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Observation needs for climate information, prediction and application: capabilities of existing and future observing systems

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Abstract: The demand for long-term, sustained, reliable data and derived information on climate and its changes has never been greater than today. Long-term, well-calibrated, global observations of Essential Climate Variables (ECV) such as air temperature, precipitation, and sea-surface temperature are critical for defining the evolving state of the Earth's climate. Observing systems routinely collect much of the required data covering 49 ECVs, and significant progress has been made in coverage and technological capability over the two decades since the Second World Climate Conference. However, many key regions and climatic zones remain poorly observed, and gaps are widening in some cases. Supporting infrastructures for data stewardship and analysis are largely in place but require strengthening, while those for linking with socio-economic data and for providing user-oriented information services require more substantial development. The current capabilities are summarized, and further actions are identified to ensure that climate observation activities more fully meet the needs of science and society. The Global Climate Observing System (GCOS) was established in 1992 with the goal of providing comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical and biological observations of the atmosphere, oceans and land. GCOS is a "system of systems" that builds on the climate-relevant components of existing observing systems, and relies almost entirely upon national efforts to maintain and enhance those systems. Contributing systems include the World Meteorological Organization Global Observing System (GOS) for meteorology, its Global Atmosphere Watch (GAW) for atmospheric composition, the Global Ocean Observing System (GOOS), led by the United Nations Educational, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission (IOC), and the Global Terrestrial Observing System (GTOS), led by the Food and Agriculture Organization of the United Nations (FAO). GCOS itself is the climate observing system within the Global Earth Observation System of Systems (GEOSS) developed under the auspices of the Group on Earth Observations (GEO). The established in situ networks and space-based components must be sustained and operated with ongoing attention to data quality in accordance with the GCOS Climate Monitoring Principles; enhancements must be made for some types of observations; the exchange of observations and delivery of data and information to users must be ensured; reprocessing and reanalysis must be strengthened; and national and international coordination must be improved. The consequence of not meeting these requirements would be to seriously compromise the information on, and predictions of, climate variability and change. Detailed information on GCOS and the datasets that are produced as a result of GCOS observing activities can be found at the Global Observing Systems Information Center (GOSIC) at http://gosic.org.

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Observation Needs for Climate Information, Prediction and Application: Capabilities of Existing and Future Observing Systems

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Abstract

The demand for long-term, sustained, reliable data and derived information on climate and its changes has never been greater than today. Long-term, well-calibrated, global observations of Essential Climate Variables (ECV) such as air temperature, precipitation, and sea-surface temperature are critical for defining the evolving state of the Earth's climate. Observing systems routinely collect much of the required data covering 49 ECVs, and significant progress has been made in coverage and technological capability over the two decades since the Second World Climate Conference. However, many key regions and climatic zones remain poorly observed, and gaps are widening in some cases. Supporting infrastructures for data stewardship and analysis are largely in place but require strengthening, while those for linking with socio-economic data and for providing user-oriented information services require more substantial development. The current capabilities are summarized, and further actions are identified to ensure that climate observation activities more fully meet the needs of science and society. The Global Climate Observing System (GCOS) was established in 1992 with the goal of providing comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical and biological observations of the atmosphere, oceans and land. GCOS is a "system of systems" that builds on the climate-relevant components of existing observing systems, and relies almost entirely upon national efforts to maintain and enhance those systems. Contributing systems include the World Meteorological Organization Global Observing System (GOS) for meteorology, its Global Atmosphere Watch (GAW) for atmospheric composition, the Global Ocean Observing System (GOOS), led by the United Nations Educational, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission (IOC), and the Global Terrestrial Observing System (GTOS), led by the Food and Agriculture Organization of the United Nations (FAO). GCOS itself is the climate observing system within the Global Earth Observation System of Systems (GEOSS) developed under the auspices of the Group on Earth Observations (GEO). The established in situ networks and space-based components must be sustained and operated with ongoing attention to data quality in accordance with the GCOS Climate Monitoring Principles; enhancements must be made for some types of observations; the exchange of observations and delivery of data and information to users must be ensured; reprocessing and reanalysis must be strengthened; and national and international coordination must be improved. The consequence of not meeting these requirements would be to seriously compromise the information on, and predictions of, climate variability and change. Detailed information on GCOS and the datasets that are produced as a result of GCOS observing activities can be found at the Global Observing Systems Information Center (GOSIC) at http://gosic.org.

Keywords: GAW, GCOS, GEO, GEOSS, GOOS, GTOS, climate observations, essential climate variables, ECV.

1. Introduction

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International recognition of the need for sustained global observations has roots dating back to August 1853, when the First International Meteorological Conference held in Brussels stated that

> …all maritime nations should co-operate and make these meteorological observations in such a manner and with such means and implements, that the system might be uniform and the observations made on board the public ship be readily referred to and compared with the observations made on board all other public ships, in whatever part of the world [1].

Subsequent international activities developed under the auspices of the International Meteorological Organization, founded in 1871, and its successor, the World Meteorological Organization (WMO). A key stage was the establishment of the World Weather Watch (WWW) in 1963 by the Fourth World Meteorological Congress. The WWW has provided much of the required capability for seamless weather and climate observations and has been an outstanding example of global international cooperation.

At the Second World Climate Conference, in 1990, it was stated that "Present observational systems for monitoring the climate system are inadequate for operational and research purposes... There is an urgent need to create a Global Climate Observing System built upon the World Weather Watch Global Observing System..." [2]. Since 1992, the implementation of GCOS (see http://www.wmo.int/pages/prog/gcos/index.php), co-sponsored by WMO, IOC/UNESCO, the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU), has been guided by a steering committee, with support from scientific panels and a secretariat. Since the late 1990s, the status of observing systems contributing to GCOS in support of the United Nations Framework Convention on Climate Change (UNFCCC) has been a regular topic at sessions of the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) under agenda item 6, Research and systematic observation.

The Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, in short IP-04 [3], which was compiled based on the Second Adequacy Report [4], provides a baseline for the implementation of GCOS. The observing system components of GCOS are drawn from the meteorological and atmospheric composition components (GOS and GAW) of the WMO Integrated Global Observing System (WIGOS), from GOOS for the ocean and from GTOS for the land, with supporting observations from research initiatives coordinated by the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP). Co-sponsorship of scientific panels ensures essential collaboration with the WCRP.

The GCOS Essential Climate Variables (ECV) are a set of key variables that meet critical needs and are feasible to observe. (See Appendix 1.) Observations relating to these variables are based on ground-based, airborne and space-based platforms, and are made in situ and by remote sensing. The observations and supporting information encompass a broad range, including (a) routine weather observations, which are collected consistently over a long period of time; (b) observations collected as part of research investigations or one-time satellite missions to elucidate climate processes or demonstrate the technical feasibility of particular observations; (c) highly precise, sustained observations collected for the express purposes of detailed documentation of local changes and calibration of other observations, from a limited set of sites sampling different climatic regimes; (d) climate observations designed to document more generally the changing state of the oceans, atmosphere, sea ice and land systems; (e) proxy information based on documentary records and natural palaeoclimatic data, used to extend the instrumental climate record to remote regions and back in time; and (f) observations of climate forcing constituents, such as greenhouse gases and aerosols.

The data gathered for traditional meteorological purposes are not always of sufficient quality for climate science purposes because operational meteorology relies more on relative change over short periods of time, while climate science relies on continuity and stability of calibration over long periods of time. Recognition of this led to the establishment of the GCOS Climate Monitoring Principles (GCMP). (See Appendix 2.) Although the GCMP have been adopted by the UNFCCC, WMO and other international organizations, complete implementation of these principles is often not easy and is far from standard. This has implications for the organization and priorities of various national atmospheric, oceanic and terrestrial data collection institutions and organizations. Climate data extend far beyond meteorological data, and the requirements for climate data collection and data processing are distinctly greater than the requirements for weather purposes.

The late Professor Bert Bolin, who was the first Chairman of the Intergovernmental Panel on Climate Change (IPCC), stated in "The Report to the Seventh Session of the Subsidiary Body for Scientific and Technological Advice on behalf of the IPCC" held in October 1997 [5]:

> The current global observational network is declining. If this decline is not stopped we may, say, twenty years from now, be in a worse situation than today, when trying to determine to what extent and how climate is changing. We will have less capability of clarifying to what extent an ongoing climate change might be the result of human activities or be an expression of natural variability in the climate system. A continuous close observation of the climate system is an absolute requirement for dealing adequately with the climate issue.

Since then, some of the decline has been halted and new observing systems have been established, but a number of past concerns remain, and new requirements have emerged.

2. Status of climate observation

At its twenty-third session (December 2005) the SBSTA invited the GCOS Secretariat to "provide a comprehensive report at its thirtieth session (June 2009) on progress with the IP-04, that is, progress on actions recommended in the IP-04 to maintain, strengthen or otherwise facilitate global observations of the climate system, including adherence to the GCOS Climate Monitoring Principles". In response to this invitation, a report was submitted to the UNFCCC in April 2009, and has also been made available for open review by the community [6]. The report shows evidence that developed countries have improved many of their climate observation capabilities, although commitment to sustained long-term operation remains to be secured for several important observing systems. Developing countries, however, have made only limited progress in filling gaps in their in situ observing networks, with some evidence of decline in some regions. Support for capacity-building remains small in relation to needs. Overall, the GCOS has progressed significantly, but still falls short of meeting all the climate information needs of the UNFCCC and broader user communities at regional and national levels.

The following sections summarize the atmospheric, oceanic and terrestrial observing systems that contribute to GCOS and discuss additional aspects of the space-based component, gaps in coverage, reanalysis, national and international coordination, capacity-building and new priorities for climate information services and for indicators and standards.

3.1 Observations of the atmosphere

The atmosphere is the most volatile component of the climate system and the domain where humans live and breathe. Chaotic weather systems and changes in the state of water between snow, rain, cloud and vapour give the atmosphere a unique role in the climate system. Heat, moisture, aerosols and chemical species are moved around rapidly by winds, and trapping of species in the cold stratospheric polar vortex can lead to chemical depletion of the ozone layer. Cloud and water vapour feedbacks are major factors in determining the response of the climate system to forcing from rising levels of greenhouse gases and changes in aerosol distributions. Natural modes of variability, such as El Niño and the North Atlantic Oscillation, are associated with changes in atmospheric circulation and storm tracks, making it vital to determine and understand the processes involved, as their intermittent occurrence can obscure climate change detection, and climate change itself may be manifested partly in changes in the frequency of occurrence.

Measurements of temperature, water vapour, wind, pressure, precipitation amounts and atmospheric constituents are needed to characterize the atmosphere at the land and ocean surfaces. Since precipitation is episodic and tends to be highly localized, high-resolution observations are needed in both space and time. The radiosonde network of ground-tracked balloon-borne instruments has traditionally provided the measurements of temperature, water vapour and wind needed to track the movement and changes in weather systems and the evolving general circulation of the troposphere and stratosphere. Satellites are unique in providing global coverage for many ECVs. Their measurements of radiances are now an essential complement of the observations provided by radiosondes, but although the radiances form climate data records in their own right, they generally require direct interpretation in geophysical terms or assimilation into reanalysis models for widespread application. Satellite observations also are vital for information on clouds and the radiation budget. The data records from satellites stretch back only some four decades, however, so do not give a full historical perspective. Instrumental and proxy reconstructions of temperature, precipitation and other variables are essential to provide the long-term view.

Overall, there has been steady progress in maintaining and enhancing the global atmospheric observing systems for climate. This has been based on efforts by the national and nationally sponsored regional operators of ground- and space-based observing systems. The global trend of declining in situ meteorological network performance prevailing through the 1990s has been slowed or reversed in all regions except for Africa in the case of upper-air data. Yet in spite of overall progress, some regions of the world have seen no real improvement in their poor observational coverage. Much more attention must be dedicated to building capacity in developing and least developed countries, to ensure that these countries have the observational coverage and capacity to use climate data that they require both to adapt to a changing climate and to meet general needs.

One facet of progress has been the improved reception of observational data in international data centres. This is at least in part due to increased engagement by centres dedicated to monitoring in situ network performance. These centres act in liaison with network operators, mostly national meteorological services, and with the programmes responsible for network management. The work of the GCOS Surface Network (GSN) and GCOS Upper-Air Network (GUAN) monitoring, analysis and archive centres has been complemented by the recent establishment of nine Lead Centres for GCOS working to improve network performance in their respective regions worldwide. Nevertheless, there remain significant gaps both in network coverage and in the frequency and accuracy of reporting from existing stations. These gaps are of particular concern with respect to understanding and predicting regional climate.

Increasing emphasis has been placed on reference-quality networks for detecting climate trends, providing anchor points for existing networks, for calibrating satellite data and for validating data products. To this end, planning for the GCOS Reference Upper-Air Network (GRUAN) was initiated in 2006. (See http://www.gruan.org.) In addition to meteorological upper-air variables measured from high quality radiosondes, the GRUAN concept includes a number of other reference measurements, such as of ozone, and includes making use of Global Positioning System (GPS) delay and lidars. A Lead Centre for developing the GRUAN has started its work. Initially, implementation is being concentrated on a set of about 10–15 candidate sites worldwide.

The networks of the WMO Global Atmosphere Watch provide important sets of measurements of CO_2, methane, ozone and other constituents. The GAW monitoring programme provides data for scientific assessments and for early warnings of changes in the chemical composition that may have adverse environmental effects. Monitoring priorities have been given to greenhouse gases, ozone and ultraviolet radiation for both climate change and biological concerns, and to certain reactive gases and the chemistry of precipitation for their roles relating to air quality.

3.2 Observations of the oceans

Ocean waters cover 70 per cent of the Earth's surface. They have a major influence on the seasonal, interannual, and decadal variability of the climate system and on the response to long-term change in the radiative forcing of climate. The ocean has much greater capacity to store heat than the atmosphere and land and vastly more capacity to store carbon. It holds most of the water in the global hydrological cycle, providing through evaporation the vital water that falls over land as rain and snow. Prolonged drought is influenced by persistent patterns of ocean surface temperature and consequent influences on evaporation and atmospheric circulation patterns. Coupled atmosphere–ocean regimes such as El Niño change seasonal weather and storm patterns around the world. The transport of heat from the tropics toward the poles is a major factor in determining the surface temperature of many of our nations;

transport along and under ice shelves may determine how rapidly they separate from land and buttress glaciers, and in turn affect sea level, rise of which is one of the societally significant concerns of climate change. Moreover, due to its storage and transport of heat, the ocean is a possible origin of rapid climate change through alteration of its deep circulation. The ocean now holds about 50 times more carbon than the atmosphere, and its sediments store thousands of times more.

Upwelling zones in the ocean provide nutrients that support some of the most biologically productive regions of the planet, and there is growing evidence that physical and chemical changes strongly control ocean ecosystems and may affect them more in the decades ahead. Observing changes in the biogeochemical system and marine ecosystems is critical to projecting their future states and the oceans' ability to continue to provide food to vulnerable societies. Observations of ocean colour are made for this purpose. Tracking the heat and carbon stored and the exchanges of heat, moisture, momentum and greenhouse gas species with the atmosphere is vital for understanding and forecasting climate variability and change. Ocean heat and fresh water content and transports are observed in order to: (a) identify changes in the global water cycle; (b) identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change; (c) identify changes in energy stored in the ocean and (d) identify where anomalies originate in the ocean, how they move and are transformed and where they are lost as the ocean interacts with the atmosphere. Additionally, sea-surface pressure and air–sea exchanges of heat, momentum and freshwater are observed in order to identity interactions between ocean and atmosphere.

Sea level is a critical variable for low-lying regions. Globally, it is driven by volume expansion or contraction due to changes in subsurface ocean density, especially from heat, and by exchange of water between the oceans and other reservoirs, such as land-based ice and lakes and the atmosphere. Local sea-level changes can also be strongly influenced by regional and local circulation changes, by isostatic rebound from the last glaciation period and by land use changes.

Any forecast of weather conditions requires observations of sea-surface temperature, and an evolving ocean is required for conditions beyond a week or two. Under many storm conditions even short-term weather forecasts are improved by including evolving ocean temperatures. The longer the timescale of concern, the more important the ocean becomes. Hence, observations of the ocean state and sea ice are essential not only to assess the changing state of the climate, but also to initialize the models used for climate prediction.

Projecting decadal to centennial global climate change is closely linked to assumptions about feedback effects between the ocean and atmosphere related to sequestering of carbon in the ocean and additional input of carbon dioxide into the atmosphere. International ocean observing partners are implementing an ongoing ocean carbon inventory, with decadal surveys of the globe supplemented by autonomous carbon dioxide sampling instruments on ships and moored buoys that sample air–sea exchange seasonally. Understanding the global carbon cycle and accurate measurement of the regional sources and sinks of carbon are of critical importance to international policymaking as well as to forecasting long-term trends in climate.

Observations of sea ice extent, concentrations and thickness are essential because the amount of sea ice is important as an indicator of climate change and has a great impact on polar ecosystems; additionally it plays a critical role in the overall global albedo process. Melting or forming sea ice affects salinity and hence water density and ocean currents. Technology is developing rapidly to permit additional observations in coastal regions and of boundary currents, narrow straits and shallow regions (choke points where flow is limited), biogeochemical variables, primary productivity and other ecosystem variables.

Significant progress has been made in implementing the ocean observing system for climate (the climate component of the GOOS) as recommended in IP-04, but most elements of the system require substantial additional national efforts. As of the end of 2008, 60 per cent of the global ocean observing system has been completed in relation to its initial design in 1999. Notable milestones have been meeting the targets of 3 000 Argo profiling floats and 1 250 surface drifting buoys, which have led to systematic observation of the temperature and salinity of the ice-free upper ocean. Further, there has been a substantial increase in the number of tide gauges now reporting in near-real time with tsunami-detection capability. Several new reference site moorings have been deployed, and the tropical moored array continues to be developed in the Atlantic and Indian Oceans. Nevertheless, only from about 2004 onwards have the temperature and salinity of the ice-free upper ocean been systematically observed on a global basis.

A particular shortcoming is that there has been very limited progress in the establishment of national ocean or climate institutions with the responsibility for sustaining climate quality ocean observing systems. The primary agents of implementation for ocean observations and analyses thus remain national and regional research organizations, with their project timescale focus and emphasis on activities driven by principal investigators. Attaining full global coverage for all in situ networks and sustaining both in situ and satellite activities is essential to understand, attribute and predict climate variability and change.

3.3 Observations of the terrestrial domain

The terrestrial portion of the climate system provides human beings with important resources such as food, fibre, forest and water. At the same time, variability and change in fundamental properties of the hydrological and biogeochemical cycles affect climate and the livelihood of millions of people. The primary way in which the terrestrial domain features in climate variability and change is through changes in water storage, carbon storage and land cover, such as by deforestation. Precipitation, evapotranspiration, snow, glaciers, frozen ground, soil moisture, groundwater, lake levels and river discharge all constitute critical components of the hydrological cycle often with direct impact on water availability, droughts and floods.

Land has a wide variety of natural features, slopes, vegetation and soils that affect water budgets, carbon fluxes and the reflective properties of the surface. Land is often covered by vegetation; importantly, almost 40 per cent of the Earth's land surface is now under some form of management. Land use changes the characteristics of the land surface and thus can induce important local climate effects, especially through changes in albedo, roughness, soil moisture and evapotranspiration. When large areas are concerned (such as in tropical deforestation), regional and even global climate may be affected. Some land is covered by snow and ice on a seasonal basis and/or features glaciers, ice sheets, permafrost and frozen lakes. Snow and ice albedo play an important role in affecting climate. Further, as land-based ice – such as contained in glaciers – melts, river flow is affected and sea level rises.

Disturbances to land cover (vegetation change, fire, disease and pests) have the capacity to alter climate and affect the ground (for example, permafrost), but disturbances also respond to climate in a complex manner through changes in biogeochemical and physical properties. Precise quantification of the rate of change is important to determine whether feedback or amplification mechanisms are operating through terrestrial processes to affect the climate system.

Foundations for both in situ observation networks and space-based observing components for the terrestrial ECVs are in place, but need to be strengthened. Improvements in understanding of the terrestrial components of the climate system, the causes and response of this system to change and the consequences in terms of impact and adaptation are vital to society. Increasing significance is being placed on terrestrial data for estimating climate forcing and better understanding of climate change and variability, as well as for impact and mitigation assessment. Recognition of this has led to substantial progress in observation of a number of types of terrestrial variables, although advances are still limited or absent in others.

There has been good progress in both defining internationally accepted standards for the terrestrial ECVs, and in establishing several Global Terrestrial Networks (for hydrology, permafrost and glaciers) to observe them. The increasing commitment of space agencies to produce fundamental climate records from existing systems has led to improved availability of global datasets of, for example, burned area, fAPAR and land cover. The community now increasingly uses these datasets. Substantial deficiencies remain in quality control, and need to be addressed through comparison and validation.

There are still significant issues involved in making available in situ data that have more than just climate value or that are considered to contain economic or national value. This has, for instance, led to a declining number of reports of river discharge. However, some networks, such as the one for glaciers, have shown remarkable resilience and now operate very effectively. Similar progress has been made in the production of fire-related global datasets.

Observations that are crucial to our understanding of important terms of the hydrological and carbon cycles are necessary to be able to close the terrestrial budgets of these components and to detect change. New areas for observations include the use of microwave techniques to estimate (surface) soil moisture and also biomass, fAPAR and flux measurements to estimate the terrestrial component of carbon uptake. These measurements need to be moved from the largely research-driven funding base to a secure longer-term monitoring network that fully adheres to the GCMP.

3.4 The satellite-based component

Satellite-based observations of the climate system have evolved substantially since the early 1960s when the first operational weather satellite systems were launched. Satellites provide a unique global perspective of the Earth’s climate system, and now have proven capability to monitor many aspects of the Earth system including the evolution of El Niño events, weather phenomena, natural hazards, vegetation cycles, the ozone hole, solar fluctuations, top-of-atmosphere radiation, changes in snow cover, sea ice and ice sheets, ocean surface temperatures and biological activity, coastal zones and algal blooms, deforestation and forest fires, urban development, volcanic activity and distributions of water vapour, clouds and aerosols. Recognizing the importance and challenges of observation from space for climate monitoring, the GCMP includes ten satellite-specific principles.

The space agencies have been responsive to the needs expressed by GCOS, and they have advanced matching implementation plans. Parties that support space agencies coordinated their response through the Committee on Earth Observation Satellites (CEOS), the primary focal point for international coordination of space-related Earth observation activities. In its response to the GCOS Implementation Plan, CEOS reviewed the requirements for satellite observations of the climate system as outlined in IP-04 [7]. In addition, CEOS evaluated the capability of the current observing system to meet these requirements, and developed an action plan to address inadequacies [8]. The CEOS report identified 59 actions covering key climate-related observations of the atmosphere, ocean and land. These actions fall into six categories: (a) ensuring continuity of climate-relevant satellite measurements; (b) taking a systematic approach to generating Fundamental Climate Data Records; (c) preserving climate data records; (d) ensuring access to climate data products; (e) coordinating international communities and interaction with users; and (f) addressing future measurement needs. In 2006, the space agencies reported to the UNFCCC via CEOS, and that report included a list of actions [8]; a follow-up report detailing the agencies’ progress in meeting their commitments to those actions was submitted in 2008 [9].

The Committee on Earth Observation Satellites (CEOS) also functions as the space component of the GEOSS. Its 2007 Implementation Plan for Space-Based Observations for the GEOSS [10] identifies the targets and actions required and the efforts of space agencies to implement them. As part of this effort, CEOS developed the concept of virtual, space-based constellations. A virtual constellation is a set of satellite missions operating together in a coordinated manner, in effect a virtual system that overlaps in coverage in order to meet a combined and common set of earth observation requirements. The individual satellites can belong to a single owner or to multiple owners. The concept builds upon, or serves to refocus, already existing projects and activities. The six planned constellations are (a) Land Surface Imaging; (b) Ocean Surface Topography; (c) Atmospheric Composition; (d) Precipitation; (e) Ocean Surface Vector Winds; and (f) Ocean Colour Radiometry. All contribute to meeting climate requirements. The cross-cutting constellations are equally important in providing resources and attention to the issue of continuity of space-based observations of key ocean, atmosphere and land variables.

A key part of the overall strategy in creating climate data records (CDRs) is a vibrant programme of reprocessing of past data [3]. The Fourth Assessment Report of the IPCC demonstrates shortcomings in many climate records, especially those from space [11]. Related research has demonstrated the potential for improvements as progress is made on algorithm development and solutions are found to problems such as discontinuities in the record across different instruments and satellites, effects of orbital drift and other issues related to the creation of true CDRs. In response, coordination among the space agencies has been established to agree on calibration procedures, algorithms and reprocessing programmes. Two major initiatives are the Global Space-based Inter-Calibration System (GSICS) and the Sustained Coordinated Processing of Environmental Satellite Data for Climate Monitoring project (SCOPE-CM) carried out under the WMO Space Programme and supported in particular by the Coordination Group for Meteorological

Satellites (CGMS). The need for reprocessing and generation of ECV records has also prompted individual responses such as the European Space Agency Climate Change Initiative.

3.5 Identification and response to information gaps

Gaps in spatial or temporal coverage of climate observations cause difficulty in interpreting past climate records and contribute to the inaccuracy of forecasts. For in situ networks this often demands capacity-building activities in developing and emerging countries (discussed further below) to ensure adequate geographical coverage and adequate maintenance and supply of expendables. Improvements in coverage are also needed in the remote and challenging terrain of high latitudes, where potential changes to the cryosphere introduce significant uncertainty into projections of future climate. Gap analysis is a key feature of the planning for future satellite missions. Although plans exist for sustained future observation related to many of the ECVs, concerns remain over future provision in a number of cases, for example related to precipitation, the radiation budget, the distributions of the main greenhouse gases and the general continuity of provision of data of sufficient vertical resolution, particularly in the upper troposphere and lower stratosphere.

Gaps in the climate record will nevertheless arise because even if the efforts to put instruments in place are realized, there will be instrument failures and other contingencies. For some measurements, such as of solar irradiance measured from space, it may be impossible to bridge a gap to retrieve a complete climate record, and in such cases resilience should be built into the observing system to the extent reasonably possible. For other measurements, it may be possible to bridge gaps by using either sets of neighbouring measurements or reanalyses.

Reference measurements such as to be provided by the GRUAN may be used to adjust data records to account for known changes of instrument type. Such measurements must be of sufficient quality, accuracy and sampling density that they can act as a transfer standard. Reference-type observing networks in all domains, exploiting existing or partially completed networks with reference sites taking multiple measurements, will minimize costs and increase efficiency. Implementation of these reference networks must take a high priority to ensure the value of past and future observations and to increase resilience of the global climate observing system against likely gaps. This is a special and largely unmet challenge for the terrestrial domain in particular. Placing a high priority on establishing the GRUAN helps build in some insurance for likely gaps as well and therefore is an exceedingly important priority.

3.6 Reanalysis

Integrated datasets based on combining observations from the diverse component observing systems of the GCOS are required to meet the needs for comprehensive documentation of global change and for model development and verification. The observations must be analysed and reanalysed in a multivariate physical framework in order to provide a complete record of globally or regionally gridded variables.

Atmospheric analyses provide a synthesis of the available observations in the context of a physical model. Global analyses have been routinely made since the late 1970s for purposes of numerical weather prediction. These atmospheric analyses were instrumental in shaping our understanding of climate variations on relatively short timescales, but the frequent changes in procedures used introduced many spurious variations in the perceived climate, thus leading to calls to reanalyse the past observations using a constant state-of-the-art data assimilation system.

The first generation of atmospheric reanalyses carried out in Europe and the United States of America in the mid- to late-1990s have proven to be among the most valuable and widely used datasets in the history of climate science, as indicated both by the number of scholarly publications that rely upon them and by their widespread use in climate services. They nevertheless had substantial problems that limited their use for global climate change and variability studies. Besides being based on now outdated assimilation systems and models that exhibited significant biases, the effects of changes in the observing system produced spurious changes in the perceived climate. As a result, trends and low frequencies are unreliable. Two second generation global reanalyses, Europe's ERA-40 and Japan's JRA-25, have addressed some of the shortcomings. Further advances have been demonstrated already in the subsequent ERA-Interim reanalysis, and more are expected from the new reanalysis efforts that are underway or planned in several institutions worldwide. Problems tied to observing system changes and model deficiencies are nevertheless likely to remain, and will require further effort devoted to reducing biases in the assimilating models and correcting for biases in the various types of assimilated observations.

While the origins of reanalysis have been in weather and atmospheric climate, there have been significant advances in reanalysis (or synthesis) of ocean data. Other promising developments are occurring in sea ice, Arctic and land surface reanalysis. There has also been an initial development of coupled atmosphere–ocean data assimilation, which transforms the forcing problem and lays the foundation for future coupled reanalysis studies that may lead to more consistent representations of the energy and water cycles. Hence, with the ongoing development of analysis and reanalysis in the ocean, land and sea-ice domains, there is huge potential for further progress and improved knowledge of the climate record.

Reanalysis has proved to be as valuable for monitoring climate, climate research and applications as was believed when it was proposed twenty years ago. As the scope of global reanalysis grows, however, the effort needed to collect the comprehensive input datasets, to address the problems of bias, to improve more generally the data assimilation and to provide the user with comprehensive information on the quality and applicability of products is so large that international cooperation is essential. Collaboration between centres has been active, but the lack of sustained long-term funding (as called for in IP-04) has inhibited coordination. Such funding is needed to maintain technical competence between production cycles and to facilitate a staggered timing of production so that each centre may benefit from earlier experience and contribute to progressive improvement in both observational databases and data assimilation systems.

3.7 International centres for data archiving, monitoring, calibration and access

To determine the state and variability of the climate system, either directly from observations or through reanalysis, measurements need to be globally standardized, preserved and made accessible. The necessary activities of data collection, monitoring, storage and redistribution are undertaken by centres around the world on behalf of the international community. International data centres have been established for many of the ECVs. The monitoring centres and regionally focused lead centres assess and work to improve the flow and accuracy of data. International calibration centres, with their reference instruments and regular comparison activities, also make a vital contribution to the quality of the data from global observation programmes. Continued attention to the resourcing and operation of the network of international data centres is essential for ensuring that the data from the various observing platforms are properly archived and made accessible. It is critical that data be received in a timely and consistent manner along with the necessary metadata documentation in order to make the data understandable and useful to users, and that the data centres have the resources to manage the increasing volume and diversity of data that builds up with the passage of time. Funding support for this critical component of the climate observing system is sometimes less than adequate, but again, it is vital to the overall value of climate observations.

In order to make climate data widely accessible, the Global Observing Systems Information Center (GOSIC) was initiated in 1997 [12]. The GOSIC is essentially an online portal (http://gosic.org) that does not itself hold data but rather provides a common access point to global and regional datasets and analyses for use in various aspects of climate research. It provides a central source to detail the various global observing systems by providing an integrated overview of the data, information and services that comprise each of the observing systems. The GOSIC portal provides data and metadata search capabilities optimized to facilitate access to a worldwide set of observations and derived products. The GOSIC Data Registry is now available as a data access service on the GEO portal (http://www.geoportal.org/) in order to aid access to data related to the nine GEO Societal Benefit Areas: agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water and weather. The GEO portal is intended to provide a comprehensive data discovery, access, retrieval and delivery system based on existing national, regional and international systems. The GOSIC works with the GEO portal to aid in providing comprehensive, coordinated, Earth observations from thousands of services, instruments, collections, libraries and catalogues worldwide, transforming the data collected into vital information for society [13].

3.8 National and international coordination

The effective functioning of the Global Climate Observing System requires good coordination mechanisms at global, regional and national levels. At the global level, the GCOS Secretariat was established in 1992 in part to facilitate international coordination and to promote the improvement of the observing networks that contribute to GCOS. It works hard, in collaboration with the Secretariats of the component observing systems, to fulfil its mandate despite staff and resource limitations and increasing responsibilities over the years. The GCOS Secretariat and Steering Committee have long called for the appointment of national GCOS coordinators and committees. These can act as national advocates for sustainable climate observing systems and for climate data generally across domains and disciplines; provide a national focus to coordinate reporting to the UNFCCC and communication with the GCOS Secretariat; promote adherence to the GCMP and other standards for climate observations; help national colleagues understand the priorities of potential donor agencies and identify sources of funding for both national and international GCOS activities; and facilitate the identification and provision of climate data to international data centres. Despite the critical importance of this range of activities, only 16 countries to date have designated such national coordinators or committees. Coordination at the regional level is equally important in that it would facilitate harmonized action to address common issues, but few regions (with the notable exception of the Pacific Islands) have designated an effective regional coordinator.

3.9 Capacity-building

Technology transfer and local training are important means of enhancing the quality of climate-related observations, especially in developing and emerging countries. The GCOS Cooperation Mechanism (GCM) was initiated in 2002 as a voluntary multi-governmental funding mechanism. The purpose of the GCM is to identify and make the most effective use of resources available for improving global observing systems for climate in developing countries, particularly in order "to enable them to collect, exchange, and utilize data on a continuing basis in pursuance of the UNFCCC" in Decision 5/CP.5 [14]. The GCM comprises a governing board and fund (administered by the GCOS Secretariat), and has been successful in addressing a number of gaps in observing infrastructure. For example, there were 20 silent radiosonde stations in the GUAN that were not operating for various resource-related reasons in 2001, but by 2008 that number had been reduced to close to zero. Some important improvements to GSN stations have also been made.

There is still much work to be done, however, and the GCM needs to work to increase the pool of donors and associated resources to continue to address gaps in global climate observing in developing nations. As part of the GCM, a number of developed countries have provided bilateral and multilateral assistance, including assistance for both infrastructure needs and training, to help build the capacities of developing countries to participate in systematic observation. In addition, with funds from the Global Environment Facility/United Nations Development Programme and individual donor counties, the GCOS Secretariat implemented a Regional Workshop Programme between 2000 and 2006 to help regions identify gaps and deficiencies in their climate observing networks and consequent needs for capacity-building. As part of the Programme, Regional Action Plans containing projects addressing the highest priority needs were developed by regional experts for each of ten regions. In the framework of the WMO World Climate Data and Monitoring Programme (WCDMP), a number of projects have been carried out in the developing world devoted to the digitization of historical climate data records, efficient data management and data analysis for regional and local purposes (for example, the Climate Outlook Forums).

The continent of Africa has perhaps the greatest capacity-building needs of any region in the world and, as is the case globally, the available bilateral funds are simply not enough to address all needs. A new programme, Climate for Development in Africa (or

ClimDev Africa), was launched in 2009 with support by a number of donors. The total budget for the 4-year programme is US$134 million, although only a fraction of that amount has been raised to date. The principal partners are the African Union Commission, the United Nations Economic Commission for Africa, the African Development Bank, as well as GCOS, which had an important role in facilitating the launch of the programme. Closely linked to the ClimDev Africa initiative is the establishment of the African Climate Policy Centre (ACPC) at the United Nations Economic Commission for Africa with the overall goal of supporting ClimDev Africa. The ACPC will develop linkages and partnerships with other institutions working on climate issues in Africa. The initial beneficiaries of ClimDev Africa will be policymakers from a diverse group of organizations across Africa including (a) regional economic communities, (b) river basin organizations, (c) national governments (including National Meteorological and Hydrological Services), (d) parliamentarians, (e) climate negotiators and (f) other regional climate, weather and water organizations.

3.10 Climate service provision

Weather and climate variations have economic, social and environmental impacts at the national and regional levels and affect the course of global markets. Managing weather- and climate-sensitive enterprises is enhanced through access to critical climate information from the past and present and through anticipation of future climate. A good deal of relevant information on past climate is now available, particularly at the global scale, and current conditions are monitored though routine observation and analysis. Global-scale seasonal-to-interannual climate forecasts are produced at several centres. However, improved interpretation of present conditions and increases in the accuracy and range of forecasts are needed, and the knowledge and tools available need to be adapted, improved and made available to enable the best choice of options for climate change adaptation, disaster risk reduction, development and sustainability. Integration of climate information into decision-making in all sectors of society would foster more effective climate risk management strategies in support of the achievement of economic and development goals, including the United Nations Millennium Development Goals. All of this requires a more thorough assessment of what exists and implementation of what is needed, including the required observations, reprocessing, reanalysis, forecasting and better integration and service delivery [15].

Successful adaptation will depend on the validity of predictions and on sound political and economic policies implemented at national and international levels. Decision-makers from the policy level to the individual level need objective and reliable sources of information about the variations and changes in the climate system, including their causal mechanisms and potential environmental and socio-economic consequences. The Hyogo Framework for Action 2005–2015[1] [16] is a global blueprint for disaster risk reduction efforts, and calls for increased engagement of all stakeholders, particularly communities, for building awareness and taking preventive and preparedness measures for risk management. Accordingly, climate scientists must address the concerns of various user groups and develop understanding and products to address their needs. The ability of science to provide robust estimates of climate-related risks to society is showing increasing potential at global levels, but at the regional and local levels it is in many cases constrained by limitations in observations, understanding of basic processes, modelling capability and computer power.

3.11 Indicators and standards related to socio-economics and decision-making

Just as economic policies are usually set after the examination of key economic data, there is a need for global climate change policy and management to be based on similar broadly accepted indicators. In response to this need, objectives for a system of environmental and natural resource indicators, including a pilot system related to climate change and water availability, are being developed as part of a United States National Environmental Status and Trends (NEST) Indicators Project led by the United States Council on Environmental Quality[2]. The NEST indicators are envisaged to be a set of high quality, science-based statistical measures of selected conditions of our environment and natural resources. They address topics that are sufficiently important and cross-cutting to warrant the acquisition of data using measurement methods and statistical designs that are consistent across the entire country and repeated regularly over time. An approach for identifying a suite of such linked environmental and socio-economic indicators has been outlined by the NEST team. A related issue is the development of robust observing capabilities to support a system that addresses a reportable and verifiable measurement of greenhouse gas emissions, inventories and fluxes that are critical to any climate mitigation effort. To this end, WMO has begun working with the Bureau International des Poids et Mesures (BIPM) on the issue. In 2008 the European Environment Agency (EEA) and the Joint Research Centre of the European Union (JRC) published a report [17] that summarizes the relevance, past trends and future projections for about 40 indicators. The indicators cover atmosphere and climate, the cryosphere, marine systems, terrestrial systems and biodiversity, agriculture and forestry, soil, water quantity (including floods and droughts), water quality and fresh water ecology and human health. The report also addresses adaptation and the economics of climate-change impacts and adaptation strategies and policies, and data availability and uncertainty.

4. Conclusions and recommendations

4.1 Sustain and develop observing systems to meet climate needs

Long-term and continuous observation of the GCOS ECVs through the operation of well calibrated component observing systems is critical to the capability of the Global Climate Observing System to provide data and derived information on climate and how it is changing. Observations are also essential to determine the initial state for climate predictions. It is therefore vital to sustain what is already in place and effective, and to address identified shortcomings. The established in situ networks and space-based components must be maintained and operated with ongoing attention to data quality and with application of the GCOS Climate Monitoring Principles to manage the inevitable changes that will occur. Efforts have to continue to be devoted to reducing gaps in the in situ network coverage and in the provision of the required range of space-based measurements. This includes the need to devote additional resources towards the rescue and digitization of historical climate data records currently in paper or other non-digital media form; such data are critical for improving climate prediction models. Key networks developed under research funding that have proved to be beneficial in meeting long-term needs must be put on a firm operational footing. Initiatives for establishing long-

[1] See http://unisdr.org/wcdr/intergover/official-doc/L-docs/Hyogo-framework-for-action-english.pdf
[2] See http://ceq.hss.doe.gov/nepa/regs/CEQ_OSTP_OMB_NEST_IndicatorsLetter.pdf

term reference measurements at selected sites must be developed further. It is essential that the GRUAN should be established with high priority to build in modest insurance for likely gaps.

Observations have to be sufficient not only for monitoring, understanding and predicting climate change, but also for assessing social and economic vulnerabilities to change. They must also be sufficient for supporting the actions needed to limit and adapt to change, including the making and implementation of policy. Increasing attention must accordingly be paid to observing the key variables for these purposes, such as those related to water and carbon cycles, and to such matters as the density of regional networks, urban climate observation and regulatory measurement standards. Not meeting the requirements discussed here would seriously compromise the quality of information and predictions of climate variability and change.

4.2 Ensure availability of information to all communities

The infrastructure for global data exchange between providers and for data supply to international archive centres is largely in place for atmospheric and oceanic climate variables, despite some deficiencies. More effort has to be expended in the terrestrial domain where there is a less complete designation of international data centres. However, the exchange of vital climate-relevant data still faces many obstacles in all domains. It is important that action be taken to address the issues, which are related to, among other things, (a) the reluctance of some countries to exchange climate data, for a number of reasons, (b) the need to improve the awareness by national operators of the urgent need for prompt global climate data exchange, (c) technical problems in preparation, transmission and receipt of climate data messages, (d) resource limitations in developing countries and, to some extent, in archive and monitoring centres and (e) consistent data and metadata standardization and data stewardship [18].

In addition, users may experience difficulties in finding or getting access to the specific data they need and to the supporting information (metadata on instrument changes, quality control information from use of the data in reanalysis, and so on) that may enable better use of the data. Systems for data discovery and access such as GOSIC and the GEO portal, and the emerging WMO Information System already provide or will soon provide important capabilities in this regard, but continued system development is likely to be needed to meet the full requirements both of end-users and of intermediate providers of user-oriented climate information services.

4.3 Strengthen and sustain reprocessing and reanalysis

Much more work is needed to take advantage of the many observations that have already been made, to improve knowledge of what has happened and why and to determine how well past events can be reproduced by the models used to make climate predictions.

Cooperative initiatives established recently for the reprocessing of satellite data records by space agencies should be sustained and expanded to include a wider range of ECVs. The broader scientific community should be engaged in assessing the derived data products and refining the algorithms for the generation of these products. Parallel efforts on the collection, management and homogenization of in situ data records must be continued.

Reanalysis of comprehensive, multivariate sets of observations is becoming increasingly valuable for climate monitoring, research and applications. It should be put on a more operational basis, with core centres operating sustained cyclical production schedules and providing enhanced delivery of processed data products, user support and feedback on observational data quality, complemented by a more distributed set of research activities aimed at improving the scope and quality of products and services.

4.4 Improve national and international coordination and capacity

Climate observation cannot be fully effective without further development of coordination mechanisms at national, regional and global levels, building on what has been set up during the development of GCOS as a composite of observing systems. Appointment of national and regional GCOS coordinators or committees should be expanded, and the GCOS Secretariat strengthened. The implementation of GCOS as a comprehensive global observing programme in support of the full range of climate services has itself to be carried out in coordination with the principal research programmes, WCRP and IGBP, with the operators of climate forecasting systems and with the providers of climate information services derived from observations, analysis and forecasting. This is envisaged to take place within an overall global framework for the provision of climate services.

Moreover, capacity-building must be undertaken to ensure that all countries are able to make and communicate the observations that they need for adaptation to local and regional change and that are needed more widely for improving understanding and predictive capability. Capacity-building is also needed to ensure that all countries can access and benefit from the observations, data products and services made available by global and regional providers.

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Appendix 1. Essential climate variables[3]

1. Atmosphere	
1.1 Surface	*1.2 Upper Atmosphere*
Air Pressure	Cloud properties
Air temperature	Earth radiation budget (including solar irradiance)
Precipitation	Upper air temperature
Surface Radiation Budget	Water vapour
Water vapour	Wind speed and direction
Wind speed and direction	
1.3 Atmospheric Composition	
Carbon Dioxide, Methane and other long-lived greenhouse gases	
Ozone, Aerosol, supported by their precursors (in IP-10)	
2. Oceans	
2.1 Ocean Surface	*2.2 Ocean Subsurface*
Sea-surface temperature	Temperature
Sea-surface salinity	Salinity
Sea level	Current
Sea state	Nutrients
Sea ice	Carbon dioxide partial pressure
Surface current	Ocean acidity/pH (in IP-10)
Ocean colour (for biological activity)	Oxygen (in IP-10)
Carbon dioxide partial pressure	Ocean tracers
Ocean acidity/pH (in IP-10)	Phytoplankton
3. Terrestrial	
Above-ground Biomass	
Albedo	
Fire disturbance	
Fraction of absorbed photosynthetically active radiation (FAPAR)	
Glaciers and ice caps	
Ground water	
Ice sheets (in IP-10)	
Lakes	
Land cover (including vegetation type)	
Leaf Area Index (LAI)	

[3] Based on the list in the Second Adequacy Report, with additions from an update to IP-04 that is currently in preparation and set for release in September 2010, and referred to as IP-10.

Permafrost and seasonally frozen ground
River discharge
Soil Carbon (in IP-10)
Soil Moisture (in IP-10)
Snow cover
Water use

Appendix 2. GCOS climate monitoring principles[4]

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

(a) The impact of new systems or changes to existing systems should be assessed prior to implementation;

(b) A suitable period of overlap for new and old observing systems is required;

(c) The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (metadata) should be documented and treated with the same care as the data themselves;

(d) The quality and homogeneity of data should be regularly assessed as a part of routine operations;

(e) Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities;

(f) Operation of historically uninterrupted stations and observing systems should be maintained;

(g) High priority for additional observations should be focused on data-poor regions, poorly observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution;

(h) Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation;

(i) The conversion of research observing systems to long-term operations in a carefully planned manner should be promoted;

(j) Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

Furthermore, operators of satellite systems for monitoring climate need to:

(a) Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system;

(b) Take steps to sample the Earth system in such a way that climate-relevant (diurnal, seasonal, and long-term interannual) changes can be resolved. Thus satellite systems for climate monitoring should adhere to the following specific principles:

 (1) Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained;

 (2) A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time series observations;

 (3) Continuity of satellite measurements (elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured;

 (4) Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured;

 (5) On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored;

 (6) Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate;

 (7) Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained;

 (8) Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on decommissioned satellites;

 (9) Complementary in situ baseline observations for satellite measurements should be maintained through appropriate activities and cooperation;

[4] From http://www.wmo.int/pages/prog/gcos/index.php?name=monitoringprinciples

(10) Random errors and time-dependent biases in satellite observations and derived products should be identified.