mortality; growth rates, and Above Ground Biomass (AGB) are measured by the National Forest Inventory (NFI). Under the Swiss Long-term Forest Ecosystem Research (LWF) project, more intensive and wide-ranging studies have been pursued since 1994 as part of an integrated approach to forest monitoring. At 19 monitoring sites (LWF plots) in Switzerland, (a) anthropogenic and natural influences are evaluated (e. g. air pollution and Photosynthetically Active Radiation (PAR)), (b) changes in important components of the forest ecosystem traits and functions are assessed (among many other variables, Leaf Area Index, LAI), (c) forest health indicators are developed, and (d) comprehensive risk assessments are conducted under various stress scenarios and compared to long-term experimental manipulation. To this end, numerous site-specific variables are permanently monitored. Meteorological measurements are carried out automatically according to international standards, with one station located in the forest stand and a second in a nearby unstocked open area. In addition, stand, vegetation, soil and nutrient data are collected at varying temporal resolution (hourly to yearly). At the Seehornwald research station (Davos), microclimate and tree physiological data have been recorded for two decades. Covering a period of about 10 years, almost continuous records of gas exchange rates are available for a forest patch for individual trees and branches. Over the same period, stem radius changes and sap flow rates have also been continuously measured. Other specific areas are being studied as part of forest fire ecology projects (→ 3.13 Forest fires).

Monitoring network in Switzerland with the LWF intensively monitoring and TreeNet research plots (red dots), Sanasilva (black dots), Stillberg experimental afforestation and BUEWAK (Bündner Wald im Klimawandel) (brown crosses), the larch research plots in the Engadine (black crosses), and experimental sites (brown dots).

Long time series and their importance

The LWF project, involving permanent monitoring and experimental sites, extends our understanding of the impacts of air pollution and climate change. The systematic sampling grid of the Sanasilva Inventory has become less dense over the years. From 8000 trees in a 4×4 km grid in the period from 1985 to 1992 now around 1100 trees in a 16×16 km grid have been sampled intensively since 1998.

Some intensive bioclimatic studies were initiated 15 years ago and it is planned to continue them in the future. Furthermore, the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) is an ICOS (Integrated Carbon Observation System) partner, where together with the ETH Zurich, intensive samplings and also eddy covariance measurements have been carried out at the Seehornwald in Davos for more than 20 years now.

Yearly Means of Photosynthetically Active Radiation (PAR), from 19 Long-term Forests Ecosystem Research (LWF) plots

Annual means of PAR in µmol m^{-2} s^{-1} (raw data) from all 19 LWF forest research sites (always in pairs of open field stations and below canopy stations) from 1998 to 2016. Typically the forest stations (below canopy measurements) have lower values than the open field stations.

International integration

As part of the LWF programme and since 1994, Switzerland has been contributing to the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) which, in agreement with the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP), determines the effects of pollution on forests (SR 0.814.323, Art. 6). Around 800 ICP Forests Level II plots throughout Europe are an example of international, cooperative surveys addressing global issues. Through the long-term data series from its 19 Level II plots of the LWF programme, Switzerland provides valuable information to global issues. The data from various parameters are submitted yearly to the central data base of ICP Forests, hosted and managed by the ICP Forests Programme Coordinating Centre at the Thünen Institute at Eberswalde. Furthermore, the LWF is part of the International Long-Term Ecological Research Network (ILTER).

Resources required

Routine data collection and maintenance of LWF sites are being conducted by WSL. Upgrading or expansion of infrastructure and data processing is carried out within several projects in collaboration with the Federal Office for the Envionment (FOEN) and international projects (e. g. UNECE/ICP Forests) on the basis of separate funding as well as under the umbrella of the SwissForestLab, a strategic initiative by the WSL.

WSL:
- **Home**
- **Long-term Forest Ecosystem Research**
- **SwissForestLab**

Legal basis

With the partial revision of the Federal Forest Act (WaG, SR 921.0), the Federal Council intends to safeguard the forest's protective function and natural diversity in the long-term. The FOEN supports forest monitoring projects developed by the WSL. Under the ETH Zurich Board Ordinance on Research Institutes of the ETH Domain (SR 414.161), the WSL is responsible for forest ecology activities.

3.12 Soil carbon

Soil organic carbon (SOC) strongly influences soil properties. Thus, it is a key factor with respect to soil functions. While the impact of climate change on SOC and the role of soil as a potential carbon sink have been widely recognised, consistent SOC measurements over extended periods are still rare although very necessary for model calibration and validation.

Measurements in Switzerland

The Swiss Soil Monitoring Network (NABO) operates 110 long-term monitoring sites throughout Switzerland which cover all relevant land uses (Gubler et al. 2015). The three major categories of utilisation are cropland, permanent grassland, and forest. Most sites were sampled for the first time between 1985 and 1989 and have been re-sampled every five years since then. For each sampling campaign and site, four replicate samples are collected from the top 20 cm of soil for SOC analyses. In addition, bulk density has been recorded since 2003. The whole soil profile was sampled at the occasions of the first (1985–1989) and sixth sampling campaigns (2010–2014). Dried samples are also archived for retrospective analyses. For a subset of the sites, agricultural management data are recorded additionally. Published data are stored in the National Soil Information System (NABODAT).

Furthermore, two long-term arable field experiments are ongoing. In the DOK long-term comparison of biodynamic (D), organic (O) and conventional (K) production systems of arable crops, which has been conducted since 1978 at Therwil by Agroscope and the Research Institute of Organic Agriculture (FiBL), SOC concentrations are analysed both on a yearly basis at 0–20 cm as well as every 7 years at 30–50 cm depth. In the Zurich Organic Fertilization Experiment (ZOFE) trial at Agroscope Reckenholz-Zurich SOC has been measured yearly at a depth of 0–20 cm since 1949.

A large database of more than 1000 forest soil profiles is hosted by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). Soil samples are stored in an archive and soil organic carbon contents were measured for the entire soil profiles. These are currently single measurements in time and not time series. However, C-stocks for Swiss forest soils have been estimated based on these measurements (Nussbaum et al. 2012, 2014). In the frame of the Long Term Ecological Research (LTER) network, WSL operates 19 long-term monitoring sites throughout Switzerland where among other parameters soil organic carbon is periodically measured. These long-term time series are a fundamental requirement for research on climate change impact.

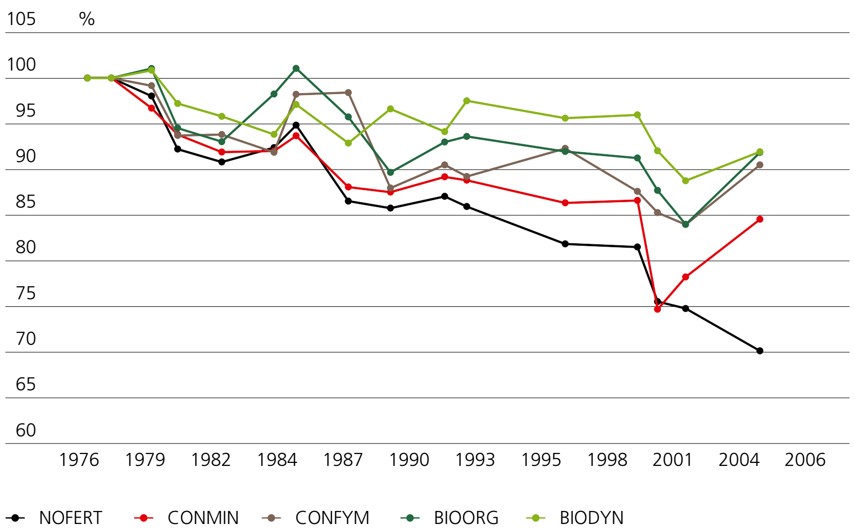
Distribution of NABO and LTER sites according to use category. Black cross: grassland, brown cross: field crops, red cross: forest, black dot: urban park, brown dot: LTER-site, red dot: conservation site, black square: orcharding, brown square: arable field experiment, red square: vineyard.

Long time series and their importance

The longest Swiss measurement series ZOFE extends over more than 70 years, whereas the DOK trials cover almost four decades and the approximately 100 sites of the NABO network more than three decades.

For all of the above-mentioned surveys homogenous SOC time series are documented and soil sample archived for additional analyses. By combining SOC and soil bulk measurements SOC stocks can be calculated to show developments over time. Consistent SOC data series over decades are still scarce but necessary for assessing long-term trends as well as model calibration and validation. SOC data have been and continue to be utilised in several scientific models, e.g. the Rothamsted carbon model, Sticks, etc. as well as for applied C-balances.

SOC development relative to 1977–2004



Development of SOC stocks in the top soil (0–20 cm) of the DOK long term systems comparison (Therwil, Switzerland) from 1977 to 2004 relative to the start of the experiment in 1977 (Leifeld et al. 2009). SOC stock at start of the experiment were 43 tons ha⁻¹. NOFERT: control without fertilisation; CONFYM: conventional mixed farming system; CONMIN: conventional farming system without manure and sole mineral fertilisation; BIOORG: bio-organic mixed farming system; BIODYN: bio-dynamic mixed farming system.

International integration

Switzerland ratified the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and its Doha Amendment, and the Paris Agreement. For Switzerland, it is therefore mandatory to submit its national greenhouse gas inventory, based on the guidelines by the Intergovernmental Panel on Climate Change (IPCC 2006, 2013a, 2013b). Carbon stocks and carbon stock changes of mineral and organic soils under different land uses as well as concomitant non-carbon dioxide emissions are estimated in the sectors Agriculture, Land Use, Land-Use Change and Forestry (LULUCF), and LULUCF under the Kyoto Protocol (KP-LULUCF) of the Swiss Greenhouse Gas Inventory (FOEN 2017).

The SOC data of NABO are periodically sent to the Joint Research Centre (JRC) via the European Environment Information and Observation Network (EIONET).

Resources required

NABO monitoring activities are financed by the Federal Office for the Environment and the Federal Office for Agriculture. DOK experiments are financed by Agroscope and FiBL. ZOFE experiments are financed by Agroscope.

Agroscope:
- **NABO**
- **Long-term trials**

WSL

Swiss climate reporting under the UNFCCC

Legal basis

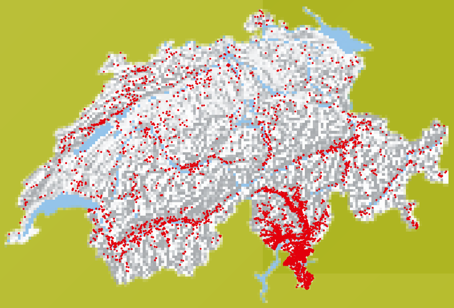
Soil has been protected by law in Switzerland since 1983, when the Environment Protection Act (EPA) was passed. The EPA and the Ordinance relating to Impacts on the Soil (OIS) of 1 July 1998 set the legal basis for soil protection in Switzerland. The purpose of the legislation is to ensure soil fertility in the long term and regulates observation, monitoring and assessment of chemical, biological and physical burdens of soils. Art 3 defines the observation by the Swiss Confederation. The Federal Office for the Environment (FOEN) operates NABO in cooperation with the Federal Office for Agriculture (FOAG). The FOEN informs the cantons and publishes the results.

3.13 Forest fires

Forest fires may have anthropogenic or natural origin. In Switzerland the yearly number of forest fires is approx. 100 for a total burnt area of 300 hectares. Depending on the site concerned and the severity of the fire, the protection capacity of the forest may be temporarily compromised. Climate change may in future impact both regional fire risks and the dynamics of fuel accumulation (i.e. combustible material such as litter, humus, wood) in forests.

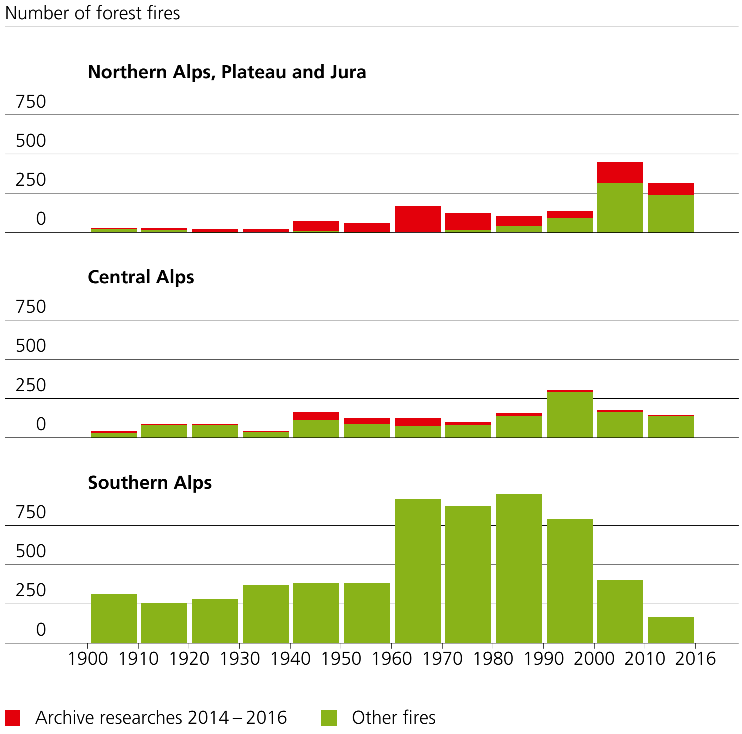
Measurements in Switzerland

Forest fire statistics are an indispensable instrument for forest and fire services planning, fire-fighting facilities, and prevention measures. The Swiss Federal Institute for Forest, Snow and Landscape Research WSL manages the Swiss forest fire database (Swissfire), where more than 9000 events covering the whole national territory and, in some cases, dating back to the 19th century, are registered. The cantonal services collect and register directly fire data regarding ignition site, topography and cause, affected forest types and forest dominant species, litter, grass and shrub abundance, fire type and damages to soil or forest. In the cantons of Ticino, Valais and Uri, data on the most relevant forest fires since the beginning of the 20th century have been compiled, whereas for the remaining regions data are presently completed through archive researches. Furthermore, possible fire regime shifts as a consequence of climate change may be detected through the analysis of time series (Pezzatti et al. 2016)



Forest fire events (red dots) for the period 1960–2016. (source: Swissfire-Database, Pezzatti et al. 2010).

Forest fires in Switzerland 1900–2016



Evolution of the decadal fire frequency in the period 1900–2016. Recent archive research in the Northern Alps has allowed to integrate a significant amount of events in the statistics.

Long time series and their importance

Long-term data series allow analyses of forest fire trends for specific regions and over lengthy periods, including the evolving impact of fire regime drivers such as socio-economic conditions, land use, fire brigade organization, and legislation.

The spatial distribution of ignition points and fire perimeters allows to analyse fire selectivity or the distribution of specific type of fires, like lightning fires. Georeferenced fire scars are also very important for designing ecological studies on the post-fire recovery of the forest stands and their functionality (Moser et al. 2006; Maringer et al. 2016).

With forest fire data going back years or even decades, analyses of various kinds can be carried out: (a) to identify areas or forest types particularly susceptible to forest fires, (b) to assess the forest fire danger on the basis of meteorological conditions as an aid to decision-making concerning fire bans, (c) to optimise prevention measures, and (d) to assess the historical effectiveness of changes in forest fire control.

International integration

Switzerland has three delegates in the European Commission's Forest Fire Expert Group. Swissfire data are yearly forwarded to the European Forest Fire Information System (EFFIS) and published by the European Commission.

Resources required

Routine maintenance of forest fire statistics is assured by the WSL. Upgrading or expansion of the database is carried out in ad hoc projects in collaboration with the Federal Office for the Environment (FOEN) on the basis of separate funding.

WSL – Swissfire

Copernicus – Annual Fire Reports

Legal basis

Under Article 77 of the Federal Constitution (SR 101), the federal authorities are required to ensure that forests can fulfil their productive, protective and welfare functions. According to the Forest Act (WaG, SR 921.0), forests must contribute to the protection of human life and assets. Under the Forest Ordinance (WaV, SR 921.01), the cantons are required to take measures against causes of damage that may endanger forests, including the establishment of permanent fire prevention facilities. Cantonal forest services monitor forest fire risk levels and prohibit fire lighting in or near forests. Under the Federal Ordinance on Alerts, Alarms and the National Security Radio Network (OALNRN, SR 520.12), the FOEN is responsible for issuing forest fire danger warnings. The same Ordinance regulates the collaboration between the Federal and Cantonal authorities as well as the danger scales (five categories) in Switzerland.

3.14 Land surface temperature

Land surface temperature is a measure on how hot or cold the uppermost surface of the Earth is. From a climate perspective, the Earth skin temperature is essential to study land surface and land atmosphere exchange. Complementary to the air temperature, it is an independent temperature measure to quantify climate change.

Measurements in Switzerland

Quality-controlled land surface temperature measurements are not available in Switzerland. The WSL Institute for Snow and Avalanche Research (SLF) conducts direct land surface temperature measurements at about 100 mountain stations on snow and ground dating back to 1996. This data is not quality-controlled. Therefore, proxies are necessary to deduce land surface temperatures from radiation measurements. Those estimations rely on proxies of the Earth's emissivity. The outgoing longwave radiation (→ 2.6 Radiation) at ground level is measured at the SwissMetNet sites (automatic monitoring network of the Federal Office of Meteorology and Climatology MeteoSwiss) Altdorf Magadino and Tänikon (Long time series of the upward radiation component are only available from the Baseline Surface Radiation Network (BSRN) station Payerne. In Payerne longwave radiation fluxes are measured in accordance with BSRN and World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) guidelines. The SLF also maintains two former Alpine Surface Radiation Budget (ASRB) network stations with quality-controlled outgoing longwave radiation measurements at the station Davos and Weissfluhjoch. Surface energy balance measurements suitable for land surface temperature retrieval are also conducted by the University of Basel (→ 4.2 Anthropogenic GHG Fluxes).

Stations with Land Surface Temperature measurements: SwissMetNet stations (red), BSRN site (black), University of Basel (brown), and SLF measurements (orange).

GCOS requests satellite-based land surface temperature measurements rather than ground-based data to complement air temperature observations. Land surface temperature can be determined from satellite sensor measurements in the infrared atmospheric windows. State-of-the-art land surface temperature climate-data records fulfil the GCOS precision requirement and are close to the defined GCOS stability. A long-term land surface temperature climate data record was released in 2017 as part of the Meteo-Swiss contribution to the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Climate Satellite Application Facility (CM SAF). This 25-year climate data record is available at hourly time steps and covers Switzerland with a 0.05° spatial resolution. Satellite-based land surface temperature data with a higher spatial resolution are available for selected time periods and regions.

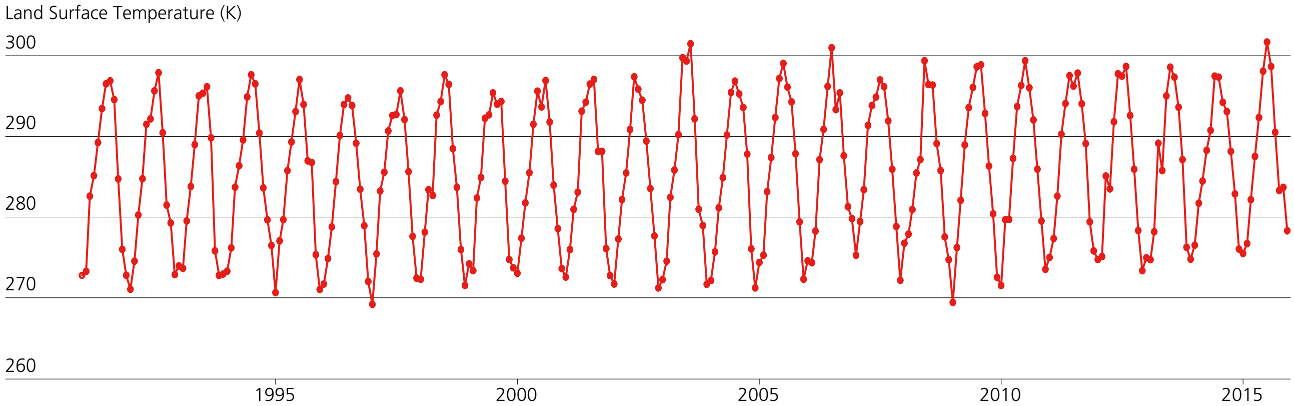
Long time series and their importance

Outgoing longwave radiation measurements at ground-level were initiated at the Payerne BSRN site in 1992 (➞ 2.6 Radiation). Long time series of the outgoing radiation component are also available from the SLF with the first measurements starting in 1997 in Davos and 1996 in Weissfluhjoch. In addition, surface energy balance measurements from the University Basel have now been available for 20 years (➞ 4.2 Anthropogenic GHG Fluxes).

The SwissMetNet outgoing radiation measurements only began in 2008 (Altdorf), 2012 (Magadino) and 2013 (Tänikon).

Satellite instruments have collected data about land surface temperatures since the late 1980s. Reliable satellite based retrievals have been available since 1991 from Meteosat and since 2003 from Moderate-resolution Imaging Spectroradiometer (MODIS).

Land surface temperature based on Meteosat satellite data in Switzerland (Geneva)



Land surface temperature retrieved from Meteosat satellite data in Geneva 1991 to 2015. This climate data record from the EUMETSAT CM SAF is available at hourly time steps at a 0.05° spatial resolution covering entire Switzerland. In cloud-free conditions, these measurements can be used to augment long-term air temperature measurements in regions with sparse station coverage and high spatial variability such as the Swiss mountains

International integration

Satellite-based monitoring of land surface temperature is well embedded in international activities. The EUMETSAT CM SAF, a joint project involving several European meteorological services, will continue to develop land surface temperature climate data in the upcoming years. MeteoSwiss, as partner of this project, is actively enrolled in the generation of land surface temperature climate data. Land surface temperature is also a key topic for the upcoming European Space Agency (ESA) Climate Change Initiative (CCI+). Ground-based radiation measurements are associated to the WMO GAW programme (➞ 2.6 Radiation).

Resources required

The operation of the SwissMetNet and BSRN outgoing longwave radiation measurements is assured both under the legal mandate of MeteoSwiss and through the Swiss GAW programme (➞ 2.6 Radiation). The satellite-based climate monitoring of land surface temperatures in ensured until 2022 in the Third Continuous Development and Operations Phase of the CM SAF.

WSL Institute for Snow and Avalanche Research SLF

University of Bern, Institute of Geography – Remote Sensing

MeteoSwiss – CM SAF

CM SAF

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout the territory of Switzerland. The legal framework does not explicitly specify long-term monitoring of land surface temperature. Under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), MeteoSwiss performs surface radiation measurements (➞ 2.6 Radiation), which can be used to deduce land surface temperature.

3.15 Phenology

Plant growth and development are strongly influenced by climatic conditions. Accordingly, the trends observed in phenological time series are largely attributable to climate warming in recent decades. Phenological observations are an important indicator of climate change. Moreover, they are applicable in healthcare (pollen forecasts) and in agriculture.

Measurements in Switzerland

The first phenological observation network in Switzerland was created in 1760 by the Economic Society of Bern. About 100 years later, from 1869 to 1882, the Forest Agency of the Canton of Bern carried out a phenological observation programme in forests. A national phenological monitoring network was established by The Federal Office of Meteorology and Climatology MeteoSwiss in 1951. This now comprises some 160 stations, distributed across various regions and elevations of Switzerland. The lowest-lying station is located in Ticino (Vira) at 210 m a. s. l., and the highest-altitude station is in the Engadine (St. Moritz) at 1800 m a. s. l. Each year, observers record the dates of leaf unfolding (needle appearance), flowering, fruit ripening, leaf colouring and leaf fall for selected wild plants and crops. These observations cover 26 plant species and 69 phenophases.

Observations are submitted to MeteoSwiss at the end of the year for use in studies on the long-term effects of the climate on plant development. More and more, the immediate online data-transfer is used, which permits conclusions on the current state of vegetation and provides a basis for reports on vegetation status. Observations of pollen distribution – another phenophase – are of major public health relevance. They are carried out by the National Pollen Monitoring Network (NAPOL) (➞ 2.16 Pollen).

A forest phenology programme is maintained by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL).

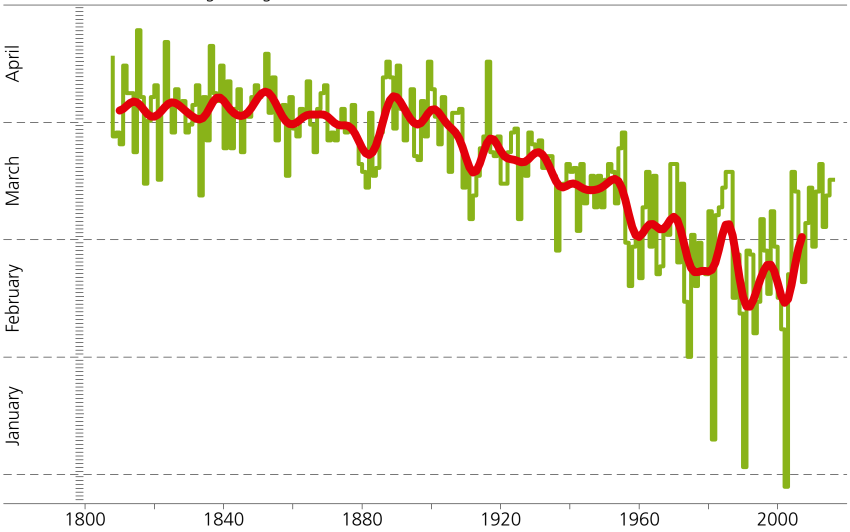
The main sites for phenological observations in Switzerland, covering a variety of regions and elevations, where long observation series of tree, shrub and herb phenophases are available (red dots). Black cross: sites of the two historical data series.

Long time series and their importance

Since 1808, the bud burst date for horse chestnut has been recorded in Geneva. This is Switzerland's longest phenological time series. Of equal importance is a second historical series – cherry tree flowering dates at the rural Liestal-Weideli station – which goes back to 1894. Observations from the stations of the national phenological monitoring network are more recent, going back to the beginning of the 1950s. The selection of the country's most important observation sites includes a wide variety of regions and elevations, taking into account the quality of observations of tree, shrub and herb phenophases, preferably of long duration. Twelve of the most important sites are Liestal, Davos, Enges, Murg, Prato-Sornico, Rafz, Sarnen, St. Moritz, Trient, La Valsainte, Versoix and Wildhaus.

Horse chestnut bud burst Geneva 1808 – 2016

Dates of onset and running average



The onset of horse chestnut bud burst in Geneva varies widely. In 1816, for example, it was observed on 23 April, while for 2003 it was already recorded on 29 December 2002. From around 1900, a clear trend towards earlier onset is obvious. This is attributable not only to global climate change, but also to changes in the local city climate (Defila and Clot, 2001). Given the strong temperature dependence of plant development, phenological time series are good indicators of the impacts of climate change.

International integration

MeteoSwiss is member the Pan European Phenology Database (PEP725). At Birmensdorf WSL the observation site participates in the European International Phenological Gardens (IPG) observation programme. The Global Observation Research Initiative in Alpine Environments (GLORIA) aims to establish a worldwide long-term observation network of sites collecting data on vegetation in Alpine environments. Switzerland is contributing to this initiative with two sites – one in the National Park and one in Valais.

Resources required

The continued operation of the twelve main phenological stations is assured under the legal mandate of MeteoSwiss. The Geneva and Liestal-Weideli sites are not part of the phenological monitoring network; as they are operated on a voluntary basis, the observations are not considered to be guaranteed.

MeteoSwiss – Swiss phenology network

Legal basis

Under the Federal Act on Meteorology and Climatology (MetG, SR 429.1), the federal authorities are required to record meteorological and climatological data continuously throughout Switzerland. In addition, they are responsible for the implementation of measures contributing to the long-term preservation of an intact environment. MeteoSwiss, which is responsible for these tasks under the Federal Ordinance on Meteorology and Climatology (MetV, SR 429.11), conducts detailed phenological observations. Also involved in phenological aspects of biodiversity, agriculture and healthcare are the Federal Office for the Environment (FOEN), the Federal Office for Agriculture (FOAG) and the Federal Office of Public Health (FOPH).

4.1 Water use

Water resource availability is essential for the provision of supplies to the public and for various economic sectors. With rising temperatures, longer dry periods and seasonal fluctuations, climate change affects water supplies and demand. In-depth knowledge of water consumption is therefore of great importance.

Measurements in Switzerland

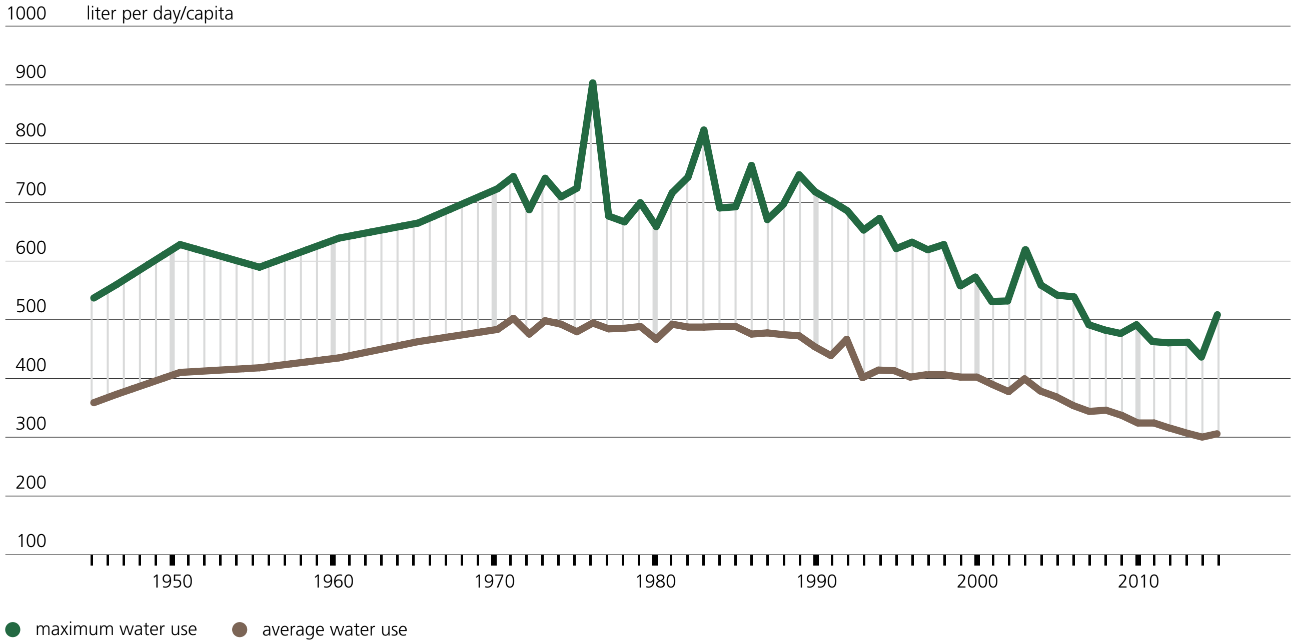
The natural geography of the Alps makes Switzerland a water-rich country. In Switzerland, water consumption data are collected by different agencies to different extents and with varying degrees of regularity. The Swiss Association of the Gas and Water Industry (SVGW) collects data on the extraction, treatment and supply of drinking water and industrial water through public water suppliers on an annual basis. However, data collection is only possible among its members, which supply 67 % of the population. Therefore, an extrapolation is necessary in order to estimate the water consumption of the total amount of water used. The main source of drinking water in Switzerland is groundwater, which is accordingly of great importance and subject to systematic qualitative and quantitative monitoring (→ 3.2 Groundwater).

Water consumption associated with Swiss agriculture is confined to relatively small areas and essentially to extremely dry areas and vegetable farming. Sparse information is available on the distribution and extent of agricultural irrigation. This is due to Switzerland's federalist structures, which explain the lack of uniform data. Quantitative values concerning irrigated areas are determined with the aid of surveys conducted by the Swiss Farmers' Union and the Federal Office for Agriculture (FOAG). The latest update took place in 2007.

Long time series and their importance

Since 1945, data on the per capita drinking water consumption in Switzerland has been collected through the SVGW. This offers the potential for a detailed analysis of the long-term development and allows for the estimation of future trends. As such, it reveals that the total drinking water consumption per capita is declining in Switzerland (see figure below). Despite a steady increase in population, it has been reduced by more than 100 liters per person per day since the end of the 1990s. It is estimated to be around 300 liters today, whereof only 142 liters are consumed in the households. This development is due to the spread of water-saving technologies in households which includes the increased efficiency of washing machines, dishwashers and water-saving fittings in kitchen and bathrooms. Furthermore, various branches of industry have moved their production sites and thus a portion of their water consumption abroad, which contributes to the lower per capita consumption of the industry sector.

Changes in use of drinking water for 1945–2015



The long-term development of the maximum (dark green) and average (brown) drinking water consumption per day per capita in Switzerland shows an increase until the mid-1970s and a steady decrease thereafter. Non-revenue-water and water losses are also included. Source: SVGW

International integration

Per capita water consumption is a standard international environmental indicator used by the Organisation for Economic Cooperation and Development (OECD) and the Food and Agriculture Organization (FAO) in various studies to assess sustainability. The FAO maintains a global information system on agricultural water use, particularly in developing and emerging countries (AQUASTAT). AQUASTAT is part of the Global Terrestrial network for Hydrology (GTN-H), to which the global networks on river discharge (GRDC) and groundwater (IGRAC) also belong (➞ 3.1 Rivers and ➞ 3.2 Groundwater). The information on water consumption in Swiss agriculture supplied to the AQUASTAT database is based on FOAG estimates.

Resources required

The last survey concerning agricultural irrigation dates back to 2007. In view of the growing demand for water arising from climate change and associated changes in production conditions, there is a need for systematic data collection efforts so as to estimate the country's irrigation requirements.

SVGW

Bundesamt für Statistik – Umweltindikator – Trinkwasserverbrauch

Legal basis

The Federal Water Protection Act (GSchG, SR 814.20) aims at ensuring economic use of drinking and process water and at protecting water used for agricultural irrigation from adverse impacts. The legislation also includes provisions on residual flows, i.e. restricting water withdrawals from surface waters. Concessions or licenses granted by the cantonal authorities are required where water is used for irrigation. In contrast, drinking water extraction has priority in the exploitation of groundwater resources. The legal basis is provided by cantonal water management legislation.

4.2 Greenhouse gas fluxes

Observing greenhouse gas fluxes is important in order to understand their sources and sinks, to validate national inventories, and to assess mitigation strategies. At ecosystem scale, fluxes are often measured by the eddy covariance technique. At regional to global scales, atmospheric measurements are combined with transport simulations and inverse modelling.

Measurements in Switzerland

Carbon dioxide (CO_2) fluxes are measured at two urban and six ecosystem sites. The six ecosystem sites are part of the Swiss FluxNet network, maintained by ETH Zurich (Grassland Sciences group). CO_2 fluxes have been measured for 10 to 20 years at two forest sites (Davos, Lägeren), three grassland sites of different management intensity (Chamau, Früebüel, Alp Weissenstein), and one cropland (Oensingen). At Chamau and Davos, methane (CH_4) and nitrous oxide (N_2O) fluxes are also measured. In addition, the University of Basel (Meteorology, Climatology and Remote Sensing Group, MCR) maintains two stations (Basel Klingelbergstrasse, Basel Aeschenplatz) for urban CO_2 fluxes. Data and metadata collected at the ecosystem sites by ETH Zurich are all uniformly processed and openly available through ETH Zurich and international databases. Data from the urban sites are stored in the MCR database and are freely available upon request.

Regional greenhouse gas emissions are quantified by Empa (Swiss Federal Laboratories for Materials Science and Technology), University of Bern and ETH Zurich using atmospheric inverse modelling, combining atmospheric concentration measurements and transport simulations. CO_2 and CH_4 concentrations are monitored at two sites: Jungfraujoch (Empa) and Beromünster (University of Bern). Furthermore, continuous measurements of N_2O and halogenated greenhouse gases are performed at the high-altitude site Jungfraujoch (Empa). The two stations Davos and Jungfraujoch are the Swiss contribution to the European Infrastructure programme ICOS RI (Integrated Carbon Observation System Research Infrastructure), both part of the ICOS-CH network.

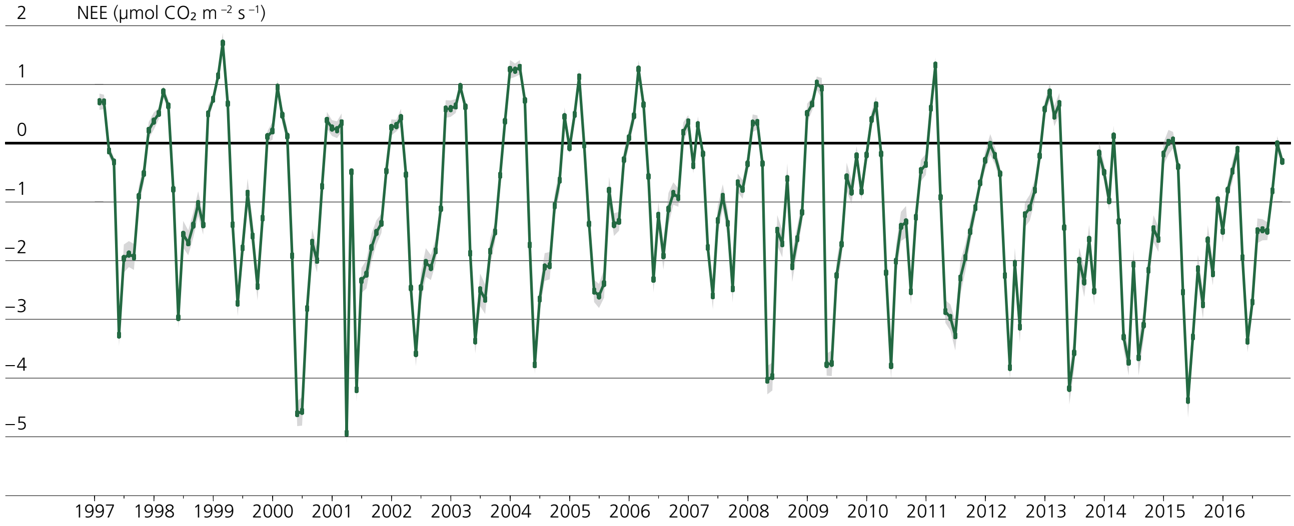
Greenhouse gas flux stations (brown dot: forest: CH-DAV, CH-LAE; red dot: grassland, CH-CHA, CH-FRU, CH-AWS; orange dot: cropland, CH-OE2; black dot: urban, BKLI, BAES).

Long time series and their importance

CO_2 flux measurements in Davos started in 1997, resulting in one of the longest time series globally. Measurements above different land use types within Swiss FluxNet provide unique information on Swiss greenhouse gas fluxes. Their high temporal resolution permits investigating functional relationships and responses of the biosphere to environmental change. Furthermore, impacts of management activities and anthropogenic emissions can be directly measured.

The measurements of anthropogenic greenhouse gases at Jungfraujoch began in 2000. Currently, CO_2, CH_4, N_2O, sulfur hexafluoride (SF_6), and over 50 halogenated synthetic gases are monitored (→ Chapters 2.11 and 2.12). These time series are combined with models to derive emissions at regional and national scales. Resulting emission estimates are used as independent estimates in comparison to Switzerland's national greenhouse gas inventory report as reported to the UNFCCC.

Davos ICOS Flux Site 1997–2016



Long-term net ecosystem CO_2 fluxes (NEE) measured at the ICOS site Davos since 1997. The green line shows the average monthly fluxes measured between 1997 and 2016; the grey area shows the standard error of the mean. Negative fluxes depict CO_2 uptake by the ecosystem, positive fluxes depict CO_2 losses from the ecosystem. The subalpine Norway spruce forest has been a carbon sink ever since measurements started. It shows a remarkable growth during the early season which peaks typically in May and then gradually declines until winter dormancy. Hence, climate change affecting the early season (May) is expected to have a much stronger influence on tree growth and thus on the C sequestration of this forest than changes affecting summer or autumn.

International integration

All Swiss FluxNet sites are part of the global FLUXNET, while both urban stations are part of the Urban Flux Network. In addition, the forest site Davos and the atmospheric station Jungfraujoch are in the process of becoming official ICOS RI Class 1 stations. Thus, quantification of greenhouse gas emissions as well as carbon sink and sources across Europe will be achieved in a standardised way within ICOS RI. These data will be open-access, also to the relevant political stakeholders, e. g. for Switzerland's National Inventory Report. The measurements at Jungfraujoch are part of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) programme and the international Advanced Global Atmospheric Gases Experiment (AGAGE) network, and are made available through the World Data Center for Greenhouse Gases (WDCGG). Furthermore, emission estimates will play a key role in a future global survey system (e. g. IG3IS, Integrated Global Greenhouse Gas Information System).

Resources required

Swiss FluxNet, the measurements of halogenated compounds at Jungfraujoch, and all computational activities at the Swiss National Supercomputing Center and the Empa Linux cluster are financed through short-term research projects. The measurements at Jungfraujoch are largely financed through the National Air Pollution Monitoring Network (NABEL: FOEN, Empa). The sites Davos and Jungfraujoch currently receive funding from the Swiss National Science Foundation (SNSF) within the ICOS-CH Network.

ETH Zurich:
- **Swiss FluxNet**
- **ICOS-CH**

CarboCount-CH

Empa – Climate Gases

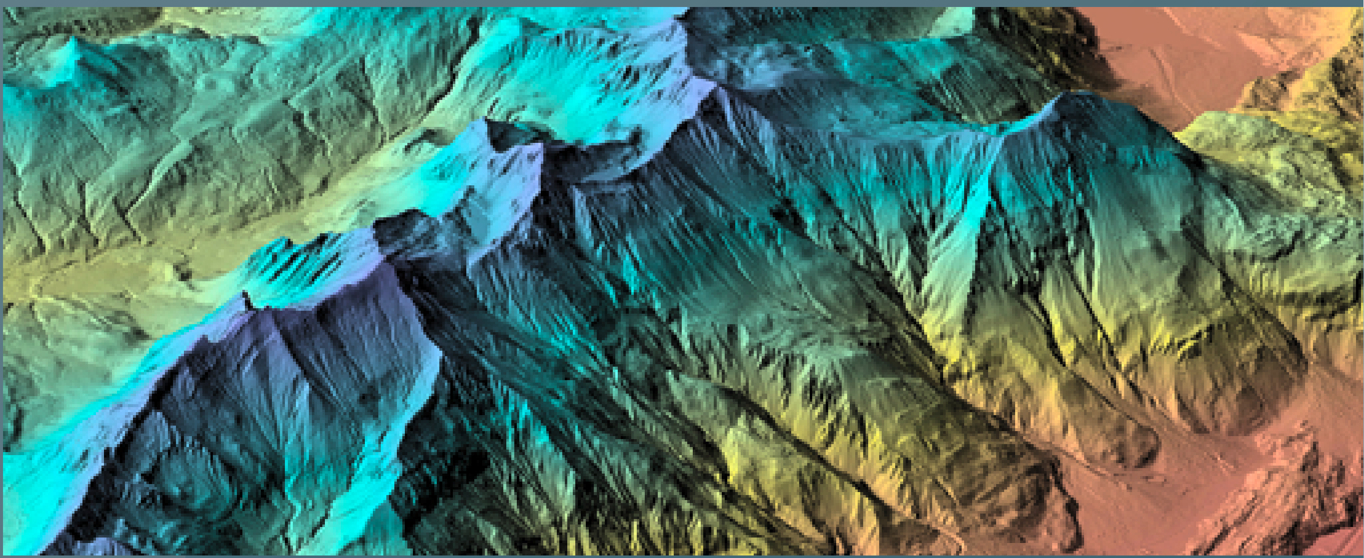
Swiss climate reporting under the UNFCCC

Legal basis

The Federal Office for the Environment (FOEN) produces an annual greenhouse gas inventory according to obligations of the United Nations Framework Convention on Climate Change (UNFCCC). The revised Swiss carbon dioxide (CO_2) law (SR 641.71) requires a reduction of nationally emitted greenhouse gases by 2020 of at least 20% compared to 1990. Validation of these goals is not regulated, but measurements are harmonised at European level within ICOS RI, both to quantify biosphere-atmosphere exchange as well as for inverse modeling of emissions on national and continental scales.

5.1 Digital Elevation Model

The Digital Elevation Model (DEM) is a three-dimensional representation of a terrain's surface. In general, changes in the topography of the solid Earth are of great interest for climate studies. For instance, any change in surface morphology will affect catchment hydrology. DEMs are of fundamental value for climate observations.



Measurements in Switzerland

swissALTI^{3D} is an extremely precise Digital Elevation Model which describes the surface of Switzerland without vegetation and development. It covers the entire territory of Switzerland and Liechtenstein and is updated in a predefined cycle of six years. The Terrain Model is available as original measurements in the form of break lines and height points or in a grid with 2 m spacing.

The Terrain Model is derived by photogrammetric means from aerial imagery produced by the Federal Office of Topography for a multitude of purposes. The imagery covers the entire territory of Switzerland and Liechtenstein and is updated in a predefined cycle of three years. swissALTI^{3D} can be used for a number of different applications and offers an ideal basis for a wide variety of areas. For example, it can be used as a height basic data set in a geographical information system; as a basis for 3D visualisations, simulations and visibility analyses; as a basis for mapping small structures and forest paths; as a planning tool in the fields of spatial planning, telecommunication, natural hazards and forestry; as a basis for orthorectification of aerial and satellite images.

swissSURFACE^{3D} is the Digital Surface Model (DSM) representing the Earth's surface including all stable and visible landscape elements such as soil, natural cover, woods and all sorts of constructive works. The DSM covers the entire territory of Switzerland and Liechtenstein and is – from 2018 onwards – updated in a predefined cycle of six years. It can be used for various applications. For example, the (true)-orthorectification of aerial and satellite images, the computation of trees and buildings height, the computation of volume for constructed and natural (forest) elements or line-of-sight analysis.

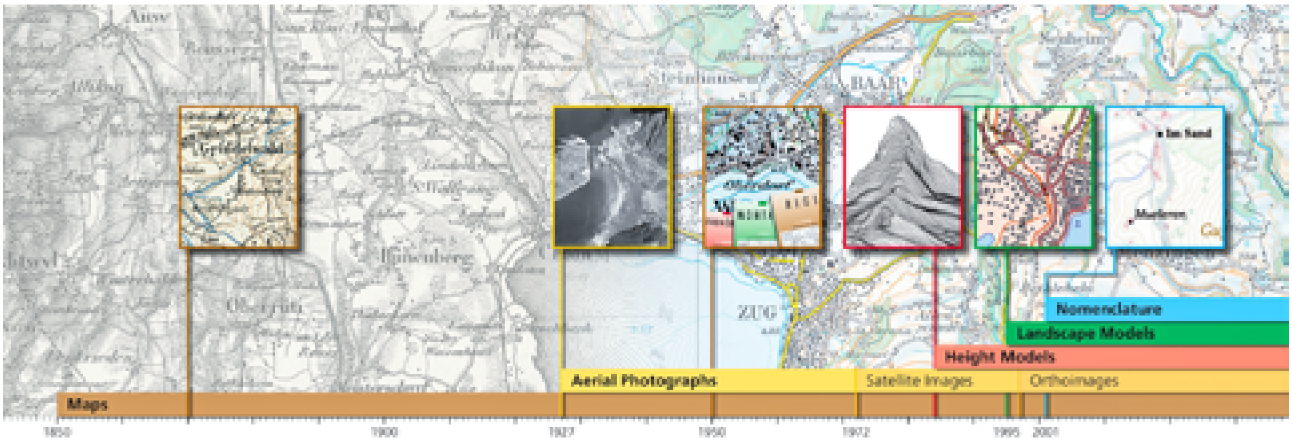
The Digital Terrain Model covers the entire territory of Switzerland and Liechtenstein and is updated in a predefined cycle of six years.

Long time series and their importance

Digital Terrain Models reflect climate change over longer periods. In Switzerland, Digital Terrain Models in different technical resolutions and accuracies have been available since the early 1980s.

Based on the archived aerial imagery of the Federal Office of Topography the reconstruction of Digital Terrain and Digital Surface Models as far back as the year 1920 is possible. Furthermore, a reconstruction of these data sets back to the mid-19th century is feasible. However, these programmes are not funded yet.

Time series of georeference data



Digital Terrain Models in Switzerland have been available since the early 1980s.

International integration

The Swiss Elevation Models are part of various Elevation Models on a European scale, such as EuroDEM (EuroGeographics) and the Terrain Model used by the European Organisation for the Safety of Air Navigation (EuroControl).

Resources required

The maintenance and updating of the Digital Elevation Models in Switzerland are covered by the activities of the national surveying scheme performed under the responsibility of the Federal Office of Topography (swisstopo).

swisstopo

swisstopo – swissALTI3D

Legal basis

Under the Federal Constitution of the Swiss Confederation (Cst; SR 101) the national surveying is a task for the federal government (Art. 75a Cst). The Federal Office of Topography (swisstopo) is the national agency responsible. The principles governing the types and collection of geodata relating to the territory of the Swiss Confederation are specified in the Ordinance on National Land Survey (NLSO; SR 510.626). The Federal Act on Geoinformation (GeoIA SR 510.62) ensures that geodata relating to the territory of the Swiss Confederation is made available for general use to the authorities of the Confederation, the cantons and communes, the private sector, the public and to academic and scientific institutions in a sustainable, up-to-date, rapid and easy manner, in the required quality and at a reasonable cost.

5.2 Topographic Landscape Model

The Topographic Landscape Model (TLM) is a three-dimensional representation of all natural and man-made objects that shape the landscape, e.g. buildings, roads, vegetation or bodies of water. In general, changes in the topography are of great interest for climate studies. Virtually all atmospheric surface and terrestrial ECVs require proper topographic information to enable meaningful interpretation.

Measurements in Switzerland

The Topographic Landscape Model is the central instrument for the production of national geodata. It contains natural and man-made objects that shape the landscape. These data are recorded, processed, managed and kept up-to-date, with a high degree of accuracy and in three-dimensional form, and are subsequently placed at the disposal of the various users.

This unique and complete 3D dataset encompasses the entire country with a high degree of quality and in homogeneous form. The database contains more than 13 million objects in three-dimensional form depicting their location and shape. For each object, supplementary details are included, e.g. object type, usage and relation to other objects. The objects are recorded in the form of point, linear or surface-based 3D vectors and subsequently geo-referenced in the Topographic Landscape Model, i.e. stored with the relevant spatial reference.

The objects contained in the Topographic Landscape Model are divided into the following eight thematic categories: roads and tracks (road and path network, cycling paths and footpaths); public transportation (railway tracks and other rail systems, shipping routes and public transport stops); buildings (buildings, walls, dams, constructions relating to transport, communication, energy, sport and leisure); areas (plots with special land usage such as transport, nature, habitat, leisure, etc.); land cover (ground coverage independent from land usage); hydrography (watercourses and lake contours); single point objects (selection of prominent landscape features which aid orientation) and names (e.g. mountains, areas, towns).

The production and updating of the Topographic Landscape Model is based on current aerial images. The various objects are digitally recorded and stored with the aid of photogrammetric 3D evaluation.

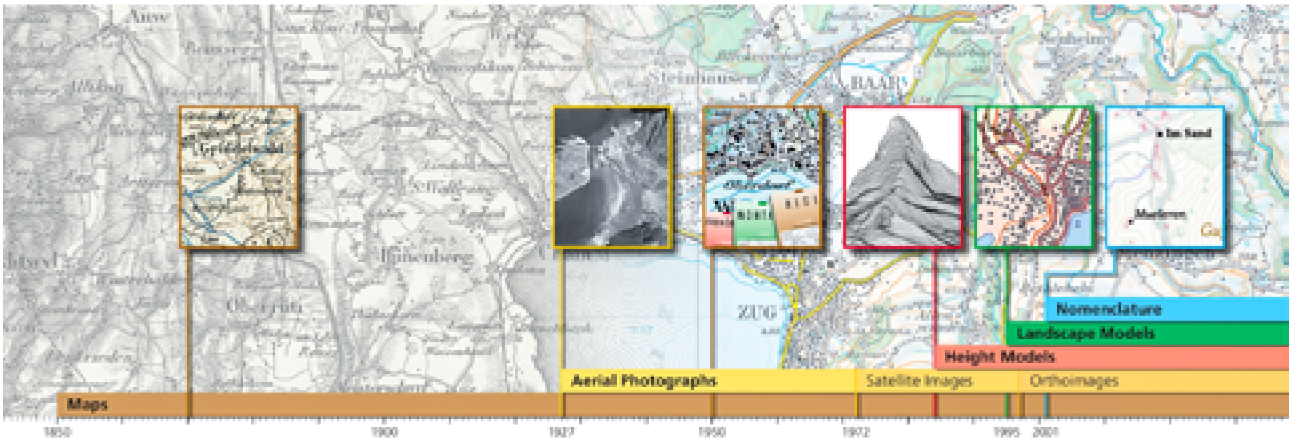
The Topographic Landscape Model covers the entire territory of Switzerland and Liechtenstein and is updated in a predefined cycle of six years.

Long time series and their importance

The Topographic Landscape Model is currently in the development stage. According to the defined schedule, the complete version is expected to be available by 2019. The derived product «swissTLM^{3D}» is available nationwide, but it does not yet meet all the applicable requirements. For example, the number of object types still needs to be increased and the geometric accuracy does not meet the quality requirements placed on the Topographic Landscape Model in those sections that have not yet been fully developed. After it has been completed, the model will be periodically updated. Those object types that have been fully integrated are already being periodically updated today.

Unlike previous landscape models in Switzerland, the Topographic Landscape Model is produced directly on the basis of aerial images instead of the national map. Because the specialists now no longer use generalised basic data, they can depict the various objects and their respective locations more accurately and in greater detail.

Time series of georeference data



Topographic Landscape Models in Switzerland have been available since the mid-1990s. However, due to the technological development and the change from a cartography-based to a primary-generated Topographic Landscape Model, the geometric comparison in time needs a lot of advanced knowledge about the generation of the different landscape models.

International integration

The Topographic Landscape Model forms a part of various Landscape Models on a European scale, such as EuroGlobalMap and EuroRegionalMap of EuroGeographics.

Resources required

The maintenance and updating of the Topographic Landscape Model in Switzerland are covered by the activities of the national surveying scheme performed under the responsibility of the Federal Office of Topography (swisstopo).

swisstopo

swisstopo – The Topographic Landscape Model TLM

swisstopo – swissTLM^{3D}

Legal basis

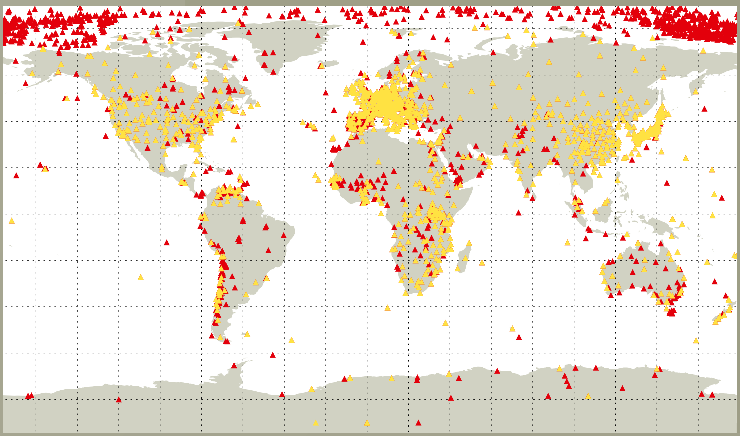
Under the Federal Constitution of the Swiss Confederation (Cst; SR 101) the national surveying is a task for the federal government (Art. 75a Cst). The Federal Office of Topography (swisstopo) is the national agency responsible. The principles governing the types and collection of geodata relating to the territory of the Swiss Confederation are specified in the Ordinance on National Land Survey (NLSO; SR 510.626). The Federal Act on Geoinformation (GeoIA SR 510.62) ensures that geodata relating to the territory of the Swiss Confederation is made available for general use to the authorities of the Confederation, the cantons and communes, the private sector, the public and to academic and scientific institutions in a sustainable, up-to-date, rapid and easy manner, in the required quality and at a reasonable cost.

6.1 GEBA

The Global Energy Balance Archive (GEBA) systematically stores observational data on energy fluxes from around 2500 stations worldwide. Energy fluxes at the Earth's surface largely determine global heat transports and the atmospheric circulation. To understand the climate and climatic changes, therefore, a detailed knowledge of the variations in the energy balance is essential.

Global measurements

The first version of the GEBA database was implemented at the ETH Zurich in 1988. In 1991, the database was first made available to the global scientific community. In 1994/1995, GEBA was redesigned and a large amount of data was added. The database is regularly updated, with great importance being attached to a series of quality control procedures. The archive currently contains 500,000 records of monthly mean energy fluxes measured at 2500 stations worldwide (see figure below). GEBA incorporates various energy balance components, with a total of 19 different variables. These include, for example, global radiation, short- and long-wave radiation and turbulent heat fluxes. It should be noted that the values have been and are measured using different instruments. In addition, at most sites, instruments have been replaced over the years. Data consistency and details of changes in instrumentation are integrated into GEBA as station history data – an important element in data analysis.

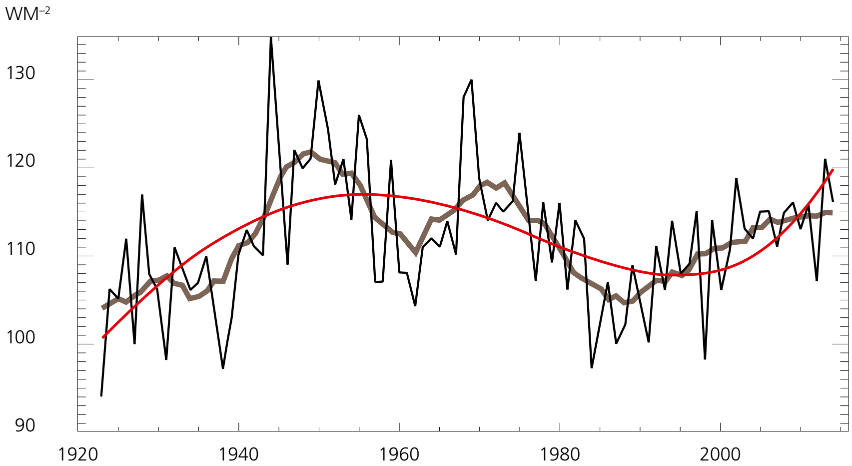


The GEBA database holds about 500,000 records of monthly mean energy fluxes measured at 2500 stations worldwide. (Adapted from Wild et al. 2017)

Importance for GCOS

The data stored in GEBA serve a variety of important functions in climate research: (a) estimating the global energy balance and its temporal variation, (b) validating surface energy fluxes derived from satellite observations as well as simulated by global and regional climate models, (c) studying absorption of solar radiation by clouds and (d) evaluating the climate impact of aerosols. On a more applied level, GEBA is also crucial for solar resource assessments in the context of solar power production. The longest energy flux data series come from European sites – Stockholm, Wageningen, Davos, Potsdam and Locarno-Monti. At these five stations, radiation measurements began before 1940. The long-term records from GEBA allowed the detection of substantial multidecadal variations in the amount of solar radiation reaching the Earth surface, known as "global dimming and brightening" (see figure below). The GEBA energy balance components are of fundamental importance in understanding a variety of key processes in the climate system (including the cryosphere).

The longest continuous record in GEBA



The longest continuous record available in GEBA: surface downward shortwave radiation (Wm²) measured in Stockholm since 1922. The brown line shows the 5-year moving average; the red line shows the fourth-order polynomial fit. Substantial multidecadal variations become evident, with an increase up to the 1950s (early brightening), an overall decline from the 1950s to the 1980s (dimming), and a recovery thereafter (brightening). (Adapted from Wild et al. 2017)

Responsibility

Since November 1986, the GEBA has been a World Climate Programme (WCP) project under the lead of the World Meteorological Organization (WMO), United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Council for Science (ICSU). The database is located at the Institute for Atmospheric and Climate Science (IAC) at the ETH Zurich.

Resources required

Continued operation of GEBA at 2018 ETH Zurich is not assured. From 2017 onward, additional funding is necessary to allow the operational continuation of GEBA.

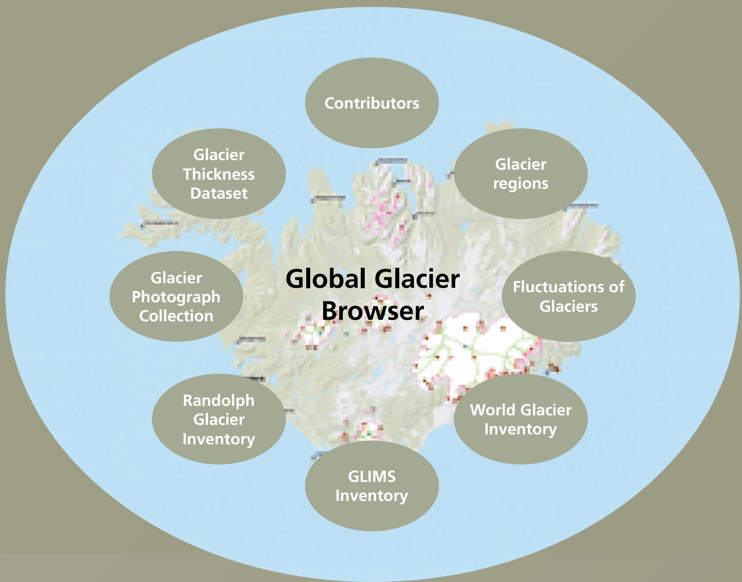
ETH Zurich – Global Energy Balance Archive

6.2 WGMS

The activities of the World Glacier Monitoring Service (WGMS) are of crucial importance for climate observation. As well as being among the most sensitive climate indicators, glaciers play a key role in the regional water balance and contribute to rising global sea levels associated with climate change.

Global measurements

The WGMS manages a very comprehensive collection of data on glaciers, their characteristics and fluctuations over time. These regularly updated data are made available to scientists and the public. The database currently holds more than 45,000 length change measurements from 2521 glaciers and over 6000 mass balance observations from 427 glaciers worldwide, extending back to the 19th century. Recently, the dataset has been extended with geodetic mass balances from 1830 glaciers, in collaboration with the European Space Agency (ESA) Climate Change Initiative. The WGMS provides an integrative assessment of worldwide and regional glacier changes in the Global Glacier Change Bulletin (GGCB) series which is published at 2-yearly intervals. Statistical information on global glacier distribution including geographical location, area, length, orientation, elevation and classification of morphological type is available from the World Glacier Inventory (WGI; historical inventory around 1970s without digital outlines), the Randolph Glacier Inventory (RGI, digital outlines around 2000), and the Global Land Ice Measurements from Space database (GLIMS; multitemporal digital outlines). In addition, a Glacier Thickness Dataset (GlaThiDa) was launched and updated. Access to all the different glacier data is granted through the Global Terrestrial Network for Glaciers (GTN-G) Global Glacier Browser.

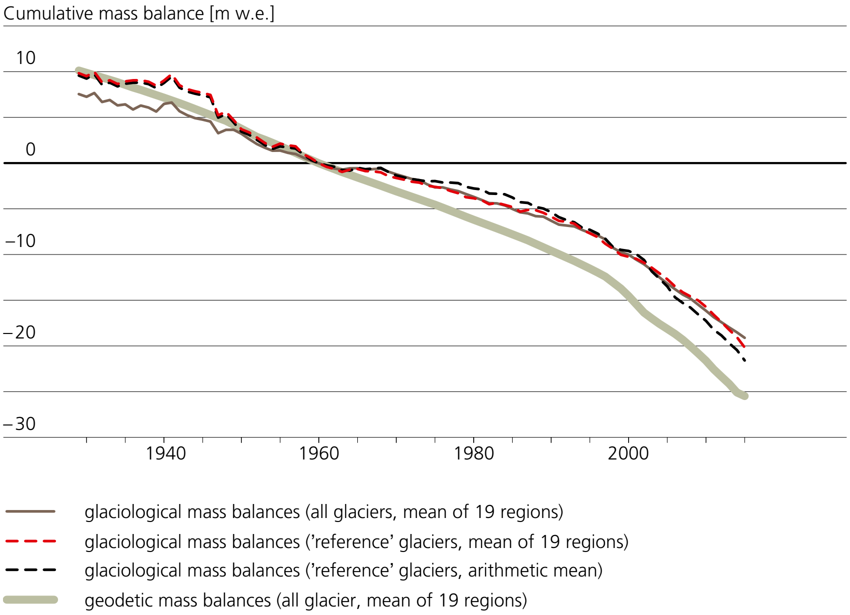


GTN-G Global Glacier Browser: Interactive scheme of the Global Glacier Browser providing an overview of and access to the different glacier datasets available on the GTN-G website (gtn-g.org/)

Importance for GCOS

The collection of data on glacier variations worldwide was initiated in 1894 with the establishment of the International Glacier Commission at the 6th International Geological Congress in Zurich. Since 1986, the WGMS, based at the University of Zurich, has coordinated the international collection and publication of glacier data. In close collaboration with the US National Snow and Ice Data Center (NSIDC) and the GLIMS initiative, the WGMS is in charge of GTN-G within GCOS. Remote sensing methods were developed in the GLIMS project and are becoming increasingly important for the creation of glacier inventories as well as for geodetic glacier change surveys (ESA Glaciers_CCI, Copernicus Climate Change Services).

Mass balance for glaciers worldwide



Cumulative mean annual mass balance from 1930 to 2015. The 'reference' glaciers include 41 glaciers with more than 30 years of ongoing measurements in nine mountain ranges. The glaciers are in North America (13), South America (1), Europe (21) and Asia (6). This internationally recognized index (cf. Haeberli, 2004; 2005) includes data on the Swiss glaciers Silvretta, Allalin, Gries, and Giétro. The average mass balance reduction of –764 m w. e. over the period 2001–2010 has been without precedent for the time period with available observations. Source: WGMS (2017).

Responsibility

The WGMS is a service of the International Association of Cryospheric Sciences (IACS) of the International Union of Geodesy and Geophysics (IUGG), and a member of the World Data System of the International Council for Science (WDS/ICSU). The WGMS maintains contacts with local researchers and national correspondents in all countries involved in glacier monitoring. The WGMS makes an important contribution to GCOS within the global climate observation programmes of major international organisations (UN Environment, WMO, UNESCO, and ICSU). Over the past years, capacity-building and twinning projects have been carried out, based on Swiss Agency for Development and Cooperation (SDC) funds (for capacity knowledge and development). The wgms Glacier App has strongly increased the visibility of internationally coordinated glacier monitoring activities at the level of international organisation and has started to reach a wider public.

Resources required

Since 2010, the core funding for the WGMS has been secured through GCOS Switzerland and the University of Zurich. Additional funds at project basis come from SDC for dedicated capacity-building and twinning activities as well as from ESA and Copernicus for specific remote-sensing products.

WGMS

wgms Glacier App

GTN-G

Global Glacier Browser

6.3 Other centres

To determine state and variability of the climate system, measurements need to be globally standardised and meet the highest quality standards. With their reference instruments and regular calibration activities, international calibration centres make a vital contribution to the quality of global observation programmes.

World Radiation Centre (PMOD/WRC)

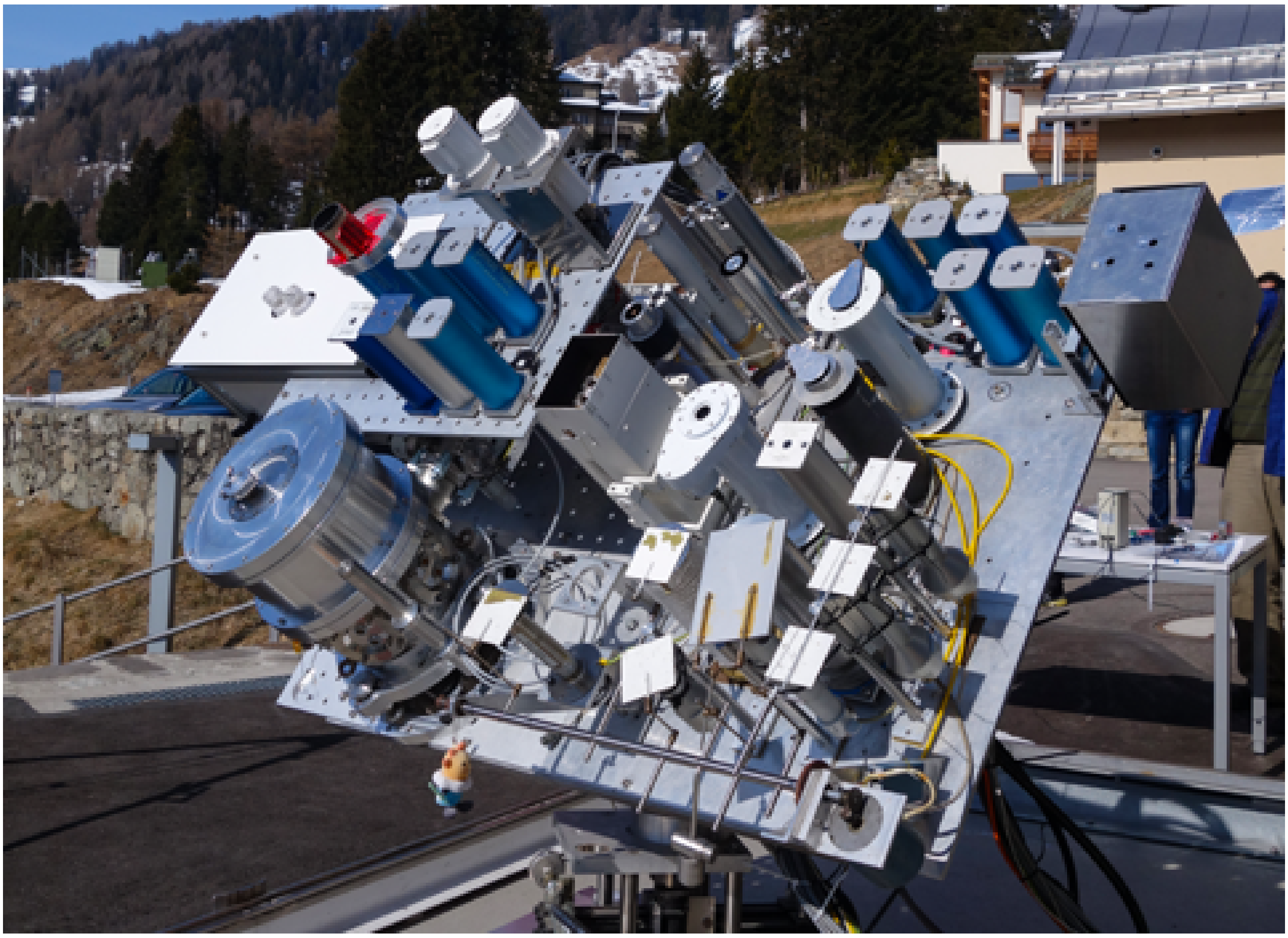
The Physical Meteorological Observatory (PMOD) was founded at Davos in 1907 to carry out research in the field of solar radiometry and to study the effects of climate and weather conditions on humans, animals and plants. In 1971, the World Radiation Center (WRC) was established at the PMOD on the recommendation of the World Meteorological Organization (WMO). In 2006, the WMO Commission for Instruments and Methods of Observation (CIMO) resolved that the WRC should be divided into four sections, including two additional World Calibration Centers belonging to the Global Atmosphere Watch Programme (GAW) of the WMO.

Solar Radiometry Section (WRC-SRS)
The main responsibilities of the WRC-SRS Section are (a) to guarantee worldwide homogeneity of meteorological radiation measurements by maintaining the World Standard Group (WSG) which is used to establish the World Radiometric Reference (WRR); (b) to support the calibration of meteorological radiation instruments; (c) to promote research and development in radiometry and methods of observation of atmospheric radiation parameters; and (d) to provide training for radiation specialists.

Infrared Radiometry Section (WRC-IRS)
The WRC-IRS was originally established at the PMOD/WRC in 2004 on the recommendation of the CIMO and has been a Section of the WRC since 2006. The WRC-IRS has established an interim WMO Pyrgeometer Infrared Reference using the procedures and instrumentation that make up the World Infrared Standard Group (WISG) of pyrgeometers. The Section holds the global infrared radiation reference and thus defines the longwave infrared scale to which all longwave infrared radiation measurements are traced. The role of the WRC-IRS is to disseminate this scale to the worldwide community either by individual instrument calibrations at the PMOD/WRC or through International Pyrgeometer Comparisons (IPgC) held every 5 years in conjunction with the International Pyrheliometer Comparisons (IPC).

World Calibration Center of GAW – World Optical depth Research and Calibration Center (WORCC)
The WORCC was established at the PMOD/WRC in 1996. Its current tasks include: (a) development of a radiometric reference for spectral radiometry to determine atmospheric optical depth (AOD); (b) development of procedures to ensure worldwide homogeneity of AOD observations; (c) development and testing of new instrumentation and methods for AOD; (d) development of quality control of data, in cooperation with the GAW Quality Assurance/Science Activity Centres (QA/SAC); (e) operation of a reference network for AOD using precision filter radiometers; and (f) training operators on AOD measurements.

World Calibration Center of GAW – World Calibration Center for UV (WCC-UV)
The WCC-UV obtained the status of World Calibration Center of the GAW Programme of the WMO in 2013, extending its role as Regional Calibration Center for UV to a global scale. Its current tasks include to (a) assist WMO Members operating WMO/GAW stations to link their UV radiation observations to the WMO/GAW UV Reference Scale through comparisons of the station instruments with the standard instruments operated by PMOD/WRC, (b) assist the WMO/GAW Scientific Advisory Group (SAG) on UV radiation in the development of the quality control procedures required to support the quality assurance of UV observations and ensure the traceability of these measurements to the corresponding primary standard, (c) maintain a set of reference irradiance standards and ensure their traceability to the International System of Units (SI) through intercomparisons of transfer standards traceable to primary irradiance standards held at National Metrological Institutes (NMIs), (d) maintain and operate the transportable reference spectroradiometer QASUME (Quality Assurance of solar Spectral Ultraviolet irradiance Measurements carried out in Europe) for the routine quality assurance and calibration of spectroradiometers measuring spectral solar UV irradiance through regular site visits, (e) maintain and operate instrumentation to provide calibration facilities for UV radiation radiometers (spectral and broadband), and (f) provide traceability to the primary spectral irradiance standards of NMIs by calibrating spectral irradiance standards of UV monitoring laboratories.



World Calibration Centre (WCC-Empa)

The Swiss Federal Laboratories for Materials Science and Technology (Empa) has operated the World Calibration Centre WCC-Empa since 1996 as a Swiss contribution to the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO). Under this mandate WCC-Empa is responsible for verifying the traceability of surface ozone, carbon dioxide, methane and carbon monoxide measurements to the designated GAW reference. To date, more than 90 audits have been made at GAW stations. The audits ensure traceability to the GAW reference and determine the measurement bias in terms of the WMO/GAW compatibility goals. Moreover, parallel measurements for carbon dioxide, methane and carbon monoxide using a travelling instrument are made during audits. These campaigns assess the overall performance of the measurements at a station including air sampling and data evaluation processes. WCC-Empa shares knowledge gained through these activities by providing substantial input to GAW and GCOS related meetings, projects, reports and scientific publications.

Quality Assurance/Scientific Activity Centre Switzerland (QA/SAC)

The QA/SAC Switzerland was established at Empa in 2000 and is one of five such facilities in the GAW programme worldwide. Being closely linked to the World Calibration Centre also hosted by Empa, QA/SAC Switzerland mainly focuses on surface ozone, carbon monoxide, methane and carbon dioxide measurements but is also broader in scope and provides technical and scientific support in general. The overarching rationale is to maintain and improve the spatial coverage of atmospheric composition measurements of known quality, high precision and global consistency. Thus, the main tasks of QA/SAC Switzerland are (a) training, twinning, and capacity-building especially in developing countries, (b) research activities promoting technical progress and scientific data analysis, (c) contribution to GAW outreach, and (d) networking / cooperation with other programmes / projects in line with the GAW and GCOS strategy.

Euro-Climhist

Euro-Climhist is a database developed at the Institute of History, University of Bern. It includes early instrumental measurements, daily, weekly and monthly weather observations as well as reports on river freezing, snow cover, phenology, the impacts of natural disasters, and weather perception mainly for the period 1300–1900. The database allows comparing narratives on daily and monthly weather reports with results of climate reconstructions. For the period after 1500, Euro-Climhist is structured in the form of regional modules following the borders of modern countries. The first one comprising 160,000 observations concerning Switzerland has been freely accessible online since 2015. For the previous period a module "Medieval Europe" comprising the whole continent is in preparation. Since 2010, Euro-Climhist has been financed through GCOS Switzerland and the University of Bern.

PMOD/WRC

Empa – Global Atmosphere Watch

Euro-Climhist

7.0 Observations outside Switzerland

Introduction

Long-term, continuous and consistent time series of adequate quality worldwide are needed in order to get a representative global picture of the behaviour and trends of essential climate variables. In particular in developing countries, the operation of continuous observations is challenging and the sustainability is often threatened as a result of the limited technical and financial resources. The observations in foreign countries described below have been strongly supported through technical and/or financial patronage from Swiss institutions. A number of examples are given, but the list is by no means exhaustive.

Ozone

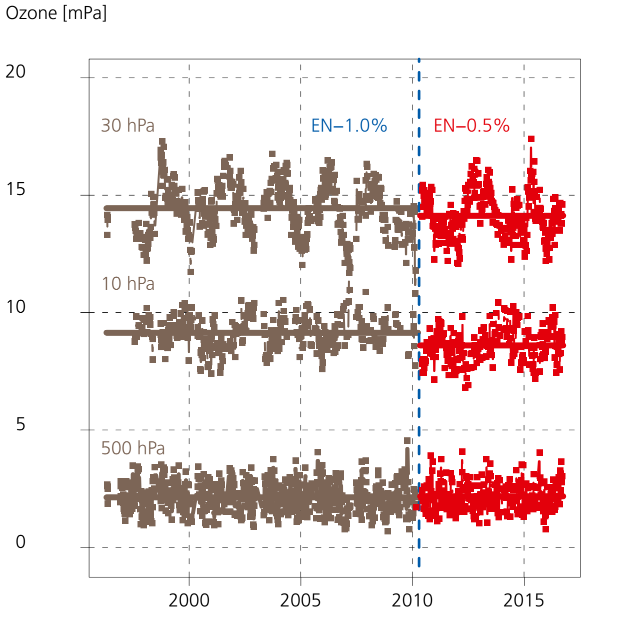
The Kenyan Meteorological Department (KMD) operates several ozone monitoring instruments at its headquarters in Nairobi. Ozone profiles are obtained on a weekly basis, total ozone is measured with a Dobson spectro-radiometer whenever possible, and surface ozone is monitored continuously.

This activity was initiated in 1996 by NASA (National Aeronautics and Space Administration) as part of the Southern Hemisphere ADditional OZonesondes (SHADOZ) network. SHADOZ was designed to produce consistent balloon-borne ozone profile data on tropical tropospheric ozone. It is currently pursued under the direction of the World Meteorological Organization (WMO), the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UN Environment). The observations are financially supported by Switzerland under the WMO Global Atmosphere Watch (GAW) programme. Continuous technical support to ensure performance and quality is provided by the Federal Office of Meteorology and Climatology MeteoSwiss.

Why is Switzerland engaged in these measurements? Ozone profiles measured in the tropics are fundamental for the understanding of the chemical and dynamic processes influencing ozone concentrations also in mid-latitudes. Ozone is produced in the tropics because of intense solar radiation. Subsequent vertical and horizontal displacement of ozone-rich air replenishes the ozone layer that protects the entire biosphere from UV radiation. Moreover, ozone profiles in the tropics play a key role in the validation of satellite data.

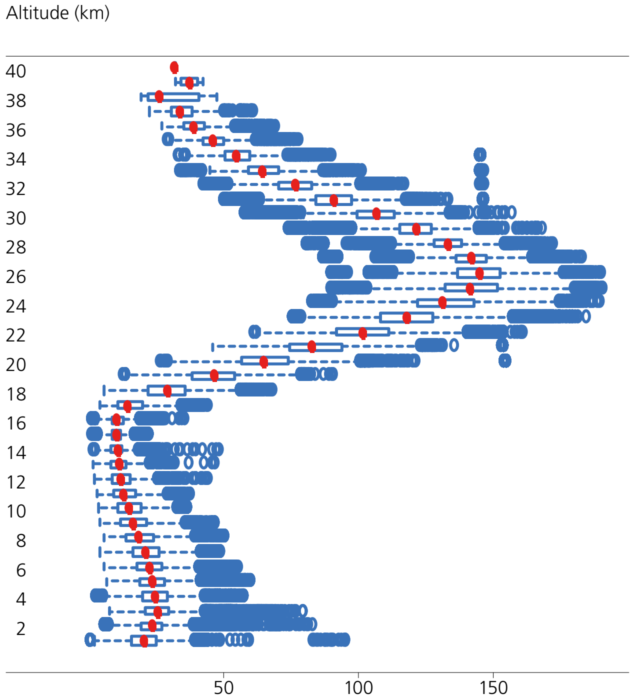
Each year, MeteoSwiss staff visit the station to train the KMD GAW team and undertake maintenance, calibration and technical upgrading of the various operational ozone measurement systems on site. The local KMD GAW team in Nairobi operates the instruments on a daily basis and performs a first level of quality control of the data. Second level quality control is carried out by MeteoSwiss in Payerne before the data are submitted to the international SHADOZ data center at the NASA Goddard Space Flight Center. A Brewer spectrophotometer will be commissioned in 2018 in Nairobi to complement the measurement programme. The KMD ozone station now provides a continuous and reliable data set going back more than 30 years that is of considerable value for various studies.

Ozone concentration time series in Nairobi, Kenya



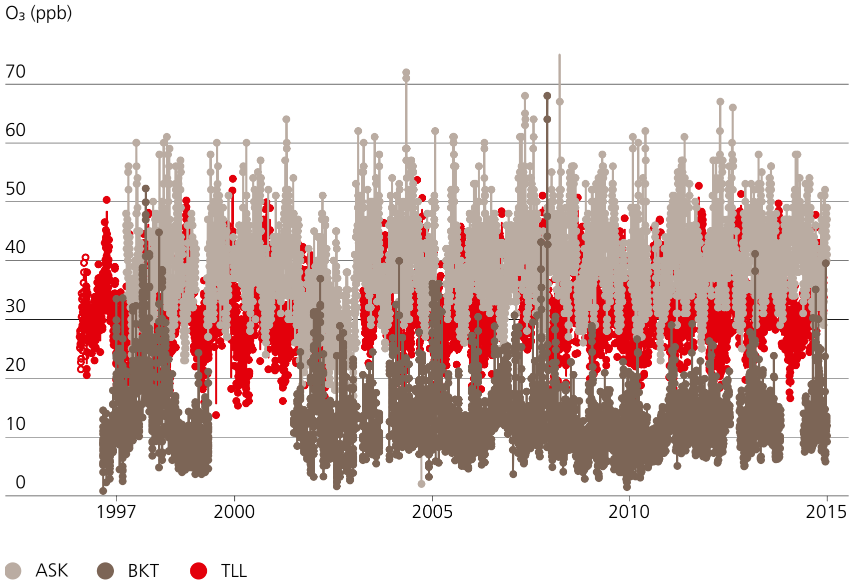
Ozone concentration time series at three characteristic levels in Nairobi, Kenya. The brown and red points display a change in the measurement procedures.

Average ozone profile above Nairobi



The IQR at all altitudes remains within ~20 nbar indicating a relatively small seasonal cycle at all altitudes.

Surface ozone at foreign GAW stations 1997–2015



Surface ozone (daily averages) at three measurement sites with Swiss support: Assekrem (ASK; Algeria; 2770 m a. s. l.), Bukit Koto Tabang (BKT; Indonesia; 964 m a. s. l.) and El Tololo (TLL; Chile; 2220 m a. s. l.). Support was given with respect to operation and maintenance, trouble-shooting, spare parts, and data processing. Different ozone levels are observed mainly due to the different station altitudes. Short-term variations reflect the complex interactions between ozone formation and destruction. Data: World Data Center for Greenhouse Gases.

Trace gases

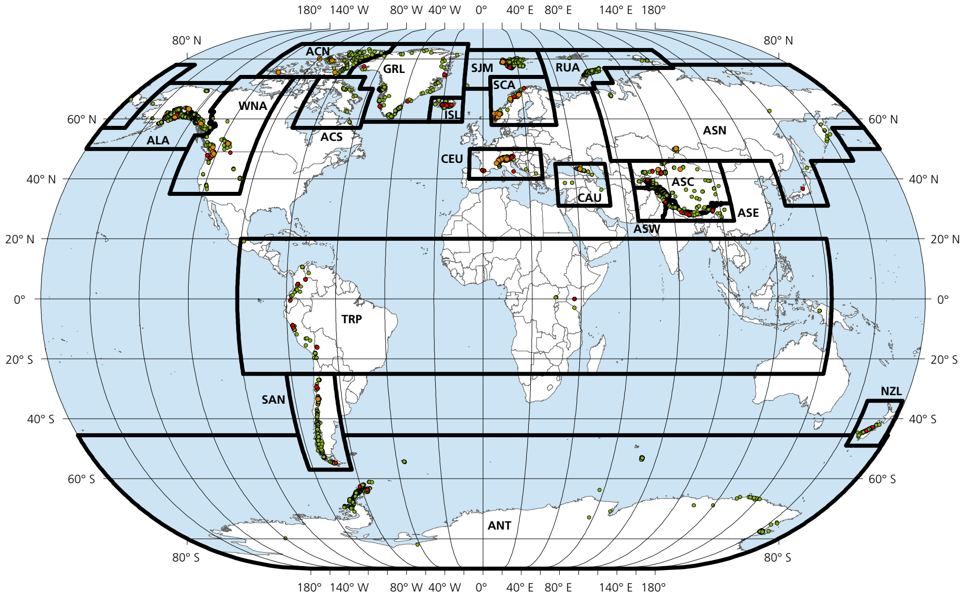
Switzerland – through operation of the World Calibration Centre (WCC-Empa) and the Quality Assurance/ Scientific Activity Centre (QA/ SAC Switzerland) (➞ 6.3 Other centres) – is a key contributor to Global Atmosphere Watch's quality management framework. Both centres jointly aim at maintaining and improving the spatial coverage of atmospheric composition measurements of known quality, high precision and global consistency. In order to achieve this, the centres focus on quality assurance, training of station staff as well as technical and scientific support. As one pillar of the support actions, twinning partnerships, i. e. close bilateral collaborations with the operators of air quality monitoring stations in developing and emerging countries, were initiated in the early 2000s. Initially, the main twinning stations were Assekrem (Algeria), Bukit Koto Tabang (Indonesia) and Mt. Kenya (Kenya). These stations were established in the mid-1990s under the Global Environment Facility (GEF: UNDP, UN Environment, World Bank) programme to fill evident gaps in the global observation network. These gaps were and are still located mainly in countries south of the equator, which are particularly vulnerable to the effects of climate change as a result of political, economic and social structures. It was recognized that a continuous support is key to maintaining high-precision observations after the end of the initial GEF programme. In the more recent past, twinning support became more diverse for various reasons. For example, the increasing renown of the centres' work resulted in a growing number of support requests, developments at some of the initial twinning stations led to changing demands, measurement networks in the partner countries were expanded towards additional sites, and technical means for remote support and trouble-shooting became available. However, all supported stations are located in data-sparse regions where technical capacities and financial resources are often lacking and where any enhanced capabilities and additional observations are highly welcomed by the GCOS community.

Considerable progress was made by some twinning partners during the last decades while less was achieved at other locations. These developments lead to a steady reassessment of the support priorities. As examples, the Mt. Waliguan station in China, also one of the stations established in the GEF programme, made considerable progress in the early years, leading to a ceasing need for support and a fully autonomous operation by the Chinese operators. The Indonesian meteorological service is currently expanding its measurements capabilities on Sulawesi and Papua based on the know-how acquired at Bukit Koto Tabang. Thus, additional advice was requested for site selection, set-up of the station and instrument procurement. In Chile, a more than 20-year ozone record was recently reprocessed and quality controlled, and then made publicly available in a data repository.

Glaciers

Glacier mass balance is the direct and undelayed reaction to the prevailing atmospheric conditions in a year and is thus one of the most important indicators used in international climate monitoring programmes. The World Glacier Monitoring Service (WGMS) at the University of Zurich supports and actively promotes the continuation of the 41 long-term 'reference' series. The WGMS also offers technical support for glacier observations, particularly in developing countries, including assurance of compliance with international methods and standards, data quality control, and training for glaciologists in the field. With support from the WGMS, new observations were recently initiated in the Tropical Andes (Colombia, Ecuador) and Central Asia (Kirgizstan, Uzbekistan). In addition to worldwide data compilation and dissemination, the WGMS is continuously involved in capacity-building and twinning activities. These activities are mostly covered by third-party funded projects. The well-known glacier monitoring programmes and the WGMS network represent ideal platforms and gateways to reach local stakeholders. They are therefore considered essential channels for capacity-building and twinning efforts. Reciprocally, these collaborations are very important enhancers of the monitoring programmes in terms of strengthening, maintaining, and improving systematic glacier and natural hazard monitoring.

Glacier observations worldwide



'reference' glaciers
glaciers with balance values 2013/2014 or 2014/2015
glaciers with balance values 2013/2014 or 2014/2015
glacier regions

Location of glaciers for which data is available from the WGMS. This overview includes 166 glaciers with reported mass balance data for the observation periods 2013/2014 and 2014/2015, and 41 'reference' glaciers with well-documented and independently calibrated, long-term mass balance programmes based on the glaciological method. Source: WGMS (2017).

Resources required

Funding of the ozone measurements in Nairobi (Kenya) is ensured through the international component of GAW-CH.

The trace gases measurements are run by the international partners but lack of resources and skills in the partner countries require systematic support by Switzerland. The degree of support is restricted by the manpower available at WCC-Empa and QA/SAC Switzerland. Moreover, hardware support can be provided only to a small extent. Expansion of the measurement programme, as is desired, to cover other regions as well as other atmospheric Essential Climate Variables would call for additional financial resources.

Additional funding is required to ensure the continuation of mass balance measurements at the 'reference' glaciers, the resumption of a number of discontinued long-term series, and the initiation of new glacier observations by WGMS and partners; as well as to extend the geodetic dataset derived from surveys with air- and space-borne sensors.

Ozone:

NASA

GAWSiS

Trace gases:

Empa – Global Atmosphere Watch

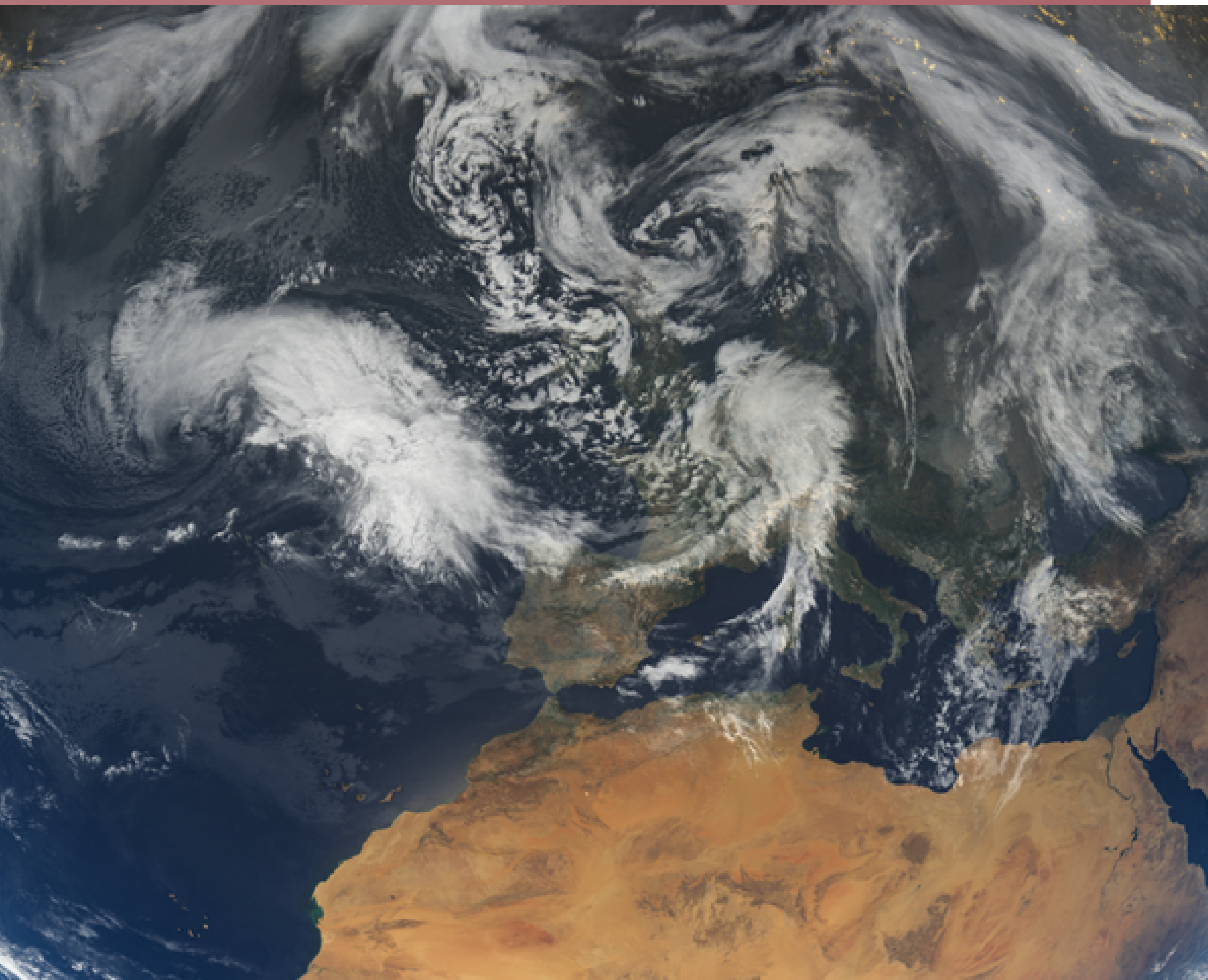
Glaciers:

WGMS capacity-building and twinning

Global Terrestrial Network for Glaciers (GTN-G)

8.0 Trends in climate monitoring

Two important trends can be identified to continuously improve climate monitoring. First, through technological advances sensors get better and cheaper, producing data sets with always higher resolution and greater accuracy. Second, new merging techniques are developed to combine data sets of different origins in order to generate enhanced long-term data sets.



Radar data for climate analysis

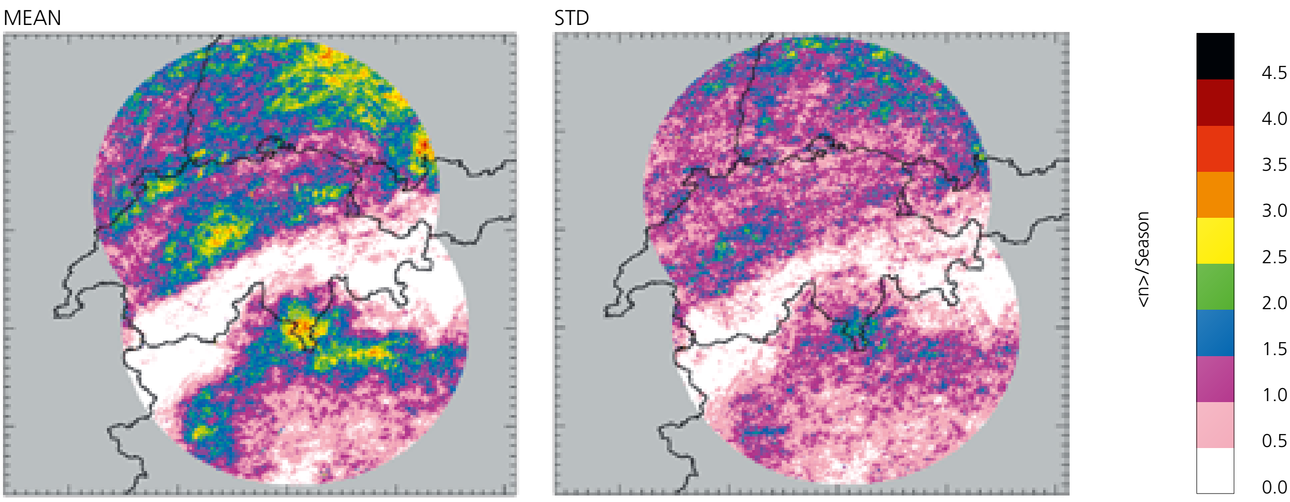
The Federal Office of Meteorology and Climatology MeteoSwiss currently operates a network of five, fully automated, weather radar stations with state-of-the-art dual-polarization and Doppler capabilities, working at C-band. The network has been fundamentally renewed over the last few years as part of the Rad4Alp project and has been substantially extended by adding two new locations in the Alps. The main utilisation area of weather radars is the very short-term forecast (nowcasting) of precipitation and storms. In recent years, however, some new important applications have also emerged in the climatological field, since the radar network covers the whole of Switzerland and the surrounding areas with a high-resolution Cartesian grid of 1 × 1 km².

The new CombiPrecip algorithm aims to produce accurate, high-resolution gridded precipitation estimation maps by integrating raingauges and radar data using a geostatistical co-kriging with external drift modelling scheme (Sideris et al. 2014). CombiPrecip is running operationally at MeteoSwiss and shows a significant improvement over radar-only rainfall maps especially in terms of bias.

Recently a thirteen-year, radar-based, high resolution hail climatology for Switzerland was published by Nisi et al. (2016). The climatology is based on long-term volumetric radar reflectivity measurements and uses two operational hail detection algorithms to derive comprehensive hail distribution maps.

The Environmental Remote Sensing Laboratory of the École polytechnique fédérale de Lausanne (EPFL) conducts applied research using smaller, mobile radar systems. Data collected with these systems deployed in Antarctica, have recently shown the importance, in a warming climate, of low-level sublimation of snowfall by katabatic winds (Grazioli et al 2017).

Map of the annual number of hail days, during the period 2002–2014



Left: average number of days with probability of hail > 80 % per season (April–September) and km² during the period 2002–2014; right: standard deviation of the number of radar-derived hail days per season. From Nisi et al. (2016).

Surface-based remote sensing

Surface-based remote sensing for atmospheric profiling is gaining importance for numerical weather prediction, now-casting and climate monitoring. Of particular interest is the capability to perform continuous measurements and to cover the boundary layer where satellite products are often not available. Major efforts have been carried out to reduce the price of commercially available instruments. The required investment for advanced lidars (light detection and ranging) and cloud radars has been reduced by a factor of 2 or more in the last decade (i. e. Spuler et al. 2015; Delanoë et al. 2016; Hayman and Spuler 2017). Advanced lidars include Raman, differential absorption, Doppler, depolarization and high spectral resolution lidars measuring temperature, humidity, wind and aerosols. Given the lower costs and the importance of the measured parameters these technologies are likely to be established as standard instrumentation and even to be deployed in upper-air networks. MeteoSwiss started routine observations with a Doppler wind lidar by the end of 2017 in Payerne and performed a measurement campaign with a cloud radar at the airport of Zurich in winter 2017/2018.

Through recent advances in microwave radiometry the set of observed parameters could be extended to middle atmospheric temperature and wind (Rüfenacht et al. 2014; Navas-Guzmàn et al. 2017). The University of Bern started routine observations – among others in La Réunion – and long data records (>20 years) can be expected provided funding is ensured (➞ 2.8 Upper-air wind speed and direction).

The role of satellites

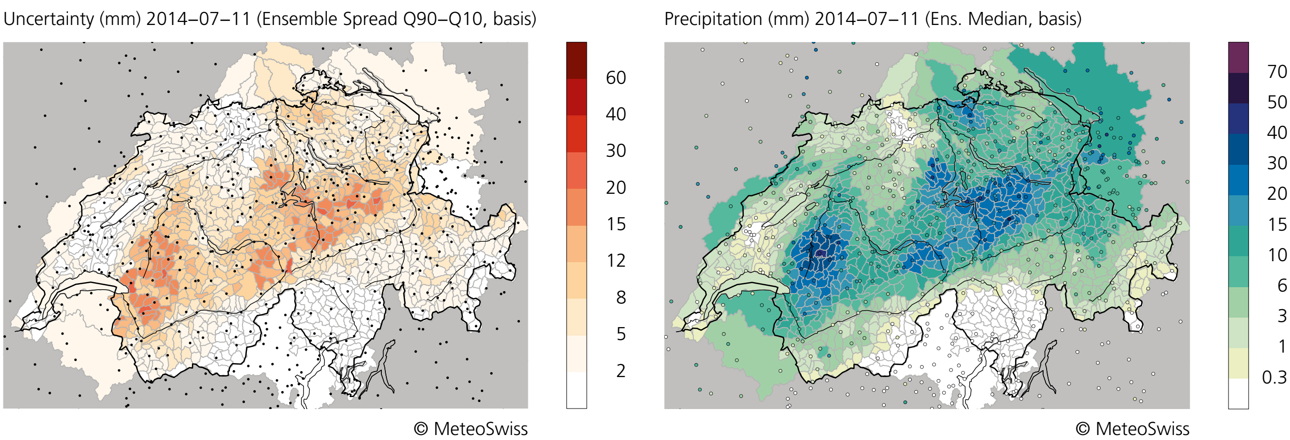
Satellite climate observations are an independent source of measurements to validate climate models and climate theories. Many satellite-based climate observations now provide adequate sampling in time and space back to the early 1980s. In the latest update of the GCOS Implementation Plan, GCOS stated that satellite-based observing systems have proven to be useful in supporting national climate decisions. Satellite data are now firmly embedded within GCOS Switzerland to complement in-situ measurements (see e.g. → 2.6 Radiation, → 2.10 Cloud properties, → 2.11 Carbon dioxide, → 3.6 Snow, → 3.7 Glaciers, → 3.9 Albedo, → 3.14 Land surface temperature).

Nevertheless, uncertainties caused by inconsistencies between continuing satellites still pose challenges for capturing long-term trends of many ECVs (Yang et al. 2014). Recently, space agencies have therefore made major efforts to improve consistency by carefully inter-calibrating satellite instrument measurements from different satellite missions. A good example are EUMETSAT's (European Organisation for the Exploitation of Meteorological Satellites) newly calibrated Meteosat satellite observations used to produce 25-year cloud fraction data which fulfil GCOS stability requirements (Bojanowski et al. 2017). Lately, also the question on how to derive uncertainty information for satellite-based climate data records has received sustained attention and methods are developed to clearly quantify those uncertainties (Merchant et al. 2017). There is also a trend towards more fine-scaled spatial coverage of satellite climate observations (Yang et al. 2014) which will furthermore foster the use of satellite climate data within GCOS Switzerland.

Statistical spatial climate analysis

One of the key developments in modern spatial climate analysis is the innovative integration of analysis methods and data sources that, traditionally, evolved in distinct scientific communities. Progress in the combination of satellite, re-analysis and in-situ observations is propelled by innovative merging techniques (e.g. Shresta et al. 2011, Sideris et al. 2014, Frei et al. 2015), by new high-resolution reanalyses (including the global ERA5 and several European reanalyses, e.g. Bollemeyer et al. 2015, Isotta et al. 2015, Soci et al. 2016), and by new multi-decadal satellite datasets (e.g. Posselt et al. 2014; Ashouri et al. 2015, Karlsson et al. 2017). This development is crucial for refining the spatial and temporal resolution of grid datasets and to improve their accuracy. Methodological advancements also enable the datasets to extend further into the past and to better satisfy quality standards needed for climate monitoring (e.g. Masson and Frei 2015). Additional developments target at a probabilistic representation of analyses in the form of ensembles, which allow users to trace uncertainties into their application (e.g. Ahrens and Jaun 2005, Wilson et al. 2014). As part of the Copernicus Climate Change Service (C3S), the European Union is about to install an integrated data service which will facilitate access to and spawn new observation-based datasets. Clearly, the number and diversity of datasets is rapidly increasing and this implies new opportunities. But it will also require that users get more involved when identifying the dataset suitable for an application.

Ensemble analysis of precipitation for Switzerland



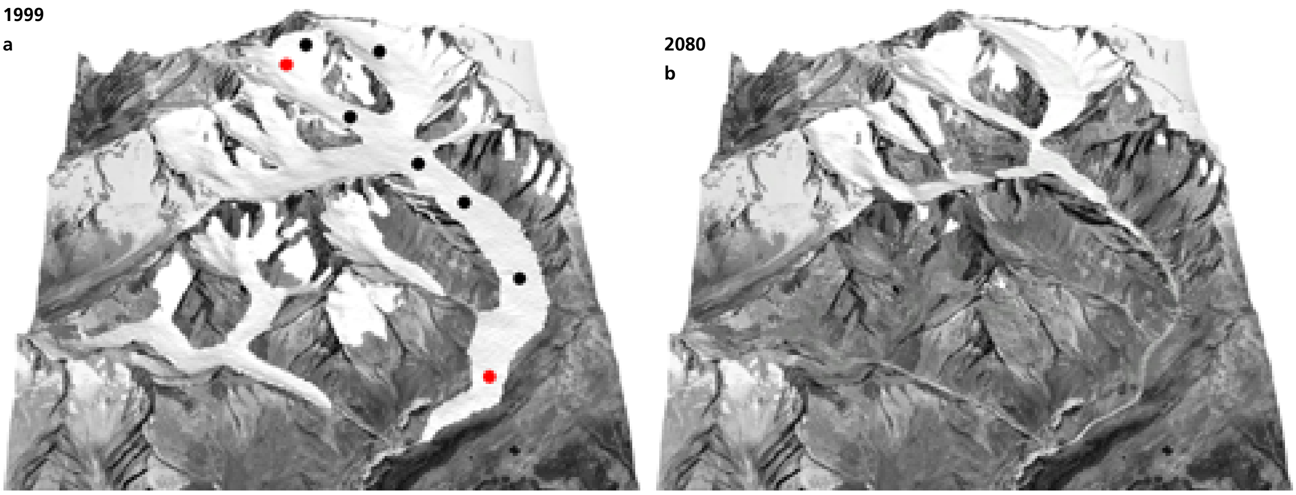
Ensemble analysis of daily areal precipitation for elementary hydrological units in Switzerland. Top panel: ensemble median, bottom panel: ensemble spread (analysis uncertainty).

Modelling

In recent years, modelling has become an essential tool supporting and complementing various ECVs (see for example → 2.1 Air temperature, → 2.12 Other long-lived greenhouse gases, → 3.1 Rivers, → 3.7 Glaciers, → 3.8 Permafrost). A combination of state-of-the-art, process-based modelling approaches with long-term measurements bears a considerable potential for filling data-gaps, homogenising time series, or increasing the value of discontinuous observations by enhancing their spatial/temporal resolution (Hibbard et al. 2010; Flato et al 2013; Giuliani et al. 2017; Trofaier et al. 2017). Furthermore, modelling also allows extrapolation and projection of ECVs into the future, which is of major interest for impact studies and mitigation measures (Taylor et al. 2012; Addor et al. 2014; Marty et al. 2017). High-quality long-term monitoring data are the backbones of all modelling studies permitting models to be tied to reality.

Here, the potential of modelling is demonstrated for glaciers. Conventional glaciological field measurements deliver seasonal to annual snow accumulation or ice melt for individual point locations on the glaciers (Huss et al. 2015). However, such data can hardly be compared between different regions. Therefore, process-based modelling can offer a substantial contribution in reducing uncertainties when extrapolating field data to obtain seasonal mass changes of the entire glacier – a useful quantity for climatological and hydrological studies. This was for example done for Grosser Aletschgletscher, the largest glacier in the European Alps. Long-term monitoring data of surface mass balance, flow velocities and overall volume change were essential to constrain the model in the past, thus permitting a realistic projection over the 21st century (Jouvet et al. 2011).

Modelled evolution of Grosser Aletschgletscher between 1999 and 2080



Modelled evolution of Grosser Aletschgletscher between 1999 and 2080 using a combined model for surface mass balance and ice dynamics. Long-term monitoring at individual sites (red dots: current measurement sites, black dots: historic sites) and combination of various data types is crucial for permitting projections into the future (figure adapted from Jouvet et al. 2011).

- GRUAN
- NDACC
- ESA-CCI
- Copernicus Climate Change Service
- Swiss Cryosphere Portal
- Atmospheric Modelling Empa

9.0 Conclusions and outlook

Conclusions

Switzerland has a long-standing tradition and expertise in climate observation. Thereby, Switzerland contributes significantly to the GCOS programme and hence to fulfilling the requirements of the United Nations Framework Convention on Climate Change (UNFCCC) with respect to systematic climate observation. In 2007, a first inventory report of the most important climate observations and international centers in Switzerland was compiled.

Moving with the times and considering the constantly evolving requirements for and advances in systematic climate observation, a new GCOS Switzerland Strategy for the period 2017–2026 was published by MeteoSwiss in 2017 (MeteoSwiss 2017b). To establish a sound basis for the strategy's implementation, the Swiss GCOS Office together with its national partner institutions and under the guidance of the GCOS Switzerland Steering Committee have again joined forces: the results are provided in this updated inventory report.

Based on the list of Essential Climate Variables (ECVs) specified in the latest update of the GCOS Implementation Plan (WMO 2016), and taking into account our national specificities, 33 climate variables were included in this report. For each variable, the type of observations carried out in Switzerland, the legal basis, the existence, importance, and international significance of long time series were described. With regard to international centers, six data or calibration centers operated by Swiss institutions were identified.

The main revisions in this report when compared with the previous edition are:

- separation of the chapters on sunshine duration and upper-air water vapor. Both chapters had previously summarized several ECVs, which are now described in individual chapters;
- inclusion of six new ECVs: river temperature, soil moisture, albedo, soil carbon, land surface temperature, and anthropogenic greenhouse gas fluxes;
- inclusion of two different kinds of ancillary data (Digital Elevation Models and digital Topographic Landscape Models);
- omission of the chapter on the Baseline Surface Radiation Network (BSRN; no longer hosted by a Swiss institution).

Based on the information collected, prospects for and possible risks to the sustainable continuation of the time series and operation of the international centers were assessed. The results of the analysis are summarized in Table 1.

Based on the Federal Council's decision in 2008, observations of six ECVs – carbon dioxide, lakes, snow, glaciers, permafrost, and phenology – and the operation of two international centers – the World Glacier Monitoring Service (WGMS) and Euro-Climhist – have so far been financially supported in the framework of GCOS Switzerland. The current assessment confirms the need for continued support for these observations and centers. Another key finding of this report is that adequate funding for the long-term continuation of observations of three other ECVs, namely upper-air water vapor, soil moisture, and anthropogenic greenhouse gas fluxes is not fully assured. Concerning the international centers, the resources required for a sustainable operation of the Global Energy Balance Archive (GEBA) were identified to be inadequate.

As the report shows, climate monitoring in Switzerland is well established. From a global perspective, however, considerable gaps in the climate observing system still exist, in particular in developing and emerging countries. Technology transfer and local training are important means of enhancing the availability and quality of climate-related observations in these countries. As presented in Chapter 7, Swiss institutions are for example engaged in development projects regarding the observation of ozone, trace gases and glaciers. Additional financial resources will be required in support of such activities.

Finally, as highlighted in Chapter 8, climate monitoring is constantly evolving. New trends in climate monitoring are driven by significant advances in technology and scientific methodology in recent years. These include, but are not limited to, the application of remote sensing techniques for climate observation, filling data-gaps with modelling, and statistical spatial analyses. While such new methodologies are gaining increasing importance, high-quality in-situ data will remain a key ingredient of the national climate observing system, for example as an independent and indispensable source of validation.

Summary (Table 1)

Overview of ECVs and international centers, their legal basis, the responsible institution(s), and the availability of funding. The start of the longest time series and initiation of operation is indicated for each ECV and international center, respectively. Detailed information on the ECVs and international centers is provided in the respective chapters. Time series and international centers whose future is at risk are shown in orange.

	ESSENTIAL CLIMATE VARIABLE	START OF LONGEST TIME SERIES	LEGAL BASIS	RESPONSIBLE INSTITUTION(S)	FUNDING
2.1	Air temperature	1863	Yes	MeteoSwiss	Assured
2.2	Wind speed and direction	1863	Yes	MeteoSwiss	Assured
2.3	Humidity	1863	Yes	MeteoSwiss	Assured
2.4	Air pressure	1863	Yes	MeteoSwiss	Assured
2.5	Precipitation	1863	Yes	MeteoSwiss	Assured
2.6	Radiation	1991	Yes	MeteoSwiss	Assured
2.7	Upper-air air temperature	1954	Yes	MeteoSwiss	Assured
2.8	Upper-air wind speed and direction	1950s	Yes	MeteoSwiss	Assured
2.9	Upper-air water vapor	1950	Yes	MeteoSwiss, University of Bern, University of Liège	Not fully assured
2.10	Cloud properties	1863	Yes	MeteoSwiss, PSI, ETH Zurich	Assured
2.11	Carbon dioxide	2000	Yes	University of Bern	Not fully assured*
2.12	Other long-lived greenhouse gases	2005	Yes	Empa, FOEN	Assured
2.13	Ozone	1926	Yes	MeteoSwiss, University of Bern	Assured
2.14	Aerosols	1973	Yes	MeteoSwiss, PSI, University of Bern, PMOD/WRC, Empa, FOEN	Assured
2.15	Ozone and aerosol precursors	1969	Yes	Empa, FOEN	Assured
2.16	Pollen	1969	Yes	MeteoSwiss	Assured
3.1	Rivers	1891	Yes	FOEN, Eawag, WSL, cantons	Assured
3.2	Groundwater	1900	Yes	FOEN, cantons	Assured
3.3	Isotopes	1970s	Yes	FOEN	Assured
3.4	Lakes	1936	Yes	Cantons, FOEN, Eawag, EPFL, municipalities, private entities	Not fully assured*
3.5	Soil moisture	2008	Partly	ETH Zurich, MeteoSwiss, Agroscope, WSL, University of Fribourg	Not fully assured
3.6	Snow	1890	Partly	MeteoSwiss, SLF, private entities	Not fully assured*
3.7	Glaciers	1893	No	GLAMOS (ETH Zurich, University of Fribourg, University of Zurich)	Not assured*
3.8	Permafrost	1987	No	PERMOS (ETH Zurich, SUPSI, University of Fribourg, University of Zurich, University of Lausanne, SLF)	Not assured*
3.9	Albedo	1990	Yes	MeteoSwiss, University of Bern	Assured
3.10	Land cover and use	1970s	Yes	FSO	Assured
3.11	Forest ecosystems	1985	Yes	FOEN, WSL	Assured
3.12	Soil carbon	1949	Yes	FOEN, FOAG, Agroscope, FiBL, WSL	Assured
3.13	Forest fires	1900	Yes	Cantons, WSL, FOEN	Assured
3.14	Land surface temperature	1991	Yes	MeteoSwiss, SLF, University of Basel	Assured
3.15	Phenology	1808	Yes	MeteoSwiss, private entities	Not fully assured*
4.1	(Anthropogenic) Water use	1945	Yes	FOAG, FOEN, cantons, private entities	Assured
4.2	(Anthropogenic) Greenhouse gas fluxes	1997	Yes	ETH Zurich, University of Basel, University of Bern, Empa, FOEN	Not fully assured
5.1	Digital Elevation Models	1980ies	Yes	Swisstopo	assured
5.2	Digital Topographic Landscape Models	1990ies	Yes	Swisstopo	assured

* continuation of observation of this ECV has been assured through GCOS Switzerland based on the Federal Council's decision in 2008.

INTERNATIONAL CENTER		START OF OPERATION	LEGAL BASIS	RESPONSIBLE INSTITUTION(S)	FUNDING
6.1	Global Energy Balance Archive (GEBA)	1988	–	ETH Zurich	Not assured
6.2	World Glacier Monitoring System (WGMS)	1986	–	University of Zurich	Not assured*
6.3.1	World Radiation Centre	1971		PMOD/WRC	Assured
6.3.2	World Calibration Centre (WCC-Empa)	1996	–	Empa	Assured
6.3.3	Quality Assurance/ Scientific Activity Centre Switzerland (QA/SAC)	2000	–	Empa	Assured
6.3.4	6.3.4 Euro-Climhist	1992	–	University of Bern	Not assured*

* continuation of operation of this international center has been assured through GCOS Switzerland based on the Federal Council's decision in 2008.

Outlook

Switzerland has contributed significantly to global climate observation in the past and will continue to do so in the future. This will only be possible thanks to the joint efforts of the many national partner institutions involved.

This inventory report describes the state of climate observation in Switzerland in 2018. It is the logical follow-up to the 2007 report and will be updated on a regular basis over the years to come. Taking into account the findings of this updated inventory report, MeteoSwiss will take the necessary steps to ensure the long-term continuation of time series and operation of international centers whose future is considered at risk (see Table 1). In addition, in implementing the GCOS Switzerland strategy 2017–2026, MeteoSwiss will put emphasis on targeted activities to enhance and strengthen the Swiss climate observing system; to promote collaboration nationally, regionally, and globally; to ensure applicability of Swiss GCOS data; and to enhance communication and outreach efforts. Detailed information on the GCOS Switzerland strategy can be found at www.gcos.ch.

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Abbreviations

a.s.l.	Above Sea Level
ACRE	Atmospheric Circulation Reconstructions over the Earth initiative
ACTRIS	European Research Infrastructure for the observation of Aerosol, Clouds and Trace gases
AERONET	AErosol RObotic NETwork
AGAGE	Advanced Global Atmospheric Gases Experiment
AGB	Above Ground Biomass
AGNES	Automated GNSS Network for Switzerland
AMDAR	Aircraft Meteorological Data Relay programme
ANETZ	Automated meteorological monitoring network
AOD	Aerosol Optical Depth
approx.	approximately
Art.	Article
ASRB	Alpine Surface Radiation Budget
AVHRR	Advanced Very High Resolution Radiometer
AWEL	The Cantonal Department of Waste, Water, Energy and Clean Air of Zurich (Amt für Abfall, Wasser, Energie und Luft)
BSRN	Baseline Surface Radiation Network
BStatG	Federal Statistics Act
BUEWAK	Bündner Wald im Klimawandel
C3S	Copernicus Climate Change Service
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMS	Copernicus Atmosphere Monitoring Service
CC4CL	Community Cloud retrieval for Climate
CFC	Cloud Fractional Cover
CHARM	Cern High energy AcceleRator Mixed field facility
ChemRRV	Chemical Risk Reduction Ordinance
CIMO	WMO Commission for Instruments and Methods of Observation
CM SAF	EUMETSAT Satellite Application Facility on Climate Monitoring
CORINE	Coordination of Information on the Environment
COST	European Cooperation in Science and Technology
Cst	Federal Constitution of the Swiss Confederation
DEM	Digital Elevation Model
DETEC	Federal Department of the Environment, Transport, Energy and Communications
DOK	Biodynamic, Organic and Conventional
DSM	Digital Surface Model
DWD	Germany's National Meteorological Service (DeutscherWetterdienst DWD)
e.g.	exempli gratia
EARLINET	European Aerosol Research Lidar Network
EAS	European Aerobiology Society
Eawag	Swiss Federal Institute of Aquatic Science and Technology
EC	Elemental Carbon
ECA&D	European Climate Assessment and Dataset
ECMWF	European Centre of Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EEA	European Environmental Agency
EFAS	European Flood Alert System
EFFIS	European Forest Fire Information System
EIONET	European Environment Information and Observation Network
EKK	Federal Cryospheric Commission
EMEP	European Monitoring and Evaluation Programme
Empa	Swiss Federal Laboratories for Materials Science and Technology
ENET	Complementary automated meteorological monitoring network
EPA	Federal Act on the Protection of the Environment
EPFL	École polytechnique fédérale de Lausanne
ERT	Electrical resistivity tomography
ESA	European Space Agency
ESA CCI	European Space Agency Climate Change Initiative
ETN-R	European Terrestrial Network for River Discharge
EU	European Union
EUBREWNET	European Brewer Network
EUMETNET	European Meteorological Service Network
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EUSAAR	European Supersites for Atmospheric Aerosol Research
FAO	Food and Agriculture Organization
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FiBL	Research Institute of Organic Agriculture
FOAG	Federal Office for Agriculture
FOEN	Federal Office for the Environment
FOPH	Federal Office of Public Health
FSO	Federal Statistical Office
GAW	Global Atmosphere Watch
GAW-CH	Global Atmosphere Watch Switzerland
GAW-PFR	Global Atmosphere Watch – Precision Filter Radiometers
GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch
GEBA	Global Energy Balance Archive
GEF	Global Environment Facility
GeoIA	Federal Act on Geoinformation
GGCB	Global Glacier Change Bulletin
GGIS	Global Groundwater Information System
GHG	Greenhouse Gas
GlaThiDa	Glacier Thickness Dataset
GLIMS	Global Land Ice Measurements from Space
GLORIA	Global Observation Research Initiative in Alpine Environments
GmbH	Limited Liability Company
GNIP	Global Network of Isotopes in Precipitation
GNIR	Global Network of Isotopes in Rivers

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GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRDC	Global Runoff Data Centre
GROMOS	Ground-Based Millimeter Wave Ozone Spectrometer
GRUAN	GCOS Reference Upper-Air Network
GSN	GCOS Surface Network
GST	Ground Surface Temperature
GTN-G	Global Terrestrial Network for Glaciers
GTN-H	Global Terrestrial Network for Hydrology
GTN-L	Global Terrestrial Network for Lakes
GTN-P	Global Terrestrial Network for Permafrost
GTOS	Global Terrestrial Observing System
GTS	Global Telecommunication System
GUAN	GCOS Upper-Air Network
HCFCs	Hydrochlorofluorocarbons
HFSJG	High Altitude Research Station Jungfraujoch
HISTALP	Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region
HUG	Hydrological Study Areas
IAC	ETH Zurich, Institute for Atmospheric and Climate Science
IACS	International Association of Cryospheric Sciences
IAEA	International Atomic Energy Agency
IAP	University of Bern, Institute of Applied Physics
ICOS	Integrated Carbon Observation System
ICOS RI	Integrated Carbon Observation System Research Infrastructure
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
ICSU	International Council for Science
IG3IS	Integrated Global Greenhouse Gas Information System
IGRA	Integrated Global Radiosonde Archive
IGRAC	International Groundwater Resources Assessment Centre
ILTER	International Long-Term Ecological Research Network
IPC	International Pyrheliometer Comparisons
IPCC	Intergovernmental Panel on Climate Change
IPG	European International Phenological Gardens
IPgC	International Pyrgeometer Comparisons
ISOT	NAQUA module for observing isotopes in the water cycle
ISPD	International Surface Pressure Databank
IUGG	International Union of Geodesy and Geophysics
JMA	Japanese Meteorological Agency
JRC	Joint Research Centre
KP-LULUCF	LULUCF activities under the Kyoto Protocol
LAI	Leaf Area Index
LKO	Light Climatic Observatory Arosa
LRTAP	Long-range Transboundary Air Pollution
LST	Land Surface Temperature
LTER	Long Term Ecological Research
LULUCF	Land Use, Land-Use Change and Forestry

LWF	Long-term Forest Ecosystem Research Programme
MCR	University of Basel, Meteorology, Climatology and Remote Sensing Group
MetG	Federal Act on Meteorology and Climatology
MetOp	Meteorological Operational Satellite
MetV	Federal Ordinance on Meteorology and Climatology
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate-resolution Imaging Spectroradiometer
MVIRI	Meteosat Visible Infra-Red Imager
NABEL	National Air Pollution Monitoring Network
NABO	Swiss Soil Monitoring Network
NABODAT	National Soil Information System
NADUF	National River Monitoring and Survey Programme
NAPOL	National Pollen Monitoring Network
NAQUA	National Groundwater Monitoring
NASA	National Aeronautics and Space Administration
NAWA	National Surface Water Quality Monitoring Programme
NBCN-S	Swiss National Basic Climatological Network
NCDC	National Climate Data Center
NCHA	Federal Act on the Protection of Nature and Cultural Heritage
NDACC	Network for the Detection of Atmospheric Composition Change
NFI	National Forest Inventory
NILU	Norwegian Institute for Air Research
NIME	Manual precipitation network
NLSO	Ordinance on National Land Survey
NMIs	National Metrological Institutes
NOAA	National Oceanic and Atmospheric Administration
NRP61	National Research Programme "Sustainable Water Management"
NSIDC	US National Snow and Ice Data Center
OALNRN	Federal Ordinance on Alerts, Alarms and the National Security Radio Network
OAPC	Ordinance on Air Pollution Control
OBS	MeteoSwiss Manual Observation network
OC	Organic Carbon
OECD	Organisation for Economic Co-operation and Development
OH	Hydroxy radical
OIS	Ordinance relating to Impacts on the Soil
OPERA	EUMETNET Operational Programme for the Exchange of weather Radar information
OV-UVEK	Organisation of the Federal Department of Environment , Transport, Energy and Communications
PAR	Photosynthetically Active Radiation
PEP725	Pan European Phenology Database
PERMOS	Swiss Permafrost Monitoring Network
PLC	Programmable Logic Controller
PM	Particulate Matter

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PMOD	Physical Meteorological Observatory in Davos
ppm	parts per million
PSI	Paul Scherrer Institute
PWS	Present Weather Sensors
QA/SAC	Quality Assurance/Scientific Activity Centre
QASUME	Quality Assurance of solar Spectral Ultraviolet irradiance Measurements carried out in Europe
QUANT	NAQUA module for observing groundwater quantity and temperature
RBCN	Regional Basic Climatological Network
RGI	Randolph Glacier Inventory
SACRaM	Swiss Alpine Climate Radiation Monitoring
SAG	Scientific Advisory Group
SCNAT	Swiss Academy for Sciences
SCOPE-CM	Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring
SDC	Swiss Agency for Development and Cooperation
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SHADOZ	Southern Hemisphere Additional Ozonesondes
SI	International System of Units
SIA	Swiss Society of Engineers and Architects
SLF	WSL Institute for Snow and Avalanche Research
SMS	Short Message Service
SNSF	Swiss National Science Foundation
SOC	Soil organic carbon
SOMOMOUNT	Soil Moisture in Mountainous Terrain
SOMORA	Stratospheric Ozone Monitoring Radiometer
SPEZ	NAQUA module for the specific monitoring of pollutants
SR	Classified Compilation (Systematische Sammlung des Bundesrechts)
SUPSI	Scuola Universitaria Professionale della Svizzera Italiana
SVGW	Swiss Association of the Gas and Water Industry
SWE	Snow Water Equivalent
SwissMetNet	Automatic monitoring network of MeteoSwiss
SwissSMEX	Swiss Soil Moisture Experiment
swisstopo	Federal Office of Topography
SYNOP	Surface Synoptic Observations
TGS	Terrestrial Geodetic Surveys
TLM	Topographic Landscape Model
TOCS	Technical Ordinance on Cadastral Surveying
TREND	NAQUA module for tracking the long-term evolution of anthropogenic and geogenic groundwater quality
TVAV	Federal Department of Defence, Civil Protection and Sport
UK	United Kingdom
UN	United Nations
UN Environment	United Nations Environment Programme
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
UTC	Universal Time Coordinated
UV	Ultraviolet
VAW	ETH Zurich, Laboratory of Hydraulics, Hydrology and Glaciology
VOC	Volatile Organic Compunds
WaG	Federal Forest Act
WaV	Forest Ordinance
WCC-UV	World Calibration Center for UV
WCP	World Climate Programme
WCRP	World Climate Research Program
WDCGG	World Data Center for Greenhouse Gases
WDS/ICSU	World Data System of the International Council for Science
WEP-CH	Swiss National Forest Programme
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WISG	World Infrared Standard Group
WMO	World Meteorological Organization
WORCC	World Optical Depth Research and Calibration Center
WOUDC	World Ozone and UV Radiation Data Center
WPA	Federal Act on the Protection of Waters
WPO	Waters Protection Ordinance
WRC	World Radiation Centre
WRC-IRS	World Radiation Center – Infrared Radiometry Section
WRC-SRS	World Radiation Center – Solar Radiometry Section
WRDC	World Radiation Data Centre
WRG	Water Rights Act (Wasserrechtsgesetz)
WRMC	World Radiation Data Centre
WRR	World Radiometric Reference
WSG	World Standard Group
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research
ZOFE	Zurich Organic Fertilization Experiment

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