

Role of observations in advancing understanding of the climate system

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Abstract

This chapter describes how observations have advanced our understanding of the climate system. Historically, new and unexplained observed signals often revealed previously unknown climate processes, laying the foundation for a theoretical understanding of their function and their role in the climate system. The chapter begins with historic examples showing how observations and paleoclimate records have led to multiple scientific discoveries that led to major advances in climate science. It then highlights several current observationally based science advances across different Earth system components including land, ocean, cryosphere and atmosphere. The chapter concludes by highlighting expectations for future climate observing systems, particularly their central role in addressing the challenges associated with climate mitigation, adaptation and climate services.

Key points

- Observations help advancing understanding of the climate system.
- New instruments or technologies make new observations possible.
- Observations are the primary source of information about how our climate has changed
- Observations provide robust evidence of climate change impacts
- In the future it will be essential to have high-quality observations and climate change information available freely to everybody around the world.

Introduction

Observations are the primary source of information about how our climate has changed or is changing, from global to local scales. Observations are used to describe the climate state and track changes in the Earth's climate system. They provide robust evidence of climate change impacts and are indispensable for developing climate predictions and projections—especially to improve our theoretical understanding of climate processes and to evaluate and improve models that are used to simulate future climates under different emission scenarios.

Past and contemporary climate knowledge generation usually involves an iterative process, in which phenomena are first identified in observations and a theoretical or mechanistic understanding is developed afterward. There are also some notable examples where theory came decades before observations, such as the discovery of the Milanković cycles. In both cases, once a theory exists, it is then tested empirically using observations, sometimes followed by a refinement of the theory and improved understanding of processes. Ultimately, the theory is implemented in a numerical model, which is used to make climate predictions or projections and is a key element of developing actionable information for decision makers. Model fidelity is also tested with observations, making observations a cornerstone for climate science—not only for developing theories and improving models, but also for detecting and attributing climate change phenomena. Because natural climate variability and human-driven changes occur on timescales ranging from weeks to decades to centuries, long-term continuous observations provide the essential foundation for understanding climate and its role in our society and environment.

The role of climate observations historically

Looking back over the history of the natural sciences, including both astronomy and climate sciences, it becomes clear that early research was typically curiosity driven and guided by observations. Major advances in understanding the processes and functioning of natural systems began with the invention of new instruments or technologies that made new kinds of observations possible. This pattern appeared across science more broadly and this remains true to some extent even today.

Classical examples go back to Galilei who was able to observe celestial bodies and their motion only after the first telescopes became available. Without these observations he would not have been able to develop the hypothesis that the Sun must be the central body of the solar system, and that the Earth is orbiting around it. The identification of the detailed orbital path of the Earth around the Sun, and the understanding of the impact on Earth's climate of changes in these paths over time, including the existence of glaciation and deglaciation cycles occurring over thousand to million years ago, came only later. Another classical example not least relevant for climate science is the discovery of gravity by Newton who, puzzled by his observation of an apple falling from the tree toward the ground as the legend has it, formulated a full theory on gravity. His findings were fundamental for the subsequent development of the Navier Stokes equation describing the motion of a fluid on the rotating Earth. This forms the foundation of modern numerical weather and climate prediction systems, as well as the understanding of tidal motions in the ocean.

Early insights into how the climate system works came from observations of components of the climate system itself—to the extent they were accessible—especially from the atmosphere, the cryosphere and the land surface. An early example of such a discovery is the vertical structure of the atmosphere in 1902. This milestone in meteorology was only made possible through the invention of instrumented, unmanned balloons to discover that the temperature stops decreasing at high altitudes, leading to the thermal layering we know today.

By contrast, understanding the central role played by the ocean in the climate system happened much later because of the lack of ocean observations and long-duration time series. Only with modern technologies capable of measuring the ocean from its surface to depth, and across wide geographical regions, did the critical role of the ocean in the climate system become clear. Using an example from the 1960s, the development of transistor technology and the deployment of modern electronics-based CTD (conductivity-temperature-depth) sondes led to the documentation of so-called “salt fingers” in the ocean, a phenomenon that appeared as spikes in high-resolution temperature salinity profiles. Interpreted initially as measurement errors, it later became clear that these spikes represent very real small-scale instabilities and mixing processes in the ocean driven by the different diffusivities of salt and temperature.

In all these instances, observations sparked curiosity and the need for understanding the underlying principles and processes, paving the way to groundbreaking discoveries and advances in science.

Applications of climate observations

Throughout this Chapter, “observations” are defined broadly, encompassing three categories used in climate science: (a) direct observations (e.g., ground based, including near surface—proximal sensors, and satellite monitoring), (b) proxy-based data (e.g., paleo), and (c) observation-based datasets (reanalysis), which are a blend of modelled and observed data (see also below). All these categories are further described in detail in Section “[Key climate observations in the climate system](#).” Here we will first introduce the major observational climate variables and summarize their applications in climate science.

The major observational variables used when describing the climate system are:

- **Atmospheric:** temperature and humidity, precipitation, greenhouse gases (including water vapor), ozone and other trace gases, aerosols and atmospheric pollutants.

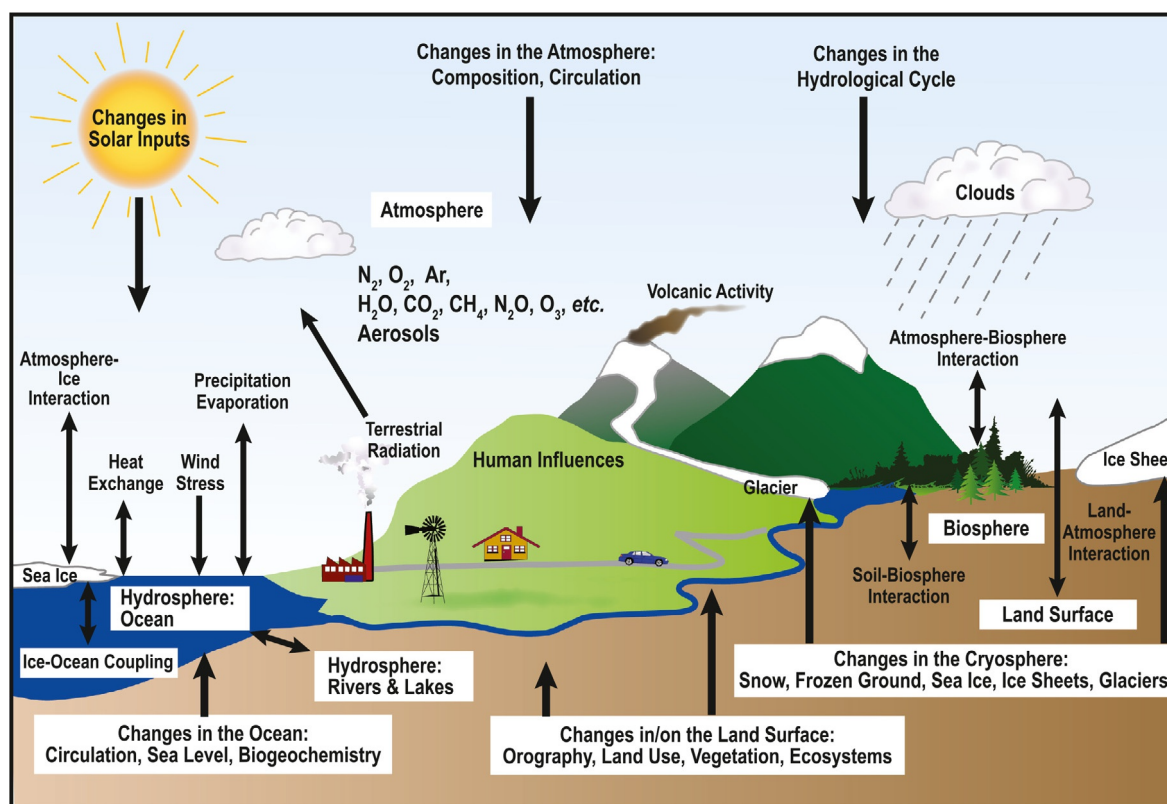


Fig. 1 Schematic view of the components of the climate system, their processes and interactions (Le Treut et al., 2007).

- **Oceanic:** temperature, sea level, ocean currents, salinity, pH, and sea ice.
- **Terrestrial:** temperature, soil moisture, snow cover, biomass, soil carbon, glacier mass balance, and permafrost.

The underpinning processes and their changes that are captured through these observations are schematically summarized in Fig. 1. The associated climate components and their interactions are further discussed in Section “Explaining the climate system.”

All these observed climate variables play a crucial role in quantifying climate variability and change, validating models, monitoring ongoing, abrupt and extreme changes, informing policy, and supporting adaptation strategies across many sectors (agriculture, energy, water, health). A long record of climate observations with sufficiently high levels of quality and consistency is needed to detect long-term changes and trends embedded in diurnal, seasonal and multi-annual variations. But it is also fundamentally important that historical observations are preserved and managed robustly and made openly available to all. And it is crucial that current and future generations of researchers and data-users can freely use and exploit data (past, present and future, at all scales from local to global) to provide the products and services required for effective climate decision-making today and, on a sustained basis, into the future.

In the following we will first summarize their application for process understanding, predictions and for climate action.

For process understanding and attribution on regional and local scales: observations are important for monitoring and understanding climate variability on timescales from sub-daily to decadal, as well as to detect long-term regional trends in climate means and extremes. To identify underlying processes and mechanisms, and to develop a full process understanding including non-linearities and feedbacks in the system, long-term, continuous records are needed. Proper representation of these processes is required for simulations using numerical climate and Earth system models. Without observations, our understanding of climate processes would never have advanced. Without these advances, we would not be able to identify feedbacks, interactions, and climate trajectories under specific forcing conditions or interventions, that are necessary for reliable future projections.

The existence of long climate records is paramount not only for the detection of trends, but also for the attribution of their occurrence, whether due to human-induced climate change or due to natural processes of the Earth system, or to external forcing (e.g. due to volcanic eruptions or changes in solar output). However, in many parts of the world, despite their importance, currently available historical and present-day observations are insufficient to adequately monitor regional and local scale climates, often limiting our understanding.

As an example, the IPCC Sixth Assessment Report (IPCC, 2021) showed that this data scarcity impedes the detection of trends in heavy precipitation over almost all of South America and Africa and parts of Australia (IPCC, 2021, Fig. SPM3, b). On smaller spatial scales than these sub-continental regions, areas with complex topography such as mountain regions lack sufficient data, both because the spatial variability of precipitation is typically large and because of the difficulties with installing and maintaining equipment.

For simulating and predicting changes in the climate system: Contemporary fully coupled Earth system models (see Section “[Explaining the climate system](#)”) capture our theoretical knowledge of the climate system—and its interaction with humans—as far as it can be realized given respective and current limitations posed by model resolution and parameterizations. It is through these models that the past and present climate state can be simulated, and projections of possible future changes in response to anticipated changes in the climate forcing (such as fossil fuel emissions) provided. However, the processes, interactions and trajectories embedded in our Earth system models must be tested against observations to assess the quality and fidelity of the models. A dense spatial network of continuous in situ measurements, spanning different topographies and land-covers, are then of utmost importance to validating the performance of climate models, to parameterize processes and calibrate climate models as well as satellite algorithms, to improve them through model-data fusion and initialize them for climate forecasting.

For climate action: Since changes in many variables in the climate system have already emerged due to unabated anthropogenic emissions of greenhouse gases (GHGs) (IPCC AR6 SPM, 2021), the responses of climate models to anthropogenic drivers can now increasingly be tested against observations. This is an ironic consequence of our inability to mitigate climate change. However, the observational basis for monitoring the effectiveness of mitigation and adaption measures, in general, needs to be expanded and optimized.

The important role that observations will play in the future to monitor the efficacy of climate mitigation policies cannot be overstated. In this respect the United Nations Framework Convention on Climate Change (UNFCCC) Global Stocktake is a fundamental component of the 2015 Paris Agreement ([parisagreement_publication.pdf](#)) and is used by the UNFCCC to monitor its implementation and evaluate the collective progress made in achieving the agreed goals. The Global Stocktake links implementation of nationally determined contributions (NDCs) with the overarching goals of the Paris Agreement. Monitoring, Reporting & Verification is particularly relevant and important in the domain of the earth energy uptake (von Schuckmann et al., 2023; Stevens et al., 2026) and for carbon accounting (e.g. Global Carbon Project [GCP Homepage](#)).

Chapter structure

As this is the first chapter in the part of the Encyclopedia dealing with climate observations, it sets the scene by explaining the important role observations play in advancing the understanding of the climate system. It does this by first introducing the climate system and its observing systems in Section “[Observing the climate system](#).” Section “[Historical perspective](#)” provides a historic perspective drawing on some prominent examples with Section “[Ongoing highlights](#)” highlighting the ongoing role of observations in advancing knowledge. Section “[The future role of climate observations](#)” discusses future requirements that the climate observing system needs to fulfil in the context of climate change related mitigation and adaptation.

Observing the climate system

Explaining the climate system

The Earth’s **climate system** comprises five interacting components schematically illustrated in Fig. 2: the atmosphere (air), the hydrosphere (water), the cryosphere (ice and permafrost), the lithosphere (the Earth’s upper rocky and soil layers) and the biosphere (where life exists). All these components interact with each other as illustrated in the figure by the blue arrows. External drivers of the climate system, which influence the mean state and part of the variability, are the energy input from the sun, gravitational forces acting from the moon and sun, and energy entering the system from the inner earth, i.e., geothermal forcing, volcanic eruptions.



Fig. 2 The five components of the climate system all interact. They are the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere.

Climate itself is then the time-varying (i.e. mean, variability and extremes) state of this coupled system on time scales beyond the weather time scale and is determined by the interaction of many processes, such as ocean currents and wind patterns. Climate is a statistical characterization of the system and represents the aggregated weather—i.e., it represents the climate state on periods from seasons to decades, to centuries and beyond. The World Meteorological Organization (WMO) uses a 30-year period to define baseline climate. This standard reference period is considered long enough to account for natural climate variability while being relevant for societal and ecosystem comparisons. The WMO recommends updating this baseline every decade to better reflect changing climate conditions. However, recent research shows that a 30-year period isn't enough to account for variability in many variables/processes, e.g., tropical rainfall, changes in teleconnections etc. (Jain et al., 2023).

Characterizing and describing the five components:

Atmosphere: Gaseous part above the Earth's surface including major and trace gases, liquids and solids. Key atmospheric processes that influence climate, include weather, radiation balance via the effect of atmospheric composition on emissivity, absorptivity and transmissivity of short and long wavelength radiation, formation of clouds and precipitation, atmospheric flow, reservoir of natural and anthropogenic trace gases, transport of heat, water vapor, tracers, dust and aerosols.

Hydrosphere: All forms of water above and below the Earth's surface, including the whole ocean and the global water cycle (also referred to as the hydrological cycle). The latter encompasses precipitation, the resulting liquid water that is directly received into the oceans or intercepted and stored on the land surface (lakes, soil moisture, and ground water) and flows across the land, between these stores and into the oceans as streamflow (runoff), and the evaporation of liquid water into the atmosphere through evaporation (from soil and open water bodies) and transpiration (from plants). Key processes in the hydrosphere that affect the climate include: (a) the distribution and intensity of precipitation, (b) the stored moisture on the land, (c) the global distribution of, and changes in, the inflow to different ocean basins, along with transport of ocean water masses, transport of heat, salt and other tracers in the ocean, and (d) exchange of water vapor, carbon dioxide (CO₂) and other gases between the ocean and land, respectively, and the atmosphere, noting the oceans are a critically important reservoir of carbon with fast turnover.

Cryosphere: All forms of ice in the climate system, including inland snow cover, ice sheets, ice shelves, sea ice, river and lake ice, glaciers and permafrost. Key processes in the cryosphere that affect the climate, include long-term water reserves, the Earth's albedo (reflectivity)—a primary factor affecting surface energy and moisture fluxes, clouds, the water cycle, atmospheric and oceanic circulation.

Lithosphere: Both the solid Earth and the land surface that are home to the terrestrial biosphere including humans. Key land surface processes that affect the climate include: the position of the continents, which determines climatic zones, ocean currents, sea level, transformation of short-wave to long-wave radiation; the albedo (reflectivity) of the Earth's surface (sand compared to rock, or other forms), reservoir of dust, and exchanges of momentum, energy and water (in all its phases).

Biosphere: This encompasses all living organisms—plants, animals, fungi and microorganisms—on the land, in the oceans and in the atmosphere. Key biospheric processes that affect the climate include: (a) the exchange of carbon between the different reservoirs, that affects the concentration of GHGs in the atmosphere, (b) the balances of water vapor, other greenhouse gases and all radiatively active gases, which affect the radiation budget, (c) influences on albedo (reflectivity) and emissivity of the surface, that affect the radiation balance (e.g., tundra different from grassland), (d) regulates the transfer of water vapor between the soil and atmosphere, and therefore (via energy conservation) exchange and storage of sensible heat, and (e) via its aerodynamic roughness, the momentum exchange between the atmosphere and the ground.

The anthroposphere is a sixth component that is particularly relevant for ongoing and future changes and is often treated as a distinct part of the climate system. It comprises processes which are caused or altered by humans, especially gases and particulates which alter the radiation balance, and land use management and change (conversion to agricultural and urban land, deforestation, desertification, and degradation).

Together, these six components are referred to as the Earth system and models describing the state of the six coupled components are usually called Earth System models which is schematically summarized in Fig. 3 (Steffen et al., 2020, see also Brasseur et al., 2025).

Key climate observations in the climate system

Long-term records from land and ship-based meteorological stations, radiosondes, satellites and other observational instruments, as well as paleo data, provide the long-term data necessary to understand our rapidly changing climate. These data have been analyzed using a variety of techniques to provide the robust scientific basis upon which to undertake scientific assessments and monitoring activities.

Recalling the three broad categories of observations from Section “Applications of climate observations”:

- **Direct observations** refer to both in situ and remotely sensed data, noting that remotely sensed data (or observations) measured by satellites rely on algorithms that need input from models, e.g. from atmospheric forecasts for evapotranspiration or atmospheric moisture content. Direct observations are available as primary data, e.g., profiles in the ocean or atmosphere. Many directly observed data are available as gridded fields based on statistical interpolation or gridding algorithms.
- **Proxy-based data** are preserved physical, chemical, or biological records that act as “extensions” for direct instrumental measurements. With the exception of temperature readings at a few locations going back to the 18th century, reliable instrumental records are available from the 1880s onwards. Therefore, climate scientists use these natural archives to reconstruct

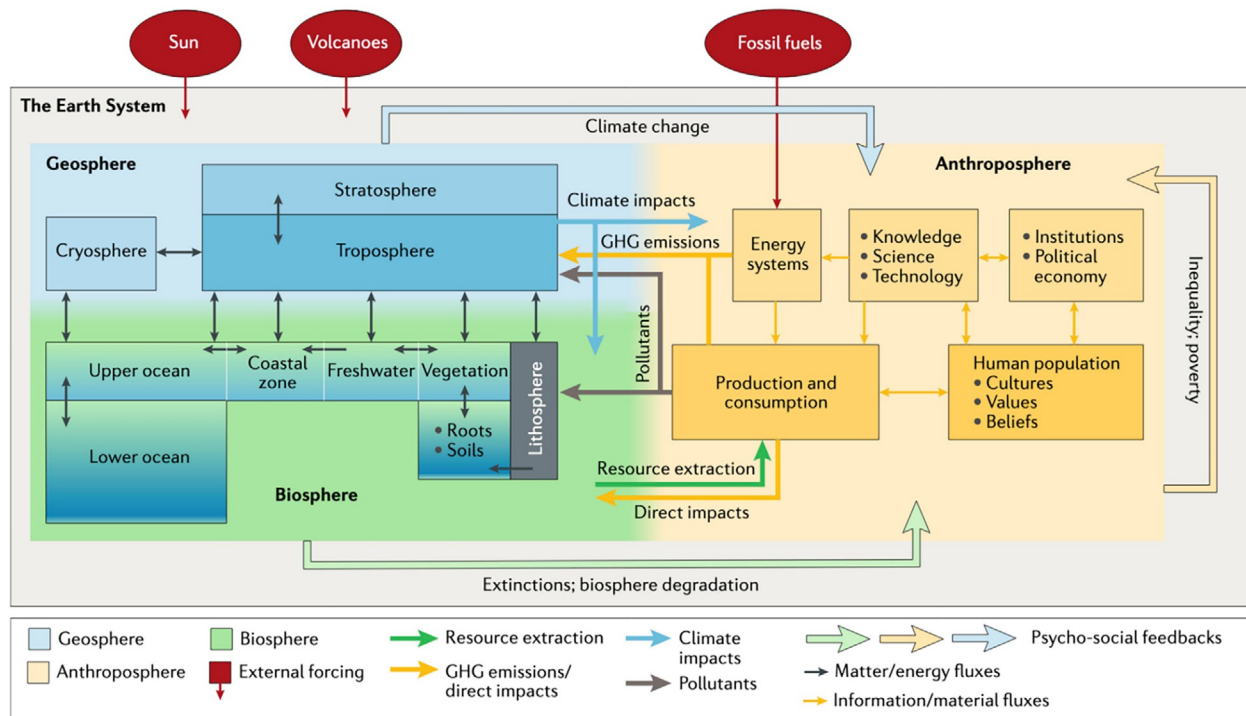


Fig. 3 Representation of the Earth system, including the physical and biogeochemical processes affecting planet Earth, as well as the internal dynamics of the human system (anthroposphere) described by a system of production and consumption. This system is “forced” by energy systems and is modulated by human societies, which are in turn influenced by their cultures, values, institutions and level of education. Interactions within the Earth system are two-way, with anthropogenic emissions of greenhouse gases and other pollutants, and resource extraction leading to impacts that reverberate through the geosphere-biosphere system. Feedbacks to the anthroposphere are also important, including the direct impacts of climate change and biosphere degradation, as well as psychosocial feedbacks from the rest of the Earth system and within the anthroposphere. Not implicitly shown in this diagram is the hydrosphere which plays an important role in the Earth system. From Steffen W, Richardson K, Rockström J et al. (2020) The emergence and evolution of Earth System Science. *Nature Reviews Earth and Environment* 1: 54–63. <https://doi.org/10.1038/s43017-019-0005-6>; <https://www.nature.com/articles/s43017-019-0005-6>.

Earth’s climate history over thousands or even millions of years. To be scientifically useful, a proxy must be linked to an environmental variable using a strict calibration process. Proxy data are vital because they establish the baseline of natural climate variability and provide information on different climate conditions such as ice ages, interglacials or significantly warmer climates several tens of million years before the present. They provide undeniable, long-term proof that current global warming trends and CO₂ levels are highly anomalous compared to the last several millennia to million years. Systematic comparisons with paleoclimate evidence have improved confidence in climate models but they have also revealed their shortcomings. For instance, fully dynamical physical-biogeochemical climate simulations of ice age cycles are still a challenge. Paleoenvironmental information has enabled a better understanding of ecosystem adaptations and the limits to adaptation. To further improve the insight into this, a good spatial and temporal coverage of proxy data is vital.

- c) **Observation-based datasets (reanalysis):** Until the 1990s, observation-based knowledge about the climate system was primarily achieved by analyzing observations with respect to variability, processes or mechanisms such as teleconnections. In recent decades it has become common to also study phenomena through a combination (fusion) of observations and models, usually by constraining models through the observed state of the climate system or its individual components and then using the results for further analyses. Methodologically this step refers to data assimilation where, in a mathematically well-defined sense, the observed state is merged with a model prediction. Such an approach has been utilized for some time in numerical weather prediction and subsequently led to reanalyses of the atmosphere in which the usually sequential assimilation/forecasting approach is applied repeatedly over a long time-window providing a long estimate of the changing atmospheric state. It is expected that in the future, forms of model-data fusion will expand significantly by using observations to constrain model parameterizations, and through the development and training of data-centric AI/ML models. An example are current atmospheric reanalyses, which provide a 4-dimensional picture of how atmospheric and surface fields have evolved over the modern era (roughly since about 1950). Classical examples are the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996) or the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses (ERA, Uppala et al., 2005) that are often used to study the atmosphere or to infer fluxes between the atmosphere and the ocean.

Climate observations today

After many years of initial planning and development by the World Climate Research Programme (WCRP, <https://www.wcrp-climate.org>), among others, the international science and service communities are operating—through WMO (<https://wmo.int>), UNEP (<https://www.unep.org>), IOC (<https://www.ioc.unesco.org/en>) and ISC (<https://council.science>)—the Global Climate Observing System (GCOS, <https://gcos.wmo.int/site/global-climate-observing-system-gcos>), encompassing both in situ and satellite-based observations.

Coordinated observational campaigns—Partly because of GCOS, we now have ample experience in observing the climate system and using observations to understand its governing principles as well as to monitor abrupt changes and longer-term trends. These observations support services such as weather forecasts, warnings of severe weather events, and seasonal climate outlooks. Some observations support tailored climate applications that require high precision and accuracy, and require long-term, continuous measurements to monitor and understand the nature of climate variability on long time scales. In situ and remote observations are the backbone of climate observing systems around the world, including GCOS.

Currently, a wealth of climate observations is being obtained from a variety of platforms, including ground-based, ship-based, and satellite-based remote sensing, coordinated by the Global Climate Observing System (GCOS) or the Global Ocean Observing System (GOOS, <https://goosocean.org>), as well as an autonomous measuring network (Argo, <https://argo.ucsd.edu>) and the global FluxNet (<https://fluxnet.org/>, Baldocchi et al., 2001). Using these global satellite networks and ground stations, scientists monitor 55 Essential Climate Variables (ECVs; Bojinski et al., 2014; *The 2022 GCOS ECV*), such as greenhouse gas concentrations, ice mass balance, and ocean temperatures.

GOOS coordinates physical, biogeochemical, and biological observing networks, ensuring standardized measurement protocols, global coverage and long-term continuity. Ocean carbon uptake is formally an Essential Ocean Variable (EOV) under GOOS Biogeochemistry. GOOS also ensures that these measurements are integrated into climate assessments (e.g., IPCC, <https://www.ipcc.ch>) as well as the Global Carbon Project's annual Global Carbon Budget (e.g., Friedlingstein et al., 2026). GOOS includes observations of surface ocean CO₂ exchanges (via SOCONET, <https://www.ioccp.org/soconet>), repeat hydrographic sections across all ocean basins, measuring carbon, nutrients, oxygen, and tracers from surface to seafloor (GO-SHIP, <https://www.go-ship.org>) and encompasses NOAA's Global Ocean Carbon Observing Network.

The Global Carbon Project (GCP, <https://www.globalcarbonproject.org>), established in 2001, has the scientific goal of developing a complete picture of the global carbon cycle, biophysical and human, together with the interactions and feedbacks between them. To achieve this goal, the GCP integrates these observations, along with modelled results, to provide global budgets for the three dominant greenhouse gases (CO₂, CH₄, and nitrous oxide (N₂O))—it produces these budgets annually, published as the Global Carbon Budget (Friedlingstein et al., 2026). The GCP also coordinates research investigating: the patterns and variability (i.e. space and time distributions) of the major pools and fluxes in the global carbon cycle; processes and interactions that determine carbon cycle dynamics; and carbon management—the dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system. Observations play a critical role in all aspects of the GCP's analyses and assessments.

FluxNet (Delwiche et al., 2024) coordinates the measurements from all regional flux observing networks around the globe. This network provides continuous measurements of the fluxes of energy (radiation and sensible heat), water vapor (evapotranspiration), momentum and carbon (CO₂ and CH₄) in terrestrial ecosystems (see e.g. Jung et al., 2019).

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Satellite measurements Products derived from satellite measurements are a very important complement to in situ measurements, especially for data scarce regions and to provide continuous global-scale time series. For example, a significant milestone was reached in 1979 when global coverage of variables such as vertical temperature and humidity profiles, cloud-motion winds, sea surface temperatures, and sea-ice information became available from satellites. This transformed the usability and reliability of global reanalyses particularly for the oceans of the Southern Hemisphere (Marshall et al., 2022). Geostationary satellites today provide highly resolved observations of cloud properties, radiation and atmospheric moisture content, while Low Earth Orbit satellites provide observations used to measure key land and ocean surface properties, such as albedo, land cover, soil moisture and ocean surface salinity. Measurements of satellite precipitation with high spatial and temporal resolution have also been available for the last 30 years.

Although many satellite products have global fields, it is important to recognize that systemic errors are introduced by the fact that many retrieval algorithms are calibrated with data from only a few regions of the world, such as Europe, United States of America and Japan. This can introduce difficulties with estimations of, e.g., vegetation indices and precipitation over the tropics and sub-tropics (Baldi et al., 2008; Salio et al., 2015).

Paleo and proxy-based datasets—Paleo data records, encompassing physical and biological proxies such as tree rings, ice cores, ocean and lake sediments, speleothems and corals enable prehistoric climates and ecosystems to be reconstructed and provide critical pre-instrumental to deep-time context to understand climate dynamics and biodiversity shifts. Paleoclimatic studies have helped understand the complex behavior of the climate system beyond the dynamical range observed today and have led to advances in the quantitative understanding of past climate variations. Examples are the response of the Earth system to natural forcing, analyses of internal variability, characteristics of the slow-changing components of the climate system, and empirical

evidence for abrupt climate changes (see e.g., Stocker, 2000; Wang et al., 2023; Berger and Loutre, 2002; Yin et al., 2021). Most importantly, paleo data records have revealed and quantified the much larger dynamical range of climate variations than present-day observations suggest.

These datasets are crucial for identifying abrupt past and current changes and trends in the climate system—including weather and climate variability and extremes. These data are also important for our ability to simulate future changes in the climate system, including potential abrupt events and climate disruptions. They provide the empirical data necessary to track environmental shifts, calibrate predictive models, and guide societal adaptation to weather and climate extremes. These proxy data, analyzed in terms of climate processes, climate variability, and climate trends, have been the basis for quantifying the long-term signals of climate change, including, but not limited to, global mean warming, changes in the hydrological cycle, Arctic amplification, changes in Antarctic and Arctic sea ice (mostly losses) and sea level rise. Taken together, they provide some of the strongest lines of evidence for anthropogenic climate change by establishing the long-term context of the past million years.

Paleo and proxy-based data sets are also the root for the concept of abrupt climate change. The analysis of ice cores from Greenland and the Antarctic, and marine sediment cores from around the world, showed that large scale rapid change within a few decades is a possibility, and that this has indeed occurred in the past. Through the reconstruction of greenhouse gas concentrations and ocean chemical status, they also provide information about the interactions between biogeochemical cycles (carbon, nitrogen, oxygen) and climate. Together, they are critically important for putting today's research on the potential impacts of human activities on tomorrow's climate into perspective (Kaufman and Masson-Delmotte, 2024).

In addition to physics and chemistry, a comprehensive understanding of the Earth System is impossible without the inclusion of biology and ecosystem science (e.g., plant physiology, vegetation dynamics). This makes climate science truly interdisciplinary. To reflect this, modern-day climate science is referred to as Earth System science (as shown in Fig. 3).

Historical perspective

The following historical perspective summarizes some prominent examples illustrating the important role that observations have played in advancing the understanding of the Earth System. Selected examples will address: the greenhouse effect, climate sensitivity, and global warming; ice ages, Milanković cycles and abrupt climate changes; boundary layer dynamics in the ocean and atmosphere; and ENSO as the most prominent mode of climate variability. This list is not exhaustive, and the selection of these examples is somewhat subjective—there are many other, equally relevant and important, examples that are not covered here because of length constraints.

Greenhouse effect, climate sensitivity, and global warming

The existence of the greenhouse effect was observed and explained first by the French mathematician and physicist, Jean-Baptiste Joseph Fourier. In seeking to determine what processes could explain the temperatures observed on Earth if solar radiation was the only source of terrestrial heating, Fourier realized that the Earth's atmosphere must play a key role. This led to his 1827 paper which is widely claimed to be the first description of the so-called “greenhouse effect”, although Fourier did not actually use the term “greenhouse”. The natural greenhouse effect is responsible for habitable conditions on Earth. Without it, Earth's mean surface temperature would be a freezing -18°C .

Climate sensitivity is used as an indicator to measure the change in the greenhouse effect. However, it is a more general quantity defined as the change in surface air temperature (T_s) resulting from a unit change in radiative forcing (RF), expressed in units of $\text{K}/(\text{W}/\text{m}^2)$. This definition is general as it is independent of the nature of the forcing (e.g., changes in atmospheric composition, GHGs, solar variation, atmospheric dust content or volcanic activity).

The notion of climate sensitivity goes back to Eunice Foote's work (1856) who experimentally demonstrated for the first time that CO_2 has a strong warming effect. Svante August Arrhenius (1859–1927) a physicist by training, was one of the founders of the science of physical chemistry. Aiming to develop a theory to explain the existence of ice ages on Earth solely through changes in atmospheric CO_2 content, Arrhenius was the first to use basic principles of physical chemistry to quantify the greenhouse effect on Earth, by calculating the extent to which increases in atmospheric CO_2 increase the Earth's surface temperature.

Arrhenius began with infra-red observations of the surface temperature of the moon obtained previously by Frank Washington Very and others to calculate how much of infra-red (thermal or heat) radiation is captured by CO_2 and water vapor in the Earth's atmosphere. Using the Stefan–Boltzmann law, he formulated the following rule for the change in radiative forcing, ΔF (in W/m^2) that is still in use today:

$$\Delta F = \alpha \ln \left(\frac{C}{C_0} \right).$$

Here C_0 is the concentration of CO_2 at the beginning (time-zero) of the period being studied; C is the CO_2 concentration at end of the period being studied; $\ln$ is the natural logarithm and α is the radiative forcing for the reference concentration of a specific greenhouse gas (in W/m^2). Derivations from atmospheric radiative transfer models have found that α for CO_2 is $5.35 (\pm 10\%) \text{ W}/\text{m}^2$ for Earth's atmosphere. Although Arrhenius accounted for water vapor feedbacks and latitudinal differences, he omitted several other key processes—most notably clouds and the vertical transport of heat—in his calculations. Even so, he is widely

regarded as the first to weave together the earlier insights of Fourier and others into a coherent explanation of global warming driven by human CO₂ emissions, an idea that sits at the foundation of contemporary climate-science understanding.

Today, climate sensitivity is usually used in the context of radiative forcing by CO₂ and is often expressed as the temperature change in degrees Kelvin (K) associated with a doubling of the CO₂ concentration in Earth's atmosphere. Recent work from Sherwood et al. (2020) suggest that the range of effective climate sensitivity is from 2.3 to 4.5 K. To come to this conclusion, authors looked at modelled data (from Earth System models like those described in 1.2 and 2.1), observations, response to recent volcanic eruptions as well as considering the evidence from paleo climate records.

Based on measurements, Arrhenius was the first to conclude in the 1890s that human-caused CO₂ emissions, from fossil-fuel burning and other combustion processes, could in principle, cause global warming. By the mid-1900s, there was finally sufficient observational evidence that human activities were continuously releasing increasing amounts of CO₂ into the atmosphere, with the potential to permanently change the global surface temperature over shorter time scales (e.g. Callendar, 1938, cited in Pearman et al., 2017).

Measurements of atmospheric CO₂ in the 19th and early 20th centuries were conducted using variations of a chemical method that were inherently noisy, making the identification of background CO₂ concentration problematic (Pearman et al., 2017). During the 1950s, efforts spun up to determine whether there was an observed trend of increasing atmospheric CO₂ concentrations globally, and to better understand the sources and sinks of carbon in the climate system, and their relative sizes. These efforts led to the International Geophysical Year (IGY) 1957–1958, which was an opportunity to obtain the critical CO₂ observations, data and information needed to answer these questions.

As part of the IGY, Charles David Keeling embarked in 1957 on a program of in situ and continuous high-precision CO₂ measurements using NDIR (non-dispersing infra-red) gas analyzers at sites in Mauna Loa (Hawaii, 20°N) and Antarctica (70°S), along with flask sampling at South Pole (90°S). Monthly observations of the CO₂ concentration in the atmosphere have thus been available since 1958 and reported as daily means since 1974. These were the measurements of atmospheric CO₂ concentrations that had sufficient precision to show the long-term increase over time (Keeling, 1960). These observations (see Fig. 4a) confirmed rates of increasing CO₂ concentration of nearly 1 ppm per year. They also show the unabated increase since the inception of this monitoring—chiefly caused by the burning of fossil fuels, deforestation and land use change. The record of global near-surface air temperatures (Fig. 4b) confirms the original theories in demonstrating the ongoing warming resulting primarily from these increase in GHGs.

For the longer-term context of these observations, paleo data are indispensable. Measurements of the greenhouse gas concentrations of air entrapped in the bubbles of Antarctic ice cores show that the increases of the major greenhouse gases (CO₂, CH₄ and N₂O) are unprecedented in the past 800,000 years (Lüthi et al., 2008). The record also documents the natural relationship between global temperature and greenhouse gas concentrations over long time scales. These observations are an excellent example of the value of long-term monitoring of climate variables. Despite continuous funding challenges, Keeling's persistence laid the foundation of one of the most important and consequential time series in climate science (Keeling, 1998).

Ice ages, Milanković cycles and abrupt climate changes

Paleo records and proxy observations, as described above, can be considered as “pre-instrumental observations”. They play a crucial role in charting the Earth system's dynamical range of variability. Paleo records from Antarctica and Greenland ice cores, along with marine sediment cores, have given unique insight into the climate and related changes over the last million years. Unlike any other observational record, they reveal that, in general, we are in a climate period of glacial cycles, where cold glacial periods lasting around 80,000 years have alternated with shorter warm interglacial periods with periods around 10,000 years, and in rare cases up to 30,000 years. These periodicities were found first in the ice core records. Their explanations came only later in the year 1864, when James Croll, a Scottish janitor at the museum of the Andersonian University in Glasgow, suggested that there are links between ice ages and variations in the Earth's orbit. Many years later, in 1920, the Serbian geophysicist and astronomer Milutin Milanković finally provided a definitive analysis that variations in eccentricity, axial tilt, and precession of the Earth's orbit around the sun lead to cyclical variations in the intra-annual and latitudinal distribution of solar radiation at the Earth's surface, and that the orbital variations of the Earth strongly influenced the Earth's climatic patterns.

The three Milanković periods of 100,000 years, 41,000 years and 25,700 years can be identified in ice core and sediment paleo records, and together they form the primary quantitative information on glacial cycles. It is recognized that the main reason for the onset of interglacials is the increase of insolation on high northern latitudes during spring and summer. As most of the Earth's land masses are in the Northern Hemisphere, where snow reflects incoming sunlight, this is the sensitive area that amplifies changes in radiative forcing. During deglaciations, major glacial ice sheets over North America, Fenno-Scandinavia and elsewhere melt and sea levels rise more than 100 m as the fresh water is released to the ocean.

Paleo proxy records show that changes of GHG concentrations are synchronized with the temperature changes (Fig. 5), so the concentrations are lower in the colder glacial periods and amplify the glacial-interglacial temperature changes. GHG concentrations are larger in colder ocean water—some of these gases are released when the atmosphere and ocean warm in interglacial periods.

As the driver for the glacial cycle is the gravitational forces between the sun and the planets, it is also possible to predict the future. It is thus interesting to note that our present interglacial is to last for at least another 10,000 years. It is one of the very long interglacials, as long as the one that occurred 400,000 years ago (stage 11). The changes in forcing that result from these Milanković cycles will thus not help to mitigate anthropogenic climate warming!

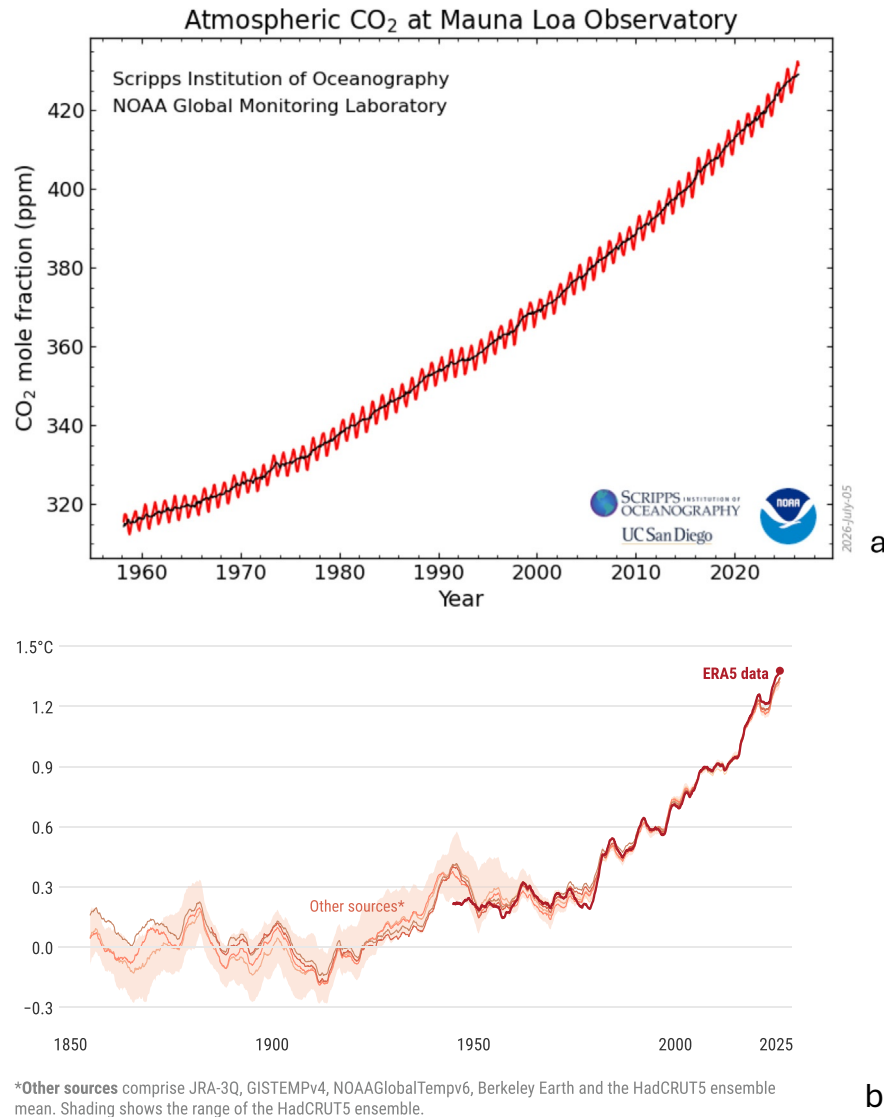


Fig. 4 (a) Monthly mean Mauna Loa CO₂ concentrations measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data on Mauna Loa constitute the longest record of direct measurements of CO₂ in the atmosphere. (b) Anomalies in global average surface air temperature (°C), shown as five-year averages (centered running 60-month periods) since 1850, relative to the average for the 1850–1900 designated pre-industrial reference period, and as annual averages since 1967, relative to the average for the 1991–2020 reference period. (a) From <https://gml.noaa.gov/ccgg/trends/>. (b) Data source: Based on six global temperature datasets. Credit: C3S/ECMWF. Source: <https://climate.copernicus.eu/climate-indicators/temperature>.

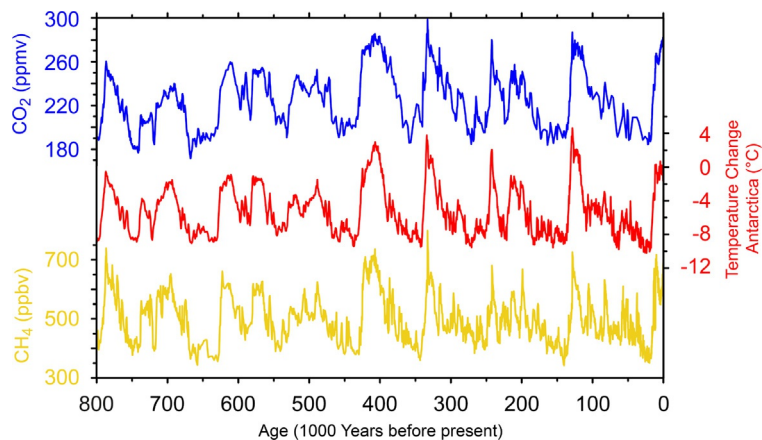


Fig. 5 Reconstructions of the two major greenhouse gases (CO₂ and CH₄) and a proxy of Antarctic temperature over the past 800,000 years, measured on the EPICA ice core from Dome Concordia, Antarctica (Lüthi et al., 2008; Jouzel et al., 2007; Loulergue et al., 2008).

Besides this example of externally forced glacial cycles, internally forced abrupt changes have been discovered, especially from Northern Hemisphere deep ice cores and ocean sediment cores. Sequences of 26 prominent abrupt climate change events (Dansgaard-Oeschger events) occurred during the last glacial period. They consist of an abrupt warming of up to 16 °C over Greenland in less than a few hundred years followed by a slow lasting about 1000 to 7000 years until cold conditions were reached again. The occurrence of Dansgaard-Oeschger events is not periodic but rather irregular. Proxy data from marine sediment cores show a significant reduction of the AMOC (Atlantic Meridional Overturning Circulation) ocean circulation during the cold phases and an intense release of fresh water from unstable ice sheets just before the abrupt warming happens (Hemming, 2004).

High-resolution ice cores from Antarctica covering the same period demonstrate the global nature of such abrupt changes with different phases, strongly involving the Southern Ocean and in general shows a bipolar seesaw—a shift of ocean heat content between the hemispheres driving the abrupt changes (Stocker and Johnsen, 2003; Buizert et al., 2026).

Our present warming climate, with melting of the cryosphere and an increase in precipitation in the Arctic, is increasing the freshwater release to the ocean, particularly the North Atlantic. These impacts conspire with the rapid warming to reduce the density of sea water and reduce convection or shift convection sites. This is of concern because it could potentially trigger a reduction of the AMOC over the coming decades to century (Portmann et al., 2026). A complete cessation of AMOC, as was seen during the glacial, cannot be excluded.

One of the major triggers of sea level rise revealed from the past is a full or partial disintegration of the West Antarctic ice sheet. The West Antarctic Ice Sheet has a volume equivalent to 7 m of mean global sea level rise and is a marine ice sheet because most of its ice is grounded several kilometers below sea level, on rock and sediment that would become the ocean floor if the ice were to retreat.

In the long term, the West Antarctic Ice Sheet is likely to disappear due to the warming which has already occurred. Paleoclimate evidence from deep ocean sediment cores (ANDRILL project, see Naish et al., 2009) clearly shows that this has happened in basically all past warm interglacials, and new evidence suggests that this also happened during the Eemian period, about 120,000 years ago, when the global temperatures were similar to those in the early 21st century.

Boundary layer dynamics in the ocean and atmosphere

Fridtjof Nansen, a Norwegian polar scientist and physical oceanographer, observed in 1890, while sitting on his boat “Fram” frozen in sea ice drifting across the Arctic Ocean, a phenomenon: sea ice transport appeared to be directed at an angle of 20°–40° to the right of the prevailing wind but not along the wind direction itself as one intuitively would expect.

It took many years until the Swedish theoretical oceanographer and fluid dynamicist, Vagn Walfrid Ekman (1874–1954), published his motion theory of the now-called Ekman spiral which explains the phenomenon Nansen had observed in terms of the balance between frictional effects in the ocean and the Coriolis force, and apparent force acting on moving bodies in a rotating environment. The underlying principle is that, when surface water molecules move by the force of the wind, they, in turn, drag deeper layers of water molecules below them. We know today that a respective Ekman layer exists also at the bottom of the ocean as well as the bottom of the atmosphere.

The vertically integrated velocity of the Ekman spiral results in the Ekman transport which is perpendicular to the driving wind. Winds are the main source of energy for driving the ocean circulation, and the Ekman transport in fact is a component of wind-driven ocean currents. As the wind blows it acts through a friction force on the ocean surface that drags the upper 10–100 m of the water column with it. The direction of transport is dependent on the hemisphere: in the Northern Hemisphere, transport veers clockwise from wind direction, while in the Southern Hemisphere it veers anticlockwise. Mass conservation requires that any water displaced within an area must be replenished. This process is important at coastal boundaries where upwelling (Ekman pumping) or downwelling (Ekman suction) occurs, depending on the wind patterns, and at the equator (Ekman suction, only).

Ekman’s motion theory is the starting point for many important theories of the wind driven ocean circulation as formulated by Sverdrup (1947), Stommel (1948), and Munk (1950a) which together laid the foundation of modern wind-driven ocean theory, based on the concept of a steady-state ocean circulation. It also is the basis for the description of so-called inertial oscillations in the ocean, of sea ice drift in the high latitudes, or motion in the atmospheric boundary layer. Because the vertical motion induced by Ekman transport also affects tracers and nutrients this has a significant impact on the physical and biogeochemical properties of the world’s oceans.

Upwelling and downwelling in the ocean is so important for marine life because of the role these processes play in transporting nutrients. It is important for horizontal heat distribution in the ocean because it leads to convergence and vertical transport of heat. It is also important for the ocean circulation—being the main driver for the large-scale wind-driven ocean circulation. In addition, Ekman’s motion theory is the starting point for Stommel’s theory (Stommel and Arons, 1959) of the until then observationally entirely elusive abyssal ocean circulation many years before observations were able to catch aspects of it. This includes the existence of a deep western boundary current flowing in the opposite direction to the North Atlantic Current. Nevertheless, it all started with Nansen’s unexplained observations of sea ice motion a few decades before, a compelling example of “theory follows observation”.

Meteorologists understood that orography and land cover influence the atmosphere and, in turn, weather and climate through interactions between the land surface, atmospheric turbulence, and larger-scale synoptic circulations. Advances in numerical weather prediction, and quantifying pollutant dispersion and transport in the lower atmospheric boundary layer (ABL), demanded deeper insights into the physical processes. However, the chaotic nature of turbulence, combined with the strong influence of atmospheric stability and larger scale atmospheric dynamics, prevented the development of robust theories and numerical models.

These barriers were overcome through a combination of observations and theoretical advances—beginning with Monin and Obukhov’s Similarity Theory (MOST, see Garratt, 1994 and Wyngaard, 2010) developed in 1954. Even though it was a significant breakthrough, by providing a unified framework for turbulent transport in the lower ABL, MOST could not be implemented without observations. The Wangara, Koorin and ITCE (Clarke, 1970; Dyer et al., 1982; Hess et al., 1981) measurement programs in Australia, and earlier campaigns in the Great Plains of the United States (Lettau and Davidson, 1957), were crucial in providing the observational data needed to empirically determine the functional forms of MOST and test its validity, especially across stability regimes.

These observational programs led to new and transformative approaches to measuring exchanges of energy, water, momentum and CO₂ between the land and the ABL, by sampling the vertical turbulent transport (e.g. Dyer, 1961; Hicks, 1969, 1980; Dyer et al., 1967). Because progress depended on new technologies and new measurements, scientists and engineers collaborated to develop the necessary instruments and data logging systems. The Evapotron (Dyer and Maher, 1965) and Fluxatron (Dyer et al., 1967) were two such systems based on the eddy covariance approach that was pioneered in these early field campaigns. These systems, and the eddy covariance approach, are the foundations of today’s FluxNet observations (Section “Climate observations today”) that underpin contemporary studies of the carbon and water cycles by providing direct observations of net CO₂ uptake in terrestrial ecosystems (Section “Observing the global carbon cycle”) and water losses through evapotranspiration (Section “Water cycles and water availability”).

Similarly, the Global Atmospheric Research Program (GARP) was launched in 1967 to provide the observations and data needed to improve numerical weather and climate prediction and study climatic changes, as well as enhancing international cooperation in global atmospheric observations and to (Heymann, 2025).

El Niño–Southern Oscillation (ENSO)

The El Niño–Southern Oscillation (ENSO) affects climate worldwide, driving large seasonal to interannual variability, especially in rainfall. El Niño events feature high atmospheric pressure over the western tropical Pacific and Indian Ocean, low pressure in the southeastern Pacific, weakened trade winds, and warming of the eastern and central equatorial Pacific. Bjerknes (1966, 1969) showed that these atmospheric and oceanic anomalies arise from coupled interactions, leading to the modern concept of ENSO.

ENSO is a classic atmospheric-oceanic coupled teleconnection, linking distant regions through large-scale climate processes. Its scientific understanding began with observations and indigenous knowledge, followed by recognition of correlations among sea-surface temperatures, pressure patterns and rainfall anomalies. A physical framework emerged only after coordinated ocean–atmosphere observation campaigns, process studies and the development of predictive models.

Peruvian fishers have long observed the warm current they named *El Niño*, which periodically displaced cold, nutrient-rich waters and disrupted fisheries. Indigenous Australians also developed knowledge systems to manage the impacts of highly variable rainfall on floods, droughts and fire regimes (Taschetto et al., 2026). Nineteenth-century reports documented synchronous droughts in Australia and India (Todd, 1988). By the early twentieth century, these observed teleconnections were termed the Southern Oscillation (Walker, 1924). In the 1960s, this oscillation was linked to Eastern Pacific warming and variations in the equatorial pressure gradient, revealing that El Niño was a basin-wide phenomenon rather than a coastal event.

The extreme 1982–1983 El Niño—neither predicted nor detected early—became a turning point, although a basic understanding was already formulated almost a decade earlier (Wyrtki, 1975). One of the strongest events on record, it caused severe droughts, fires and dust storms across Australia, Asia, Africa and Indonesia, and catastrophic floods in Peru and Ecuador, resulting in thousands of deaths and billions of dollars in damage.

In response, the WCRP launched the Tropical Ocean Global Atmosphere (TOGA) programme (1985–1994) to investigate ENSO dynamics and improve predictability. TOGA’s real-time in situ and satellite observations of winds, sea-surface and subsurface temperatures, currents and sea level transformed understanding of the coupled system. It demonstrated the essential role of sustained, globally coordinated observations and enabled the first generation of coupled models and seasonal prediction systems (e.g., McBride and Nicholls, 1983).

ENSO exemplifies how climate observations underpin understanding of short-term climate variability, especially rainfall, and support society’s ability to manage climate risks. Continued advances in observing systems and theory remain crucial as ENSO’s behavior and impacts evolve under greenhouse gas forcing.

Ongoing highlights

Albeit not complete and sustained, today’s climate observing system can observe the climate state and its changes better than ever before. In situ and space-borne activities now provide climate or climate relevant observations on a routine basis. In addition, important research-oriented expeditions take place that provide unique and unprecedented observations, e.g., of Greenland or Antarctic ice cores providing ice samples and with this information about the Earth’s history going back in time for hundreds of thousands of years.

The following provides selected examples of state-of-the-art climate science results based primarily on observations or a combination of observations and numerical models. These examples use ice core data, other paleo/proxy data as well as analyses of in situ ocean and atmospheric observations.

Global warming and ocean heat uptake

In response to anthropogenic greenhouse gas emissions, the Earth system is taking up heat (see also Section “Greenhouse effect, climate sensitivity, and global warming”). This enhanced energy content is impacting all elements of the climate system. However, the largest fraction of the excess heat that entered the climate system since the beginning of the industrial revolution is being absorbed by the ocean (until now around 89%; von Schuckmann et al., 2023). The 1993–2023 full-depth ocean warming rate of about 403 TW represents a massive accumulation of heat energy in the Earth system (Johnson et al., 2024). This build-up of heat in the oceans causes sea level to rise through the thermal expansion of sea water and by increasing melt rates of marine-terminating ice sheets and mountain glaciers.

The international global Argo array of autonomous profiling CTD (conductivity-temperature-depth) instrument-equipped floats monitors the spatial and temporal patterns of change in temperature and salinity in near real time in the upper 2000 m of the ocean. By providing this hitherto unknown and detailed information on a nominal 3° geographic grid, the array has revolutionized our understanding of ocean physics (Johnson et al., 2022; Roemmich et al., 2019). However, the oceans below 2000 m remain sparsely sampled in space and time. Deep observations are primarily undertaken by oceanographic research vessels occupying “hydrographic sections”—where CTDs are lowered from the sea surface to the sea floor or some intermediate depths at intervals along the ship’s path.

Recently a global Deep Argo array has been proposed (Johnson et al., 2015; Roemmich et al., 2019) as part of OneArgo to extend Argo’s spatial coverage to the sea floor. The first Deep Argo regional pilot array began in the Southwest Pacific Basin in 2016, with basin-scale arrays now established in the Brazil, Argentine, North Atlantic, and Australia-Antarctic basins, and additional floats in the Indian Ocean and North Pacific (Zilberman et al., 2023).

Using all available historical ship-based and Deep Argo CTD data, Johnson and Purkey (2024) examined the global distribution of anthropogenic heat in the deep and abyssal ocean. The deep (2000–4000 dbar) temperature trend map (Fig. 6a) again shows mostly warming around Antarctica, but more patchy regions of both warming and cooling to the North, with warming trends in the Greenland-Iceland-Norwegian Seas and much of the Subpolar North Atlantic, and a notable region of strong cooling throughout much of the rest of the western North Atlantic. Despite the patchiness in the deep layer, the warming trend dominates the global integral for the deep layer, as shown in Fig. 6b). The spatial distribution of the resulting local abyssal (4000–6000 dbar) temperature shows the strongest warming trends adjacent to Antarctica with the warming extending northward through much of the global oceans, generally weakening with distance from Antarctica (Fig. 6b). Abyssal cooling is found mostly in both the eastern and western deep basins of the North Atlantic as well as the Angola Basin in the eastern South Atlantic.

Sea level

Physically and geometrically, sea level is the interface between the ocean and the atmosphere. At the coastline it also represents the transition from the wet ocean to the dry land. Any change in sea level inevitably will lead to a migration of the coastline onto land or towards the ocean. Through climate change and associated sea level rise, this can have dramatic impacts on societies as these changes can lead to loss of habitats and “home” for millions of people living along low-lying coastlines or small islands.

The only way to learn about ongoing sea level change—globally or regionally, and at the coastline, is via observations. Historically this involves paleo reconstructions of sea level using various proxy records (e.g., corals, salt marshes etc.) and historic ocean observations. Recent observations use a global tide gauge network and high-precision satellite sea level observations. Global mean sea level has risen about 21–24 cm since 1880. The rising water level is mostly due to a combination of melt water from glaciers and ice sheets and thermal expansion of seawater as it warms. In 2023, global mean sea level was 10.14 cm above 1993 levels, making it the highest annual average in the satellite record (1993–present). Since the early 1990s, regional sea level observations via satellite altimetry have revealed a complex spatial geometry of SLC across the global oceans (Fig. 7).

Along coastlines, many more processes can lead to changes in sea level, e.g., changes in the ocean circulation and respective changes in heat, salt or local mass (Woodworth et al., 2019). It can also be caused by changes in the solid Earth due to redistribution of water mass and respective responses of the Earth’s crust (vertical land motion, VLM) or of gravitational attraction. In addition, near-coastal VLM can result from resource extraction (groundwater, oil, gas) or tectonic activity which on a local and regional scale can result in large relative SLCs that can be several orders of magnitude larger than changes resulting from climate related processes (Klos et al., 2019; Shirzaei et al., 2021; Tay et al., 2022; Oelsmann et al., 2024). As an example, subsidence at Nias (Indonesia) associated with the 2005 earthquake was >1 m. Accounting additionally also for land uplift, changes can be even larger, e.g., Myanmar coast uplifted by 6 m during the 1762 earthquake (Wang et al., 2013). Finally, changes in the atmospheric circulation associated with natural climate cycles or caused by increasing greenhouse gas emissions may drive significant additional changes in coastal sea level through changes in atmospheric loading or wave-induced coastal hydrodynamics (Dodet et al., 2019; Idier et al., 2019).

Cryosphere and glacier retreats

The Earth’s cryosphere, encompassing all forms of ice in the climate system, stores a large amount of water on land that, if melted, would lead to significant sea level rise on a global scale. The largest present-day contribution from the cryosphere to sea level rise comes from melting glaciers, followed by the Greenland and Antarctic ice sheets. This will likely change in the future, with ice sheets becoming the largest source of mass for the ocean from the cryosphere. The dynamics of ice sheets and glaciers is complex as is their response to change in climate forcing. Specifically, the delayed response of glaciers and ice sheets to changing climate conditions

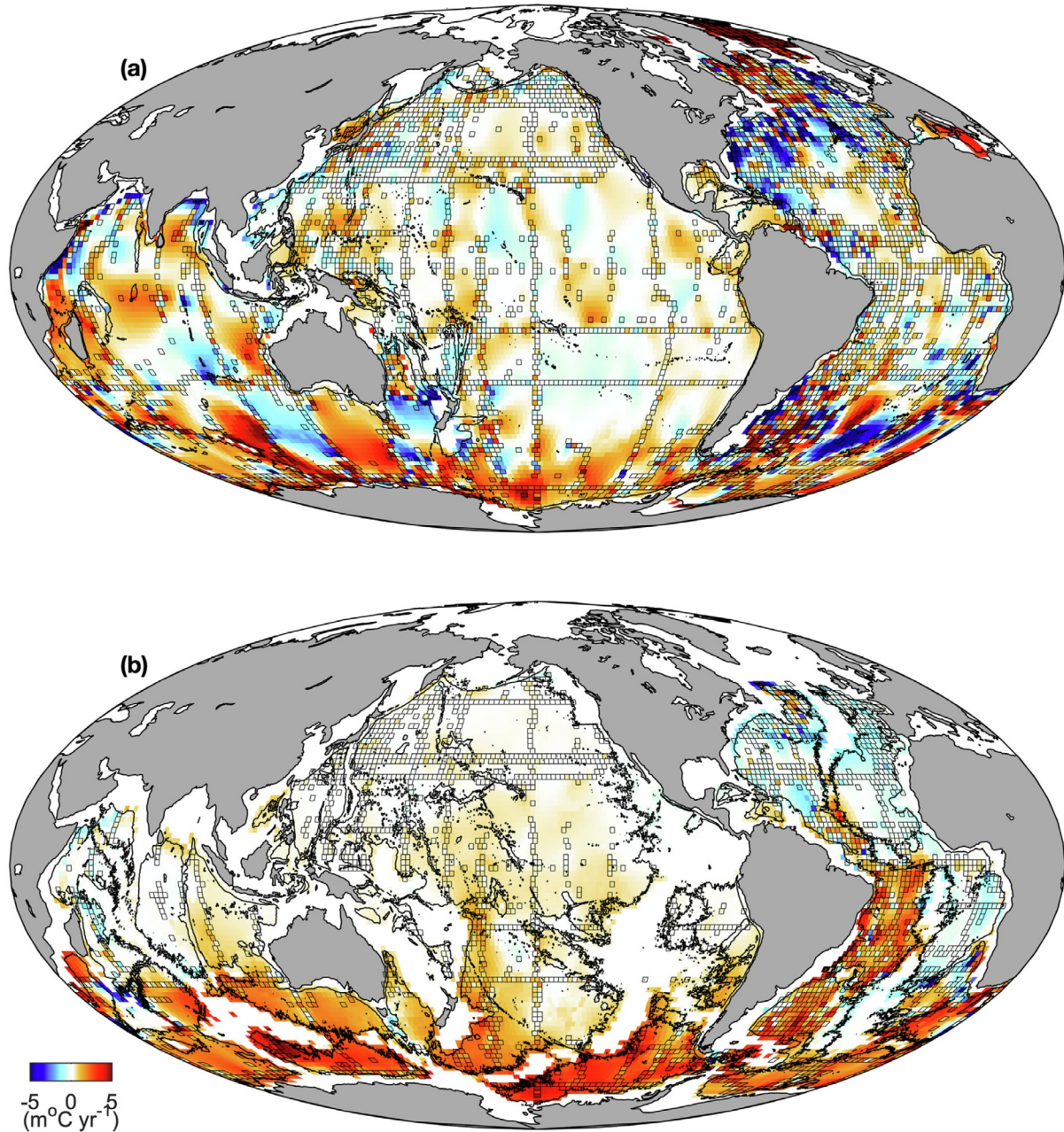


Fig. 6 (a) Deep (2000–4000 dbar) and (b) abyssal (4000–6000 dbar) pressure-averaged decadal temperature trends in 167×167 km bins with the 2000 and 4000 dbar isobars of bottom bathymetry contoured, respectively (black lines) (from Johnson and Purkey, 2024). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

leads to a systematic disequilibrium between glacier size and the local climate conditions, masked by the effects of natural variability. This makes it very difficult to identify anthropogenic impacts on glacier melting rate as opposed to natural climate variability.

Some observations of glacier length change go back several centuries (Leclercq et al., 2014); however with observations primarily from the European Alps and Scandinavia. These regions are well-studied and relatively accessible, but store relatively little ice and are thus not significant contributors to future SLR. Additionally, glacier length changes do not directly translate into glacier mass changes. Nevertheless, respective information has been used frequently to estimate global glacier mass change since 1800 (Leclercq et al., 2011). Using these sparse historic in-situ observations, supplemented with more recent and more representative remotely sensing observations, allows a reconstruction of glacier mass change contribution to SLR over the past 60 years (Zemp et al., 2019, 2020), and, for the more recent past, on the scale of individual glaciers (Dussailant et al., 2024).

Today, estimates of glacier mass change are also informed by remote sensing observations of glacier surface elevation change that have been available globally since 2000 and have led to an estimate of glacier contribution to global mean sea level rise (GMSLR) of

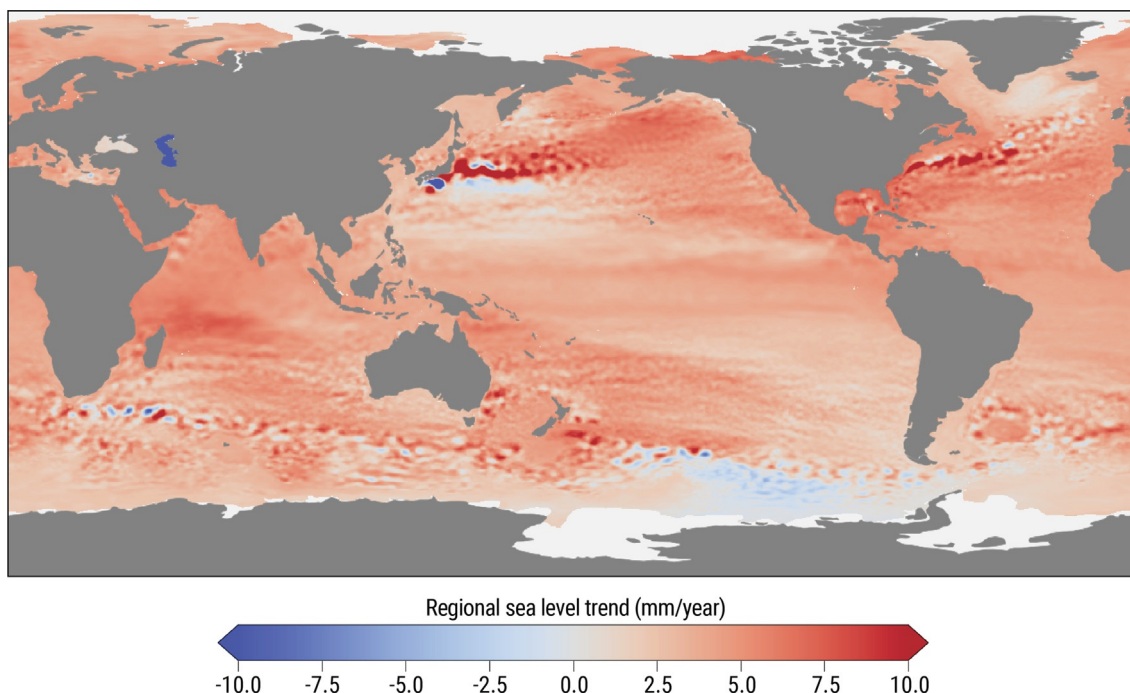


Fig. 7 Geographic map of temporal trends in sea level in mm/yr as measured by satellite altimetry over the period February 1999 to August 2025. In some regions rates of SLR during this period were higher than the global mean rate of 3.4 ± 0.3 mm/yr by up to a factor of two or more (Guérou et al., 2023), particularly in the western tropical North Pacific, in the Northwest Pacific, in the Gulf of Mexico. Slightly lower trends were present in the eastern Pacific, south of Greenland and around west Antarctica. Data: CMEMS Ocean Monitoring Indicator based on the C3S sea level product. Map lines delineate study areas and do not necessarily depict accepted national boundaries. From <https://climate.copernicus.eu/climate-indicators/sea-level>. Credit: C3S/ECMWF/CMEMS.

0.74 ± 0.04 mm/yr over the period 2000 to 2019, corresponding to $21 \pm 3\%$ of the GMSLR (Hugonnet et al., 2021). There is a strong scientific consensus that global warming is accelerating the loss of ice mass in all glacierized regions on Earth (Hugonnet et al., 2021). However, although all regions show mass loss, the magnitude of this anthropogenically driven glacier mass loss is distributed very unevenly across glacierized regions (Zekollari et al., 2025; The GlaMBIE Team, 2025). More than 100 mm additional GMSLR from melting glaciers is committed to occur over the next decades due to present-day climate conditions, irrespective of further warming.

The potential for abrupt changes of Antarctic sea ice is not well understood, but evidence is emerging that structural changes are underway in the Antarctic environment. Satellite observations since 1979 reveal unprecedented record-low sea ice extent, beginning in 2016 and especially during 2023–2025. Observations (in situ and satellite-based) suggest these changes reflect interactions driven by changes in ocean heat content, atmospheric circulation, and internal climate variability. Such structural changes matter because of the role that Antarctic sea ice plays in the Earth’s climate system, influencing planetary albedo, Southern Ocean heat exchange, deep water formation, carbon uptake, and marine ecosystems. Abram et al. (2025) suggest that a regime shift to a new sea-ice state could be underway, or that the available measurement record is too limited to fully characterize the natural range of sea-ice variability. This demonstrates the importance of sustaining observations in this important part of the Earth’s system, along with improving sea ice models—to simulate future changes and assist in reconstructing the past.

Ice cores

Deep ice cores from Greenland and Antarctica document the long-term climate, variability and abrupt changes as described above. As observation methods improve, new scientific goals and targets are being defined.

There is an ongoing search for ice core drilling sites with ice in stratigraphic order older than 1.2 million years. At Little Dome C in Antarctica, a European consortium reached this goal in January 2025 (Westhoff et al., 2026). The overarching aim is to understand the climate changes during the Mid Pleistocene Transition (MPT) from 0.8 to 1.2 million years ago when the pacing of the glacial cycle slowed down from 40,000 years to the present about 100,000 years. This will teach us about the dynamics in a warmer climate and a climate with different levels of greenhouse gas forcing.

Novel methods using small ice samples can be used to date ice even when not in stratigraphic sequence. The isotopes ^{81}Kr and $^{40}\text{Ar}/^{36}\text{Ar}$ of air in the bubbles are used to date ice around 1 million years old, and ^{10}Be , ^{36}Cl and ^{24}Al on dust, pebbles and rocks can be radiogenically dated. These observations teach us about the age of today’s ice sheets: the central part of Greenland has been ice covered for the last 1 million years. When compared with benthic paleo records, the Greenland ice sheet is clearly very resilient to climate variations and would require significant persistent warming to disappear completely.

A global atmospheric composition and CO₂ observing network

The World Meteorological Organization (WMO) have supported a global network of atmospheric composition measurements since 1969, which was consolidated into the Global Atmospheric Watch (GAW) program two decades later. Today, GAW coordinates high-quality atmospheric composition observations to advance understanding of atmospheric composition, its change, and the interactions between the atmosphere, the oceans, and the biosphere (Global Atmosphere Watch (GAW) Programme, <https://community.wmo.int/site/knowledge-hub/programmes-and-initiatives/global-atmosphere-watch-gaw-programme>).

Technical advances in analytical chemistry, instrumentation, engineering, and data processing, along with rigorous calibration procedures needed for high-precision measurements comparable across time and space, paved the way for establishing permanent ground-based observatories around the world. This led to a high-quality monitoring network that expanded the existing stations at Mauna Loa and the South Pole (see Section “Greenhouse effect, climate sensitivity, and global warming”) and added coverage of the Southern Hemisphere. Through these observations, atmospheric CO₂ concentrations have been monitored globally for many decades. Some of these observing stations included measurements throughout the atmosphere, up to the lower stratosphere, to capture the space-time variability of CO₂ concentrations.

A highly relevant example of one of these stations is the [Kennaook/Cape Grim Baseline Air Pollution Station \(KCG BAPS\)](#), established in northwestern Tasmania (Australia, 40.68°S) in 1976. KCG BAPS is one of three baseline air pollution stations, along with Mauna Loa in Hawaii (19.5°N, Section “Greenhouse effect, climate sensitivity, and global warming”) and Alert (Canada, 82.45°N), in the GAW network. Baseline stations provide crucial points of reference for the larger network of atmospheric gas observatories around the world because they measure the background global atmosphere unaffected by local pollution and human emissions (baseline air). As the only baseline station in the Southern Hemisphere, KCG BAPS provides continuous monitoring of all the greenhouse gases in clean marine air transported by the westerly winds over the vast Southern Ocean.

The KCG BAPS measurement program is complemented by analyses of air samples extracted from Antarctic ice cores to provide greenhouse gas concentrations, as well as the relative abundances of ¹²CO₂, ¹³CO₂ and ¹⁴CO₂, in current and past atmospheres. Combined, this provides a continuous record of all major greenhouse and radiatively active trace gases along with their source (biological, geological and fossil). These observations enable us to construct time series of long-term changes in background greenhouse concentrations, over recent decades (Fig. 8) and millennia (Fig. 9). They provide the empirical evidence for changes

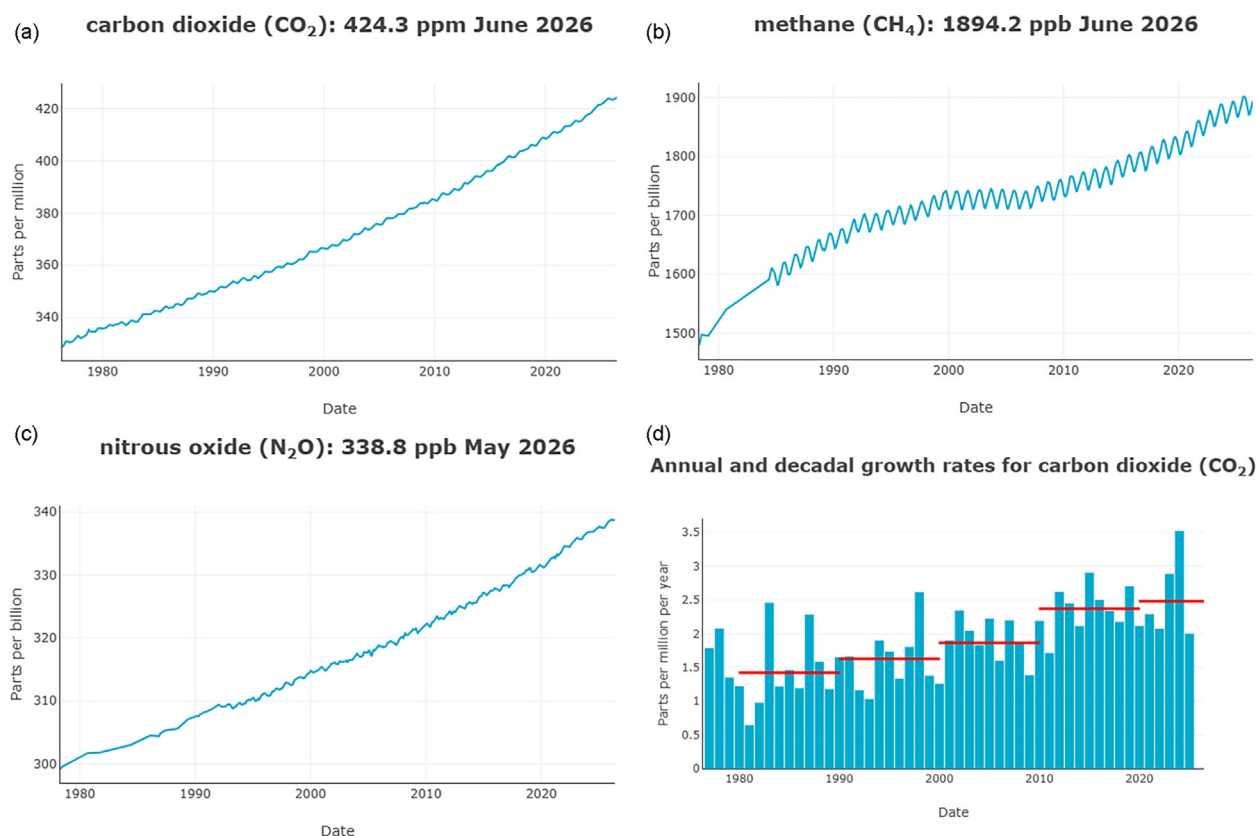


Fig. 8 In situ observations (monthly means of all baseline data) of GHG concentrations measured at the Southern Hemisphere Cape Grim/Kennaook Observatory over instrumental record (50-years): (a) CO₂, (b) CH₄, (c) N₂O; and (d) Annual (blue bars, ppm per year) and decadal (red lines, ppm per decade) growth rates for CO₂. From <https://www.csiro.au/en/research/natural-environment/atmosphere/Latest-greenhouse-gas-data>.

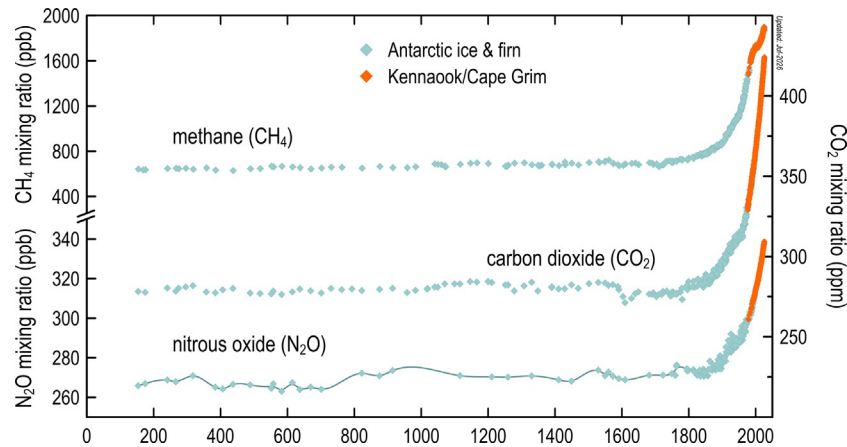


Fig. 9 Record of the three major greenhouse gases over the last two thousand years. Note the measurements of all greenhouse gases are measured using the same analyzers and calibration protocols, enabling these key observations to be presented as a single time series. From Paul Krummel, CSIRO. Sourced from Latest Kennaook/Cape Grim greenhouse gas data—CSIRO, published with permission from CSIRO and Australian Bureau of Meteorology.

being observed in the global temperature (Fig. 4) that arise from the changes in radiative forcing due to increased greenhouse gas concentrations.

These measurements are not only critically important for tracking past and current concentration of these greenhouse gases, but they also contribute to the development of models quantifying carbon-climate feedbacks in the past, present-day and into the future, along with contemporary approaches to track the budgets of all greenhouse gases (Section “Observing the global carbon cycle”). Clearly, emission reduction efforts so far have been insufficient to slow the year-on-year rise in greenhouse gases, as well as the decadal growth rate in CO_2 .

Observing the global carbon cycle

Early research on the greenhouse effect, and confirmation that human activities were increasing atmospheric CO_2 as described in Section “Greenhouse effect, climate sensitivity, and global warming,” prompted questions about the cycling of carbon between the oceans, land and atmosphere (Fig. 10). For example, Revelle and Suess (1957) used the carbon isotopic signature of CO_2 to examine

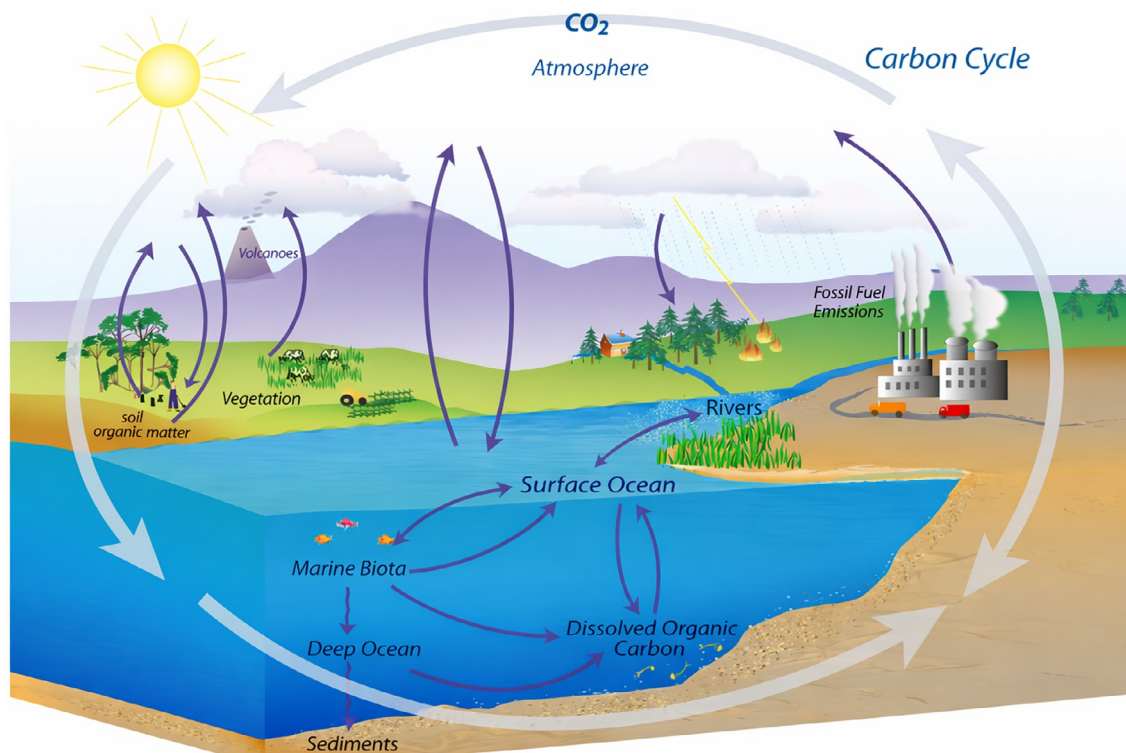


Fig. 10 The global carbon cycle. Adapted from original from NOAA. From <https://www.noaa.gov/education/resource-collections/climate/carbon-cycle>.

the partitioning of emissions between the atmosphere and ocean. Plass (1956) calculated that doubling CO_2 would warm the planet by 3.6°C —an early measure of climate sensitivity consistent with Arrhenius (Section “Greenhouse effect, climate sensitivity, and global warming”) and modern assessments from climate science. In the 1960s, pioneering measurements of CO_2 concentrations and fluxes over plant canopies using the pioneering techniques described in Section “Boundary layer dynamics in the ocean and atmosphere” (e.g. Pearman et al., 2017) highlighted the need to understand the magnitude and variability of CO_2 fluxes.

Such studies underscored the importance of understanding the cycling of carbon through the Earth’s climate system and its implications for past, present and future climates. The global observing programs described in Section “Climate observations today” were established in response. Today, they are essential for sustaining the high-quality measurements of carbon fluxes in the ocean (GOOS) and over land (FluxNet) needed to better quantify the global carbon cycle. Maintaining the consistency of these observations requires rigorous calibration and sampling protocols, quality assurance methods and data curation infrastructure—enabled by these programs. Many networks integrate in situ and satellite observations, producing combined data products that have been crucial for quantifying and constraining global and regional carbon and methane budgets.

The most recent global carbon budget (Friedlingstein et al., 2026), integrating in situ and satellite observations with modelling, finds that land and ocean sinks absorb 29% and 21% of anthropogenic CO_2 emissions, respectively. The remaining 50% leads to the observed increase in CO_2 in the atmosphere. These sinks have kept pace with rising emissions, which means they are playing a critical role in modulating the pace and magnitude of anthropogenic climate change. But they respond to drought, wildfire and changes in ocean circulation—these are processes that might weaken these sinks and result from the complex feedbacks between the various components of the carbon cycle.

Methane, the second most important anthropogenic greenhouse gas after carbon dioxide, has increased in the global atmosphere due to human activities, including agriculture (e.g. rice cultivation and farming of ruminant animals such as cattle), coal mining, and reticulation of natural gas. Methane is removed from the atmosphere by hydroxyl radicals—whose strength varies from year to year. Its short atmospheric lifetime of about 10 years and stronger per molecule-radiative forcing compared to CO_2 , as well as its accelerating growth in recent decades, makes it increasingly important to include it in climate mitigation strategies. The Northern Hemisphere is currently a net source, and the Southern Hemisphere a net sink, for methane (CSIRO, Latest Kennaook/Cape Grim greenhouse gas data—CSIRO).

The most recent global methane budget shows both emissions and atmospheric concentrations are continuing to rise (as seen in Figs. 8, 9 and Fig. 11), with ~65% of the increase attributable to human activities. Large uncertainties persist in natural methane emissions, particularly from wetlands and inland waters (Saunio et al., 2025). These emissions may be rising in response to global temperature increases.

Sustained observations of the carbon cycle are therefore critical for assessing future climate change. With the development of Earth System Models (Section “Applications of climate observations”), high-quality observations of carbon fluxes, reservoirs and their spatial and temporal variability are essential to ensuring key processes are adequately represented. Analyses of global carbon and methane budgets rely on these observations, while high-quality atmospheric concentration measurements (as described in Section “A global atmospheric composition and CO_2 observing network”) remain indispensable for tracking changes in the carbon cycle and constraining model data syntheses.

Annual and decadal growth rates for methane (CH_4)

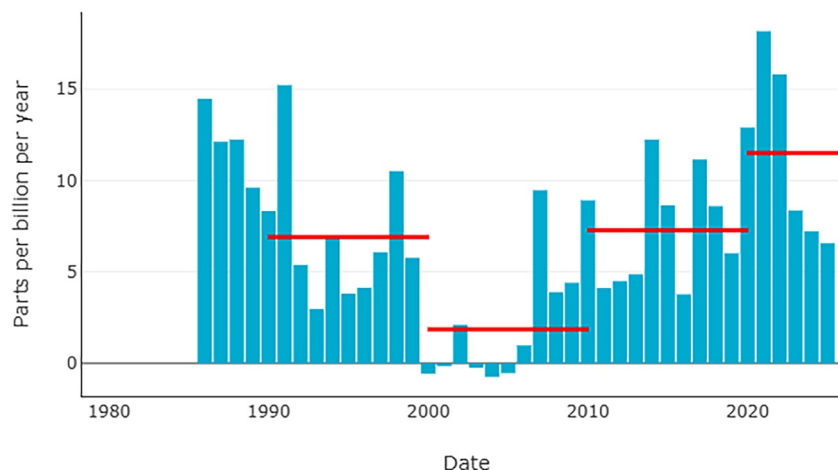


Fig. 11 Annual (blue bars) and decadal (red lines) methane growth rate, measured at Cape Grim/Kennaook observatory in Southern Hemisphere, showing large variability in growth rates, and recent increased growth rates beginning ca. 2007. From <https://www.csiro.au/en/research/natural-environment/atmosphere/Latest-greenhouse-gas-data>.

Water cycles and water availability

Water, in all its phases, is a fundamental component of the climate system because of its high heat capacity, the large energy exchanges when it changes phase, and the wide range of albedo and emissivity across those phases. Water vapor is the most powerful natural greenhouse gas.

The water cycle strongly shapes human societies, the environments they inhabit and the ecosystems that provide vital services. People intervene in the regional water cycle directly through river regulation, dams and irrigation. Global warming alters the global cycle by melting snowpacks, glaciers and ice sheets; shifting the intensity, seasonality and distribution of precipitation; and overall intensifying the hydrological cycle. These changes directly affect water availability for drinking and agriculture, making the monitoring and prediction of the water cycle one of climate science's central challenges.

The continuous cycling of water through the atmosphere, land, ocean and subsurface exerts a first order influence on climates from micro to global scales. Observations remain essential for understanding interactions between climate and the global water cycle across its three phases and along its pathways between all the Earth system components (Fig. 12).

Precipitation is measured by in situ rain and snow gauges, complemented since the 1980s by satellite-based global rainfall estimates, including over oceans. In situ data remains essential for calibrating and validating satellite products. Ensuring high-quality, representative precipitation observations is a persistent challenge for climate and water resource applications into the future (Section "The future role of climate observations").

Soil moisture is monitored using a range of methods: from point scale sensors (e.g. neutron probes, Time Domain Reflectometry) that provide high frequency but spatially limited measurements, to satellite remote sensing (e.g. SMAP satellite, Sentinel 1) that offers large scale estimates of near surface moisture but requires ground-based validation. The development of COSMOS/cosmic ray neutron sensing (CRNS), now deployed as a global network, provides area integrated soil moisture over tens of hectares and bridges the gap between point and satellite observations.

Soil water availability governs plant water status and stomatal conductance, thereby influencing CO₂ uptake. It also regulates heterotrophic respiration and partitions surface energy between sensible and latent heat fluxes—the resulting Bowen ratio shapes local to regional climates. Soil moisture therefore exerts a first order control on climate across scales.

Because evapotranspiration (ET) dominates the water balance on land—typically exceeding 95% of precipitation—ET measurements have long complemented soil moisture observations. Historically, ET was inferred from catchment water balances or from weighing lysimeters. Today, eddy covariance instrumentation mounted on flux towers and deployed via the global FluxNet provide continuous, local-scale measurements of ET and therefore water vapor exchange, subject to assumptions about surface heterogeneity and boundary layer stability.

Combining satellite observations with in situ FluxNet ET observations has yielded a continuous record of terrestrial ET and its components (soil evaporation and plant transpiration) around the globe. These data demonstrate the impact of changes in water

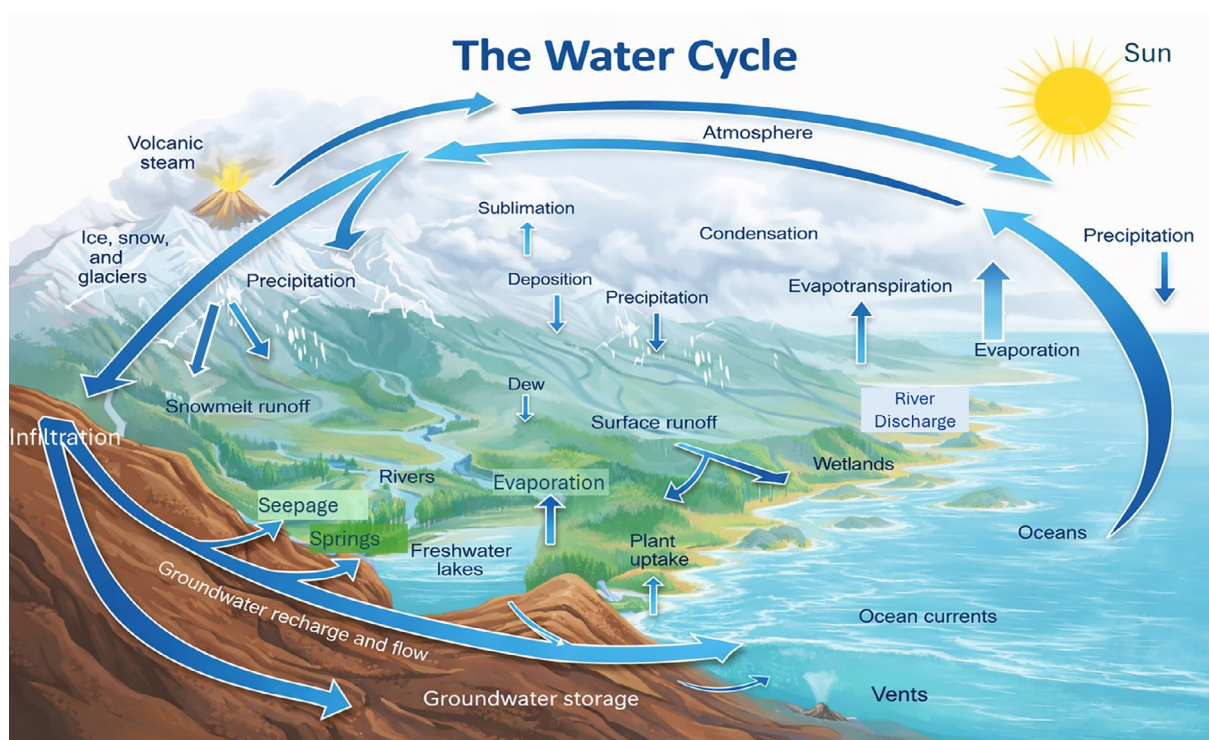


Fig. 12 Schematic of the global water cycle. Adapted from USGS <https://www.usgs.gov/media/images/natural-water-cycle-jpg>.

use—by humans and the biosphere—in response to multiple drivers including climate change. For example, Zhang et al. (2016) found that changes in vegetation cover over the period 1981–2012 had caused an increase in plant transpiration and decrease in soil evaporation. The inability of current generation Earth System Models to simulate these trends points to the importance of realistically representing vegetation in these models. Ukkola et al. (2016) used a combination of satellite-based leaf area measurements and catchment water balance-based estimates of ET to quantify the impact of increased biomass and green leaf area, and reduced leaf-level transpiration (as a result of elevated CO₂) on streamflow in Australia’s water catchments, and how these changes interact with altered precipitation under global warming to affect water resources.

The global hydrological cycle also involves the upper ocean, where evaporation, precipitation and river runoff continually modify freshwater content and thus salinity. Observed salinity changes make ocean salinity an effective indicator of large-scale hydrological change (Fig. 12). As an example, Durack and Wijffels (2010) showed large, spatially coherent, multidecadal linear trends in salinity to 2000-dbar depth in historic salinity profiles over the period 1950 to 2008. Salinity increases at the sea surface are found in evaporation-dominated regions and freshening in precipitation-dominated regions, with the spatial pattern of change strongly resembling that of the mean salinity field, consistent with an amplification of the global hydrological cycle. The authors revealed from the observational data base that qualitatively, the observed global multidecadal salinity changes are thus consonant with both broad-scale surface warming and the amplification of the global hydrological cycle. Helm et al. (2010) identified that the observed salinity changes imply a $3 \pm 2\%$ decrease in precipitation-minus evaporation (P-E) over the mid and low latitude oceans in both hemispheres, a $7 \pm 4\%$ increase in the Northern Hemisphere high latitudes, and a $16 \pm 6\%$ increase in the Southern Ocean since 1970. This pattern of increased precipitation at high latitudes and decreased precipitation in the subtropics is reflected in both land records and in the short satellite records. Lyu et al. (2025) reported more recently that horizontal advection mitigates local salinity buildup in evaporation-dominated subtropical regions, whereas vertical processes transfer excess freshwater into the deeper ocean in precipitation dominated areas. These mechanisms collectively regulate the freshwater flux imprint within the mixed layer, driving distinct salinity patterns across ocean basins and salinity classes.

The future role of climate observations

Observations will remain one of three key pillars of climate science into the future. However, their purpose is evolving from where it was a century ago—because future observations will be needed not only for scientific discovery but increasingly also for detecting, understanding and responding to emerging problems associated with anthropogenic climate change (e.g., unprecedented extremes). Observations will also remain important for tracking changes in the oceans, cryosphere, land and atmosphere (including the weather), and for monitoring and verifying greenhouse gas emissions—especially in the context of mitigation policies by nations for example nationally determined contributions (NDCs) and progress towards net zero emissions.

Current expectations are that over the next century the world will warm up by at least 2 °C and possibly 3 °C above pre-industrial values. As actual emission pathways remain uncertain, and as effective mitigation strategies cannot yet be ruled out to stabilize climate at a somewhat lower temperature than expected today, it is not clear in what world humankind will live in the future. What is clear, however, is that observations will play an important role in informing and testing all aspects of climate mitigation and adaptation strategies. This complements the critical role observations will continue to have in informing climate science, assessment and policy.

As climate is defined over long time scales, a climate observing system must be sustained to provide long and, ideally, continuous time series. The fundamental climate data records of “original” observations must be preserved, even if they are not often used directly without further processing. Only then can scientists and practitioners identify trends in important climate variables and distinguish changes due to human influences from those owing to natural climate variability. This is important for detecting and attributing anthropogenic changes; it is likewise important for identifying the efficacy of mitigation strategies that can take as many years to detect as it takes to identify climate change trends themselves.

The value of a long-term global climate observing system therefore cannot be overestimated, especially given that many parts of the Paris Agreement require signatories to commit to open access to both historical and ongoing meteorological observations (Dolman et al., 2016). As an example, the goal of limiting global warming below a specific target temperature requires observations to monitor progress towards this, and the impact of mitigation measures upon achieving the goal. Observations are also necessary to identify, attribute and predict extreme weather and slow onset events and are an essential part of emergency warning systems. Determining greenhouse gas fluxes from observations (based on measurements of atmospheric composition) can guide parties in their assessments of progress, and support reporting under the transparency framework.

High-quality climate observations with adequate space-time sampling will remain essential for improving and testing climate models. Yet, individual observations often provide only a partial view, and they can be influenced by internal variability, instrumental error, sampling variability and gaps etc. This highlights the important role of a coordinated observing system, tailored to address these problems by combining data from different components and by integrating across various variables and sensors. Observations will also be essential for providing initial conditions required for climate predictions on seasonal to decadal time scales. However, as climate models move to resolving increasingly smaller spatial scales, the climate observing system also needs to evolve to higher spatial resolution. And as climate models also need to include increasingly small-scale processes that have not previously been implemented, observations of new variables will be needed to advance and improve our understanding of smaller scale processes.

An example is the simulation of small-scale glacier processes in relatively coarse-resolution climate models. Done correctly, this requires resolving the very small-scale dynamical glacier processes, such as ice flow and its interaction with rocks underneath. It also requires closure of the glacier's mass balance by correctly representing the flow across the boundaries—e.g. precipitation inputs at the top of the glacier and losses through calving at the glacier terminus.

As described in Sections “Applications of climate observations” and “Key climate observations in the climate system,” data assimilation (DA) methods are typically used to optimize model parameters or initialize model runs using observed data. DA has significantly improved numerical weather prediction (NWP) in recent decades and is now an essential element of coupled climate modelling and providing initial conditions for seasonal to decadal climate predictions. In the future, advances in data assimilation will increasingly involve the adoption of machine learning (ML) and artificial intelligence (AI). In this sense, observations will play a larger role than in the past. Sometimes referred to collectively as model-data fusion, there are many approaches—ranging from sequential filter approaches used in NWP, to smoother approaches used especially in oceanography, e.g., to determining the ocean circulation. Comprehensive carbon budgets for a region, or the globe, are also provided by combining models and measurements (fluxes, atmospheric CO₂, and carbon pools at a wide range of space and time scales). Importantly, DA helps to improve models by estimating model parameters with reduced uncertainties and biases by reconciling model-data differences.

Machine Learning approaches are therefore currently receiving much attention, with the goal of improving models through parameter adjustments, and especially to make forecasting more efficient by training a system using either observations or model output and use the resulting emulator for efficient simulations. While still under development, some compelling examples exist already with respect to weather forecasting (Rabier et al., 2026). With respect to model improvements and to gaining insight into dynamics and new theories, the jury is still out as to what can be achieved. At the end what will be required most likely is a hybrid system using the best of each approach.

Data-driven AI/ML models are trained on observational and reanalysis data, and their skill degrades wherever those data are sparse, biased or unrepresentative. Without sufficient data for training, machine learning models have little to learn from and little against which to be tested. Such models can also be confidently wrong when extrapolated beyond the conditions on which they were trained. Assimilation methods also require a high-quality observational data base to be efficient, e.g., in estimating initial conditions. Satellite observations play a critical role in these developments, and so the continuity of satellite missions is critical and must be safeguarded against the funding pressures now threatening them. But satellite data on its own has limitations—e.g. in coverage and calibrations—and therefore well maintained, quality in situ observations are a mandatory counterpart. This holds even more so in the ocean, which is opaque to electromagnetic radiation, and therefore satellite sensors. The value of coordinated, long-term field campaigns should be recognized and adequately resourced.

During the 20th century and until the 1980s, the installation and operation of in situ measurements of many meteorological variables, in many regions of the world, were made possible by the efforts of the World Meteorological Organization and national weather services, although large regions, notably in the Global South, were still underrepresented. In the future, the long-standing gaps in Global South observations, especially in Africa, must be filled rather than allowed to widen further. Attention is needed specifically for observations that are both under-sampled and important, including high-mountain and upstream measurements that are critical for the water cycle and for downstream flood and drought risk.

Since the 1980s, instead of filling the gaps in data sparse regions, available data of many essential variables, such as precipitation, river discharge and atmospheric soundings of temperature, humidity, wind speed, wind direction and atmospheric pressure, have unfortunately declined. This evolution is perhaps most strikingly showcased by the global gridded precipitation product GPCC v7, which was based on 10,900 stations in 1901, reached a maximum of 49,470 stations in 1970 and then declined to 30,000 in 2005 and to only 10,000 in 2012 (Sun et al., 2018). Scarcity of precipitation gauges is particularly severe in Africa and the total number of stations across the continent decreased from 1247 in 1955 to 952 in 1985 (Nicholson, 2001). The decline of river discharge measurements, an essential variable for the study of the water cycle as well as local flood and drought risk assessment, has been particularly striking for Africa, Eastern Europe and around the Arctic (World Water Assessment Programme, 2003, p. 67). Meanwhile, upstream mountain measurements have declined at the expense of downstream measurements worldwide (Rodda, 2008). This decline in in situ observations has been attributed to poor maintenance and discontinuation of measurements, sometimes related to regime shifts and economic conflict (Zandler et al., 2019; Riggs et al., 2023; Doblas-Reyes et al., 2021; Su et al., 2026) but also due to a decline in the sharing of the data due to changing political, economic or administrative reasons, indicating that the data scarcity is at least in part apparent (Hannah et al., 2011; Doblas-Reyes et al., 2021).

The observational system is declining precisely at a time when society requests more adequate and trustworthy observations to face the challenges posed by increasing climatic disasters all over the world, and when scientists are developing novel tools to provide high-quality climatic information which requires high resolution observations (Thorne et al., 2018; Doblas-Reyes et al., 2021). Given this, the 2021 IPCC report (Doblas-Reyes et al., 2021) assessed that it is virtually certain that scarcity and reduced availability of adequate observations will increase the uncertainty of long-term temperature and precipitation estimates.

A sparse or thinning observing network can also actively obscure the signals that climate science seeks to detect. As networks thin, sampling variability inflates the background “noise” against which a forced trend must be distinguished, and the time of emergence of climate signals, the point at which a change becomes statistically distinguishable from internal variability, can be delayed or masked, as recent work on observational coverage and signal detectability highlights. In this sense, gaps in observation are not neutral: they degrade our ability to perceive change.

We also need to acknowledge that historically, the opposite effect has occurred. The past expansion of the global climate observing system with a growth in the number of observations in space and can lead to heterogenous sampling that in principle can

obscure the true climate variability. The importance of international coordination and cooperation, and the use of observation-model fusion to mitigate for incomplete observations cannot be overemphasized.

As ongoing events typically do not record themselves, historical instrumental records are shaped by where people lived, traveled and collected the data. This creates what scientists refer to as an observation or detection bias. Increases in recorded events over time in the 20th century sometimes reflect improved observational coverage, and it is exceptionally challenging to attribute such increases to increases in occurrence. With advancements in satellite technology, it is now possible to monitor these phenomena in remote or inaccessible regions.

Starting in 2025, new threats to the global observational system have arisen because of proposed drastic cuts to the budget of the US National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF) and the NASA Earth Science Division. The reduction of the budget and staff of NOAA will reduce their monitoring of the atmosphere and the ocean and will also force NOAA to discontinue maintenance of, and access to, historic datasets. At the same time, the cuts in NASA may affect the continuation of their global Earth Observations and, in the case of NSF, their research stations in Antarctica are threatened. Budget cuts in the US will therefore have severe effects on the global observational system ([Save the data, 2025](#)).

In the future, it will be essential to have high-quality observations and climate change information available freely to everybody around the world (FAIR: Findable, Accessible, Interoperable and Reusable; [Wilkinson et al., 2016](#)) to make sure countries can access and use these data to monitor and identify their main risks. Ensuring easy sharing and open access to data globally is paramount, particularly when it comes to forecasting and issuing early warnings. Organizations tasked with collecting or generating data sets, creating forecast products, refining information, and offering storage services play a pivotal role in this effort. The WMO Information system (WIS) could serve as a pilot for a powerful mechanism that enables this international data exchange.

With human-induced climate change leading to even more frequent and intense extreme weather conditions, the need for early warning systems is more crucial than ever. In the future, there will be a growing need for an integrated Multi-Hazard Early Warning System, which allows people to know that hazardous weather or climate events are on their way, and informs how governments, communities and individuals can respond to minimize impacts. WMO's Early Warnings for All initiative ([WMO-No. 1381, 2025](#)) aims to ensure universal protection from hazardous hydrometeorological, climatological and related environmental events through life-saving early warning systems by the end of 2027.

Most extreme weather events were experienced long before they were measured. Sailors often encountered cyclones and storms, but the measurement of these phenomena was only made possible in modern times thanks to the evolution of meteorological instruments and then satellites. Observational records are shaped by the capabilities of the observing system. Apparent long-term increases in certain extremes may sometimes reflect improved detection rather than genuine physical changes. Tropical cyclones in the open ocean are one of the classical examples of an observation or detection bias. Before the satellite era, countless storms likely went entirely undetected unless they crossed shipping lanes or made landfall. A tropical cyclone could spend its entire life over remote waters without ever being observed by a human. As a result, historical records substantially underestimate the true number of storms, particularly in sparsely traveled ocean basins over the 20th century.

Today, technologies such as weather satellites, Doppler radar, automated surface stations, ocean buoys, and lightning detection networks provide vastly better coverage and are often used to monitor cyclones. Like tropical cyclones, each type of extreme is characterized by distinct physical processes and therefore requires a combination of observational systems capable of measuring multiple variables, both directly and indirectly through derived products (e.g., translation of satellite radiation to physical state variables such as temperature).

Finally, bringing all observations together for the generation of relevant information in support of climate adaptation strategies through climate services is already an important role of climate observing systems, and this role will only grow in importance and relevance into the future. Such a step is sometimes referred to as “climate intelligence”—often regarded as the bridge between climate science and climate action. It is typically understood as the systematic generation, integration, analysis, and application of climate-related information to support decision-making under uncertainty. It goes beyond raw climate observations or model-generated projections to emphasize actionable information that is timely, credible, decision-relevant, and usable by specific actors. Access to the best climate intelligence is crucial to provide political and economic advantages and to ensure sustained habitability on Earth.

Summary

The focus of this chapter is on the role of observations in advancing understanding of the climate system. Using various examples, the chapter explained how unexplained observed signals generally reveal previously unknown climate processes and usually laying the foundation for an improved theoretical understanding of their function and their role in the climate system. An important step in this context is the continuous invention of new instruments or technologies that make new and types of observations possible. Observations are the primary source of information about how our climate has changed or is changing, from global to local scales.

Today, observations are used to describe the climate state and track changes in the Earth's climate system. They provide robust evidence of climate change impacts and are indispensable for developing climate predictions and projections—especially to improve our theoretical understanding of climate processes and to evaluate and improve models that are used to simulate future climates under different emission scenarios. But even in the future observations will remain one of three key pillars of climate

science. Nevertheless, their purpose is rapidly evolving from where it was a century ago—because future observations will be needed not only for scientific discovery but increasingly also for detecting, understanding and responding to emerging problems associated with anthropogenic climate change (e.g., unprecedented extremes).

Observations will remain important for tracking changes in the oceans, cryosphere, land and atmosphere (including the weather), and for monitoring and verifying greenhouse gas emissions—especially in the context of mitigation policies by nations for example nationally determined contributions (NDCs) and progress towards net zero emissions. High-quality climate observations with adequate space-time sampling will also remain essential for improving and testing climate models. Yet, individual observations often provide only a partial view, and they can be influenced by internal variability, instrumental error, sampling variability and gaps etc.

In the future, it will be essential to have high-quality observations and climate change information available freely to everybody around the world (FAIR: Findable, Accessible, Interoperable and Reusable; Wilkinson et al., 2016) to make sure that all countries around the world can access and use these data to monitor and identify their main risks. Ensuring easy sharing and open access to data globally is paramount, particularly when it comes to forecasting and issuing early warnings. There will be a growing need for an integrated Multi-Hazard Early Warning System, which allows people to know that hazardous weather or climate events are on their way, and informs how governments, communities and individuals can respond to minimize impacts.

Bringing all observations together for the generation of relevant information in support of climate adaptation strategies through climate services is an important role of climate observing systems, and this role will grow in importance and relevance into the future. Such a step goes beyond raw climate observations or model-generated projections to emphasize actionable information that is timely, credible, decision-relevant, and usable by specific actors. Access to the best climate intelligence is crucial to provide political and economic advantages and to ensure sustained habitability on Earth.

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