GLOBAL
CLIMATE
OBSERVING
SYSTEM

WMO of UNESCO UNEP ICSU

WORLD METEOROLOGICAL
ORGANIZATION

INTERGOVERNMENTAL
OCEANOGRAPHIC COMMISSION

THE SECOND REPORT ON THE ADEQUACY OF THE GLOBAL OBSERVING SYSTEMS FOR CLIMATE IN SUPPORT OF THE UNFCCC

April 2003

GCOS – 82

(WMO/TD No. 1143)

UNITED NATIONS
ENVIRONMENT PROGRAMME

INTERNATIONAL COUNCIL FOR
SCIENCE

NOTE

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The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC

Executive Summary

A first report[1] on the adequacy of the global observing systems for climate in providing the systematic climate observations required by the United Nations Framework Convention on Climate Change (UNFCCC) was submitted to the Conference of the Parties (COP) of the UNFCCC at their fourth meeting in 1998. Since then, the COP, individual Parties of the UNFCCC and various intergovernmental and international agencies have undertaken a range of actions to address the reported inadequacies. In 2001, the Subsidiary Body for Scientific and Technological Advice (SBSTA) to the COP endorsed the preparation of a second report on the adequacy of the global observing systems for climate to meet their needs and also those of the Intergovernmental Panel on Climate Change (IPCC). The goals of this Second Adequacy Report (the Report) were to determine what progress has been made in implementing climate observing networks and systems since the first report; determine the degree to which these networks meet with scientific requirements and conform with associated observing principles; and assess how well these current systems, together with new and emerging methods of observation, will meet the needs of the UNFCCC. The preparation of the Report, organized by the Global Climate Observing System (GCOS) Secretariat working in partnership with the other global observing systems[2] and on behalf of its Sponsors[3], has involved a wide range of experts from the scientific and observational communities as well as an open review process.

The authors of the Report, in consultation with the IPCC, established the scientific requirements for systematic climate observations underlying the needs of the Parties to the UNFCCC and the IPCC. Climate observations are required to:

- Characterize the state of the global climate system and its variability;
- Monitor the forcing of the climate system, including both natural and anthropogenic contributions;
- Support the attribution of the causes of climate change;
- Support the prediction of global climate change;
- Project global climate change information down to regional and national scales; and
- Characterize extreme events important in impact assessment and adaptation, and to assess risk and vulnerability.

Observations from the current climate observing systems have provided the information for many of the conclusions drawn by the IPCC on climate change and its potential impacts. They have also provided the Parties with information for understanding the implications of climate and climate variability on their societies and ecosystems. Notwithstanding the use being made of current information and the improvements made in the past few years, the IPCC has recently reported[4] that current climate observational networks are declining in many parts of the world and that additional and sustained climate observations are required to improve the ability to detect, attribute and understand climate change and to project future climate changes.

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[1] Report on the Adequacy of the Global Climate Observing Systems. GCOS-48, October 1998. Submitted to COP-4, November 2-13, 1998, Buenos Aires, Argentina. Available at http://www.wmo.ch/web/gcos/Publications/gcos-48.pdf

[2] The Global Ocean Observing System (GOOS), the Global Terrestrial Observing System (GTOS), the World Weather Watch (WWW) with its Global Observing System (GOS) and the Global Atmosphere Watch (GAW).

[3] The organizations that sponsor GCOS are: the World Meteorological Organization (WMO), United Nations Educational, Scientific and Cultural Organization (UNESCO) and its Intergovernmental Oceanographic Commission (IOC), the United Nations Environment Programme (UNEP), and the International Council for Science (ICSU).

[4] Climate Change 2001: The Scientific Basis (IPCC Third Assessment Report).

Based on an integrated analysis of the atmospheric, oceanic and terrestrial domains according to these scientific requirements, the Second Adequacy Report concludes that there has been progress and improvement in the implementation of global climate observing systems since the first report, especially in the use of satellite information and in the provision of some ocean observations. At the same time, the Report notes that the global terrestrial networks remain to be fully implemented; the ocean networks lack global coverage and commitment to sustained operation; and the atmospheric networks are not operating with the required global coverage and quality. The Report concludes, in agreement with the IPCC, that there remain serious deficiencies in the ability of the current global observing systems for climate to meet the observational needs of the UNFCCC. The Report in its various findings documents the needs and opportunities for improvement to the global observing systems for climate. Without urgent action to address these findings, the Parties will lack the information necessary to effectively plan for and manage their response to climate change. It requires immediate action by the Parties, the UNFCCC and intergovernmental and international agencies, and will require the allocation of additional resources.

The focus of the Report is on climate variables that are both currently feasible for global implementation and have high impact with respect to the UNFCCC and IPCC requirements. Table 1 lists these Essential Climate Variables.

Conclusion:

1) **Achieving global coverage and climate-quality observations for the variables in Table 1 is essential to ensure that the needs of the UNFCCC and the IPCC for systematic climate information are addressed.**

Table 1. Essential Climate Variables that are both currently feasible for global implementation and have a high impact on UNFCCC requirements.

Domain	Essential Climate Variables	
Atmospheric (over land, sea and ice)	**Surface:**	Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour.
	Upper-air:	Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties.
	Composition:	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases[5], Aerosol properties.
Oceanic	**Surface:**	Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.
	Sub-surface:	Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.
Terrestrial	River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Biomass, Fire disturbance.	

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[5] Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

The Report has identified a number of critical areas where immediate improvements to global observing systems for climate are required. These include providing effective access to climate data and improving its quality; achieving global coverage for *in situ* networks, particularly in the oceans and for essential climate variables in the terrestrial domain; routinely providing high-quality integrated climate products; increasing the participation of developing countries; and enhancing national, regional and international planning, reporting and coordination.

I. Data Considerations

There are many observations of the climate system being taken today. The Report notes many times where there are issues with respect to limited access to these observations and the problems with their quality. Addressing these issues would have an immediate and positive impact on the ability of the current global observing systems for climate to meet the needs of the Parties.

Effective Data Exchange and Access

In Decision 14/CP.4, the COP *Urged* Parties to undertake free and unrestricted exchange of data to meet the needs of the Convention, recognizing the various policies on data exchange of relevant intergovernmental and international organizations. Yet, as this Report points out repeatedly with respect to almost all of the variables, the record of many Parties in providing full access to their data is poor. Indeed, most Parties appear to be unaware of their performance in this respect.

Conclusion:

2) **Adherence by nations to the agreed policy of free and unrestricted exchange is urgently required for both *in situ* and satellite climate observations, particularly in respect of observations of the Essential Climate Variables listed in Table 1, as well as their associated climate products; and**

3) **Nations need to ensure that their observations and associated metadata for the Essential Climate Variables, including historical observations, are available at international data centres[6] for application to climate analyses.**

High-Quality Climate Data

One of the most important aspects of the Convention that sets it apart from most other needs for climate information is the requirement for information on change and rates of change. This requirement means the construction of data sets covering long periods (many decades if not millennia) that can be continued into the future. Such data sets must be homogeneous without extraneous and undocumented instrument or observing-system changes. The GCOS Climate Monitoring Principles[7] have been adopted by the UNFCCC as a means of ensuring such a homogeneous climate record for the future. While developed for the specific purposes of the UNFCCC, adherence to the GCOS Climate Monitoring Principles will enhance the value of the observations for all users. In many respects these principles simply represent good management practice for observing systems. Most of the Parties, in their National Reports[8],

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[6] The term “international data centre” covers the ICSU World Data Centres as well as other centres identified by GCOS and its sponsors as the organizations responsible for the storage of data for specific networks and for making it available to the users. It is implicit that these centres will adhere to GCOS data policy, apply the GCOS Climate Monitoring Principles in their operations, and implement cataloguing, auditing and reporting procedures on the availability of data.

[7] See Appendix 2 of the Report.

[8] The term “National Reports” includes: the summary information provided by Annex I Parties on systematic observation in accordance with the UNFCCC guidelines, as a part of their national communications; the detailed reports on systematic observation that were invited from all Parties; and the initial communications from non-Annex 1 Parties. An analysis of these reports is available on the GCOS website at http://www.wmo.ch/web/gcos/Publications/gcos-79.pdf

acknowledged the importance of these principles but reported that they had yet to adopt them in actual practice. It is clear from this Report that, unless these principles are adhered to, the investments being made in improving the various parts of the global observing systems for climate will be significantly undermined.

The Report has noted that satellite observations are an essential part of the global observing systems for climate for all three domains. Their contributions, though already substantial and in many cases impossible to replicate with *in situ* approaches, have not realized their full potential because the mission design parameters have not included long-term climate monitoring requirements. Many of the Earth observation missions, relevant for the climate variables, are either for research and development purposes, most of which by their very nature have a limited time horizon, or are implemented in support of weather services where the primary requirements are different. Improvements can be made by the Space Agencies' recognizing the special requirements of the UNFCCC and the importance of adherence to the GCOS Climate Monitoring Principles that have now been specifically tailored to include satellite observations.

The Report further notes that maintaining a homogeneous record requires that the operation of the individual networks be monitored on a continuous basis to ensure that standards are being maintained and that observations are being received by the designated international data centres. Such operational monitoring will ensure that problems that might affect the quality of the climate record are identified and corrected in a timely and cost-effective manner.

Conclusion:

4) **Adherence by nations to the GCOS Climate Monitoring Principles for global climate observations from both *in situ* networks and satellites is required; and**

5) **GCOS and its partners need to monitor the performance of the individual networks to ensure their continued effectiveness and the timely identification and remediation of problems that may compromise the quality of climate products.**

Data for Impact Assessment

Impact assessment and adaptation activities require information on regional patterns of climate change, variability and extreme events. These requirements cannot be met solely with observations from the GCOS baseline networks. Additional regional and national stations are required, as well as daily and/or hourly observations to establish extreme events. These networks are especially important for measurements of surface temperature, precipitation, wind and sea level. Such higher-density networks will be difficult for many countries to implement and sustain, particularly for the least-developed countries, small-island states and some countries with economies in transition.

Conclusion:

6) **Nations will need to operate climate-observing networks with a denser distribution of stations and often more frequent observations, in addition to the GCOS baseline networks, for impact assessment and the development of adaptation strategies. These regional and national networks, to the greatest extent possible, should also be operated in accordance with the GCOS Climate Monitoring Principles.**

II. Network Considerations

Specific actions to improve the adequacy of the domain networks have been identified in the Report. The necessary steps are discussed in detail in Section 6 and are summarized below.

Atmospheric Observation

The GCOS strategy for acquiring and analyzing atmospheric data is being implemented gradually, with a special emphasis on the development of GCOS baseline networks including the GCOS Surface Network (GSN) and the GCOS Upper-Air Network (GUAN). However, there are problems with the observation and exchange of many of these baseline data, and improved adherence to the GCOS Climate Monitoring Principles is required. These problems require urgent attention. Many developing countries need resources and training to resolve problems with acquisition, analysis and archival of data for climate. Increased attention is also needed to recover and access past records (both instrumental and paleoclimate reconstructions) to better establish the variability and long-term trends in climate.

Analysis of regional impacts and vulnerabilities requires high-frequency (e.g., hourly for precipitation) high-density climate observations. These high-frequency data are vital for developing information on extreme events.

To characterize global climate and to initialize and verify global climate models, there is a need to consolidate the marine-surface network. This includes the Voluntary Observing Ships (VOS) contributing to the VOSClim programme; surface-drifting buoys measuring sea-surface temperature and surface pressure; and air-sea moorings and satellites measuring surface atmospheric variables over the ocean. This need is especially important for the southern oceans and other regions where there are few shipping routes. Unbiased estimation of precipitation over the ocean requires further refinement of satellite measurement techniques together with the establishment of a reference network of ocean-surface precipitation stations on key islands and moored buoys around the globe.

Clouds and water vapour affect the Earth radiation budget and provide the strongest and most uncertain feedbacks in the climate system. Satellite observations of total solar irradiance and Earth radiation must be continued without interruption and with strict adherence to the GCOS Climate Monitoring Principles. Promising new technologies should be exploited, including for instance the use of occultation techniques and Global Positioning System (GPS)-based sensing of column water vapour.

Continuing and homogeneous observations should be made of the spatial and temporal distribution of greenhouse gases, including carbon dioxide, to help determine sources and sinks. This should be accomplished through the continued operation of the current stations, enhancement of the Global Atmosphere Watch (GAW) Global Network in selected regions, advancement of selected satellite observations, and implementation of real-time analysis and re-analysis for atmospheric composition products.   In order to characterize the nature of aerosols and their radiative properties, there is a need to consolidate baseline measurements and further develop a strategy to produce long-term homogeneous observations. There is a need for improved distribution and calibration of ground-based observations to support the use of satellite data for global monitoring of ozone.

Ocean Observation

New technology, developed and proven by the ocean climate programmes of the 1990’s, has allowed the ocean community to design and commence implementation of an initial ocean climate observing system that is well focused on the UNFCCC needs. The first priority is the full implementation of this system together with its associated data, analysis and product capabilities. Implementation will involve making existing *in situ* and satellite activities adhere to climate standards as well as the phased introduction of the essential enhancements. Continued support of climate research and technology programmes for the oceans is also needed to ensure efficiency and effectiveness and to promote development of capabilities for those climate variables that cannot currently be observed globally. This need is particularly acute for remote locations and for improved understanding of the ocean ecosystems and those processes that contribute to uncertainty in estimates of climate change.

Satellites are needed because they are the dominant source of ocean-surface data, with *in situ* networks providing necessary complementary information. High quality and continuity are primary requirements for satellite observations. Sustained support for remote wind, topography, sea-ice, sea-surface temperature and ocean-colour measurements remains a pressing issue.

Global deployment of the surface data-buoy array and of the Argo-float programme, in conjunction with the rest of the comprehensive surface and upper-ocean temperature and salinity networks, is needed for monitoring of heat and freshwater storage and transport, to test the ocean component in climate models, and for climate change detection and attribution.

Establishment of a sparse network of global-ocean reference stations is essential for providing the climate-quality time series required for model testing, climate change detection, calibration of air-sea flux estimates and technology development.

Enhancement and extension of the global baseline and regional sea-level network record is needed for climate change detection and the assessment of impacts.

The measurement of the state and change of carbon sources and sinks in the ocean is important for determining the nature of the global carbon cycle, for future scenario projections and for a full understanding of potential mitigation strategies.

Measurements of the full-depth ocean are a critical contribution to characterizing ocean climate variability and change, providing a capacity for monitoring the oceanic uptake of heat, freshwater and carbon dioxide and improving the chances of early identification of abrupt climate change arising from deep ocean processes. Regular, full-depth ocean surveys and surface altimetry are needed.

Terrestrial Observation

The climate observing system in the terrestrial domain remains the least well-developed component, whilst at the same time there is increasing significance being placed on terrestrial data for climate understanding as well as impact and mitigation assessment. Increasingly sound foundations exist for both the *in situ* observation networks and the space-based observing components of the terrestrial domain. Space Agencies and other organizations are generating new products, the Global Terrestrial Networks (GTNs) are being established and growing in effectiveness, and their associated international data centres are beginning to be populated with data.

Although progress is being made in product generation from Earth observation satellite data, in many cases there is no institutional responsibility for generating climate-quality terrestrial products. This needs to be rectified.

Appropriate long-term satellite records should be reprocessed to produce consistent data sets for the key terrestrial variables.

A coordinated reference network is needed for *in situ* observations of climate variables, such as carbon dioxide and the water variables, for process studies, to validate observations derived from Earth observation satellites, and to address intrinsic limitations in some of these, such as the saturation of leaf-area-index (LAI) measurements.

The three Global Terrestrial Networks (hydrology, glaciers, permafrost) should be fully implemented, gaps in the measurement networks that they have highlighted should be filled and data should be provided to the designated international data centres.

III. Implementation Considerations

Achieving global coverage of climate-quality observations for the variables in Table 1 is essential to ensure that the needs of the UNFCCC and IPCC for systematic climate information are met. This requires an integrated approach incorporating a mixture of high-quality satellite and *in situ* observations as well as associated infrastructure. Implementation requires the allocation of resources to priority activities, the participation of all Parties, and mechanisms for the establishment of and promulgation of standards. In addition, as understanding of the climate system increases and deployment of the required observing techniques becomes both feasible and cost-effective, observations of additional climate variables will have to be incorporated.

Conclusion:

7) **Parties, both individually and through multilateral agreements and intergovernmental mechanisms, should commit to the full implementation of integrated global observing systems for climate, sustained on the basis of a mix of high-quality satellite and *in situ* measurements, dedicated infrastructure and targeted capacity-building.**

Integrated Approach

Global climate products are commonly generated by blending data from different sources, such as *in situ* and satellite observations. It is essential that analysis centres be identified to regularly generate these products.

Maximum benefit is extracted from all climate observations through real-time data-assimilation and re-analysis systems in which different data are integrated into comprehensive and internally-consistent descriptions of the state of the climate system, although simpler approaches are currently appropriate for some products.

There is also a need to provide on-going support for satellite observations of the Essential Climate Variables and for the generation of integrated climate products from these observations. Table 2 contains a list of variables largely dependent upon satellite observations and used in integrated climate products.

Re-analysis has been applied to atmospheric data covering the past five decades. Although the resulting products have proven very useful, considerable effort is needed to ensure that re-analysis products are suitable for climate monitoring applications. Re-analysis will be improved by the inclusion of historical climate data, which together with their associated metadata need to be available in international data centres. The least-developed countries, small-island states and many countries with economies in transition will benefit from assistance in the rescue of paper records, their transcription into digital form and permanent archiving for use in global re-analysis.

Conclusion:

8) **Internationally-coordinated re-analysis activities need to be enhanced and sustained by the involved Parties to meet the requirements for monitoring climate trends, to establish ocean re-analysis for the recent satellite era, and to include variables related to atmospheric composition and other aspects of climate forcing;**

9) Parties with responsibility for space agencies should support the long-term operation of Earth observation satellites; ensure that homogeneous climate data and integrated products are produced; and strive to make them available to all Parties; and

10) Such Parties should support an internationally-coordinated approach to the development of an initial set of integrated global climate products, related to the variables[9] in Table 2, and make them accessible to all Parties. Developing a strategy for implementing these global products could be an important role for the Integrated Global Observing Strategy (IGOS) Partners, of which GCOS is a member.

Table 2. Variables largely dependent upon satellite observations.

Domain	**Variables**
Atmospheric (over land, sea and ice)	Precipitation, Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction (especially over the oceans), Water vapour, Cloud properties, Carbon dioxide, Ozone, Aerosol properties.
Oceanic	Sea-surface temperature, Sea level, Sea ice, Ocean colour (for biological activity).
Terrestrial	Snow cover, Glaciers and ice caps, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Fire disturbance.

Participation by All Parties

Many of the Parties, especially those least-developed countries and small-island developing states, as well as some countries with economies in transition, are not in a position to participate fully in global observing systems for climate. Problems include a lack of trained personnel, expensive consumables, inadequate telecommunications, and an absence of equipment. There is also limited capacity for them to draw benefits from the observations currently being taken. The Parties have previously discussed these matters within the context of the COP where Parties have been encouraged, in cooperation with the GCOS Secretariat, to explore the full range of funding options that might address these problems as well as to participate in the development and implementation of action plans for specific regions. In addition, the SBSTA has decided to consider the need to support capacity-building for systematic observations (and research) at future meetings.

Conclusion:

11) Annex 1 Parties, in conjunction with GCOS and its Sponsors, should explore the establishment of a voluntary funding mechanism for undertaking priority climate-observing-system improvements and related capacity-building with least-developed countries and small-island developing states as well as with some of those countries with economies in transition.

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[9] Or where appropriate, a surrogate, e.g., microwave radiance in a specified band for upper-air temperature.

Standards

Given that climate observations are made by many different organizations and in almost all nations, the production of homogeneous and high-quality global climate observations and associated products requires an international mechanism, to prepare regulatory and guidance material relating to climate observing systems, data management and products. The existing international mechanisms for the atmospheric and oceanic domains are encouraged to develop and promulgate standards, including those for satellite observations, for all of the Essential Climate Variables. It has been noted that many organizations make terrestrial observations, for a wide range of purposes. Various different measurement protocols are used, even for the same variable. The resulting lack of homogeneous observations limits capacity to monitor the terrestrial changes relevant to climate and to investigate the causes of observed land-surface changes. As a result, there is an urgent need for the establishment of an international mechanism for the terrestrial domain similar to those already in existence for the atmospheric and oceanic domains.

Conclusion:

12) The GCOS Sponsors, in consultation with other international or intergovernmental agencies, as appropriate, should consider the establishment of an international mechanism that would prepare and issue regulatory and guidance material relating to terrestrial observing systems and management of their data and associated products.

Planning and Reporting

The information provided by the Parties on systematic observation as part of their National Reports has proven to be useful to GCOS in the planning and implementation of global observing systems for climate. Unfortunately, detailed information was available only from a limited number of nations. Obtaining a global perspective requires regular and coherent information from all Parties. It was noted by some nations that the preparation of these reports for the UNFCCC had become a stimulus for enhanced coordination and planning. In a few cases, this planning had led to the allocation of resources and adjustments to the national observing systems to more fully meet climate needs. It is likely that many developing countries and some countries with economies in transition will need assistance to develop and implement such coordination and planning processes.

The GCOS Sponsors undertake a number of regional planning and implementation activities. In response to the request of the UNFCCC, the GCOS Regional Workshop Programme has been undertaken to supplement these activities by organizing workshops involving developing countries in a number of regions. Action plans to resolve specific deficiencies in climate observing systems are subsequently developed for each region. Five workshops have been held to date and three action plans have been developed that now require project funding for implementation. Further workshops are being held in other regions in the next two years. The development of regional action plans has the substantial benefit of sharing work across many partners with common interests who are able to learn from the experience of other regions and participants.

Conclusion:

13) Nations are encouraged to adopt a systematic approach to implementing global observing systems for climate involving active national and regional coordination and planning processes and a commitment to systematic climate observation;

14) All Parties are strongly urged to submit information on their systematic observations as part of their national communications to the UNFCCC; and

15) **The SBSTA, in consultation with the GCOS Secretariat, is urged to review the guidelines for national communications by the Parties on research and systematic observation[10] to include, *inter alia*, a specific requirement to report on the exchange of observations of the Essential Climate Variables and on the submission of current and historical observations and metadata to the international data centres.**

Developing Future Capabilities

Improved observing techniques are needed, both to make more effective measurements of Essential Climate Variables and to expand the suite of key climate variables that can be observed globally. Improvement in both satellite and *in situ* observing technology is needed. The transfer of proven research observation activities to sustained operational status needs to be encouraged. Improved understanding of climate phenomena and their impacts, as well as greater understanding of the uncertainties associated with climate projections, is also needed. The integrated observing system will need to evolve as new observing capabilities, new understanding of climate variability and change, and better awareness of the needs of society are developed.

Conclusion:

16) **Further research and development is required to improve the comprehensiveness, accuracy and efficiency with which the global climate system can be characterized.**

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[10] Decision 4/CP.5

The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC

1. Purpose and Scope of the Second Adequacy Report

A first report[1] on the adequacy of the global observing systems for climate in providing the systematic climate observations required by the United Nations Framework Convention on Climate Change (UNFCCC) was submitted to the Conference of the Parties (COP) of the UNFCCC at their fourth meeting in 1998. Since then, the COP, individual Parties of the UNFCCC and various intergovernmental and international agencies have undertaken a range of actions to address the reported inadequacies. In November 2001, the SBSTA endorsed a proposal, made by the GCOS Steering Committee, to undertake a review of the actions and commitments contained in Parties' National Reports[8] and, together with all other available information, to prepare a second report on the adequacy of global observing systems for climate to meet the systematic observation needs of the Parties and the IPCC (herein called the 'Second Adequacy Report' or 'the Report'). The preparation of the Report, organized by the Global Climate Observing System (GCOS) Secretariat working in partnership with the other global observing systems and on behalf of its Sponsors, has involved a wide range of experts from the scientific and observational communities as well as an open review process.

The goals of the Report are to:

- Determine what progress has been made in implementing climate observing networks and systems since the First Adequacy Report in 1998;
- Determine the degree to which these networks meet with scientific requirements and conform with associated observing principles; and
- Assess how well these current systems, together with new and emerging methods of observation, will meet the needs of the Convention.

The **scientific requirements** for observation of the climate system in support of the Convention and the IPCC were reviewed at a joint meeting of GCOS and IPCC representatives as a first step in August 2002. Experts for specific components of the observing system then prepared assessments of progress and adequacy of global observing systems for climate to meet these requirements. A first draft of the Report was prepared following a meeting of these experts held to discuss their findings. The draft Report was made available to governments and the scientific community for review and comment from January to March 2003. The GCOS Steering Committee reviewed and endorsed the final version of the Report at its eleventh session in April 2003.

This Report is an assessment of the ability of the climate observing system to meet the needs of the Parties to the Convention and the IPCC for climate observations at the **global** scale. Assessments at the regional and/or local scale are included only where they have been deemed to be important to monitoring the global system.

The Parties also require **detailed climate observations** to assess the local impacts of climate change and variability, and for the development of specific adaptation strategies. Their requirements for such observations will vary considerably from nation to nation and are dependent upon their specific national socio-economic interests and their vulnerability to climate change and variability. Many of the global observations considered in this Report are a subset of these detailed observations. This Report does not provide an assessment of how well these local requirements are met by national observing systems for climate. It does, however, provide an assessment of the overall ability of the global systems to establish the global context to support these local needs and how the detailed observations can be made to become part of a comprehensive climate observing system.

Many **research programmes** undertake systematic observation of the climate system. Several of the networks that provide long-term observations are an essential part of the global observing systems for climate and are therefore included in this Report. Other observations are focused on understanding specific processes within the climate system. In addition, the research programmes undertake observation of climate variables that are not currently included as part of the global observing systems for climate because *inter alia,* the techniques of systematic measurement are not yet well established and/or the technology is not yet suitable for global deployment. These latter two types of observation are not assessed in this Report. It should also be noted that the research programmes are dependent on many of the observations from the operational[11] observing systems discussed in this Report.

The **Report** describes underlying reasons for the interest of the UNFCCC in systematic climate observation (Section 2), the scientific requirements for selecting the specific variables that are required to be monitored (Section 3), and the strategy and approach for developing a system for global climate observation (Section 4). Progress in implementation of the global observing systems for climate, since the First Adequacy Report, is reviewed (Section 5) and an integrated analysis of the adequacy of the current systems is provided for each of the atmospheric, oceanic and terrestrial domains (Section 6). Section 6 also includes important findings and identifies areas where further actions are required. Finally, a number of common elements applicable to all domains are discussed (Section 7), together with a number of specific findings. The conclusions of the Report are summarized in the Executive Summary.

The **observational requirements** of the UNFCCC and the IPCC can be grouped in different ways. This Report undertakes its assessment based on six groupings relating to broad areas of concern to the Parties:

- Characterizing the state of the global climate system and its variability;
- Monitoring the forcing of the climate system, including both natural and anthropogenic contributions;
- Supporting the attribution of the causes of climate change;
- Supporting the prediction of global climate change;
- Projecting global climate change information down to regional and national scales; and
- Characterizing extreme events important in impact assessment and adaptation, and to assess risk and vulnerability.

It should be noted that many of the observations required for characterizing the state of the global climate system and its variability (i.e. the first grouping) are also necessary in the other groups. However, in some cases additional variables are required. Since the observational needs for later groupings depend heavily on those groups preceding them, there is less material required as we proceed through the six groups.

2. The UNFCCC Need for Systematic Observation

The **ultimate objective** of the UNFCCC is “to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

The **primary focus** of the Convention is the anthropogenic causes of climate change. Therefore knowledge of the concentrations, emissions and sinks of greenhouse gases is fundamental for its work. Effective implementation of measures also requires a sound understanding of both the current climate

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[11] Operational within the context of this Report means observational activities that are undertaken according to agreed standards on a routine and on-going basis with plans in place for continuity and homogeneity. It also implies compliance with the GCOS Climate Monitoring Principles.

system and how those measures themselves will respond to climate change. For example, if changes in land use are to increase terrestrial carbon storage, it is essential to know the current carbon storage characteristics and the response of both those characteristics and the proposed land-use measures to global and regional climate changes.

Climate variability and extreme events have and continue to impact human societies and ecological systems. Floods cause immediate loss of life and property. Droughts lead to major alterations in the natural environment and agricultural food production and ultimately to starvation in many countries. In the planning of socio-economic development, the risks associated with extreme events in precipitation, temperature and wind are often poorly known or not fully recognized as important. Indeed in recent decades, socio-economic developments in various societies have increased exposure to climate-related disasters, e.g., developments in coastal areas and on flood plains. It is the very limited and fragile degree of adaptation by many societies to current climate variability that makes them so vulnerable to future climate changes.

Changes in climate have led to major and abrupt changes in society and ecological systems in pre-historical times. There is evidence that such changes have been manifested in part through changes in the frequencies and intensities of extreme events. With anthropogenic global warming there may be a prospect of further and significant change in these key features of climate. It raises the possibility that in some areas, ecosystems may be unable to adapt to the changed climate; agricultural productivity may decline because of changes in the water cycle in some places, and perhaps increase in others; the boundaries of ecosystems such as forests may move; the active regions for disease and pests can change. Another possibility is the possible risk of sudden, large, non-linear changes in the climate system, for example as a result of changes in ocean currents. The latter are known to have occurred in the past, but their mechanisms are poorly understood.

Societies need to anticipate change if adaptation is to be effective. To anticipate change the Parties to the UNFCCC must have information of past and current climate conditions, particularly climate variability and extremes, as well as sound projections of future conditions.

Assessments of climate change, past, present and future, as well as the implications for society and ecosystems and the possibilities for mitigation measures, have been prepared by the IPCC and presented to the UNFCCC. This Report does not repeat the work of the IPCC. However, in each assessment report, the IPCC has stated that there are major deficiencies with global climate observations that limit the ability to assess impacts, especially at the regional and national levels, and to project climate into the future. It is essential, therefore, that the IPCC requirements for climate observation be considered as part of this Report.

3. Scientific Requirements for Climate Observation

The **climate system varies** in response to changes in external forcing as well as internal processes. Therefore it is important to track climate in such a way that the causes of the variations can be traced and future changes predicted. The latter task involves much more than observations and their analysis, and involves issues beyond the scope of this Report. The interpretation of the long climate record requires a detailed understanding of the various forcing functions occurring at that time. For the past millennium, the natural forcings of most consequence are variations in total solar irradiance (TSI) and episodic changes in composition of the atmosphere, especially aerosol loading resulting from explosive volcanic eruptions. Evidence has also emerged from the IPCC assessments that various human activities are now forcing changes to our climate, in particular, those activities that significantly alter the composition of the atmosphere and the characteristics of the land surface.

Observing Climate requires an integrated strategy of land/ocean/atmosphere observation from both *in situ* and remote-sensing platforms. No single technology can provide the needed information. Adequate global observing systems for climate will be made up of instruments on ground stations and on ships, buoys, floats, ocean profilers, balloons, samplers, aircraft and satellites. Data are needed on all time scales, for all regions of the globe and throughout the atmosphere and ocean, although spatial and temporal requirements vary with the specific application. Observations are needed at least daily, and for precipitation, hourly, to characterize variability and extremes. Information on where and how the observations are taken (metadata) is also required. Natural variability masks trends, and hence creates uncertainty in detecting and attributing the cause of climate changes. Historical and paleoclimatic records are needed to establish baselines and set the context for the interpretation of trends and variability. Also required are analysis and integration of these observations into useful products. The Essential Climate Variables required for global-scale climate monitoring are contained in Table 1 and in Appendix 1.

Goal 1. To characterize the state of the global climate system and its variability

To **characterize climate**, data should be accurate, homogeneous and continuous. Signals important for monitoring climate change can often be lost in the noise of a changing observing system unless great care is taken. Many variables need to be observed to characterize the state of the climate system and its variability. For ease of presentation the variables are separated into the three domains, atmospheric, oceanic, and terrestrial.

The ***atmosphere*** is the most volatile component of the climate system. Chaotic weather systems, and changes-in-state of water between snow, rain, cloud and water vapour give the atmosphere a unique role in the climate system. Heat, moisture and chemical species are moved around rapidly by winds. Cloud and water vapour feedbacks are major factors in determining the sensitivity of the climate system to forcings. At the land- and ocean-surface, measurements of temperatures, water vapour, wind, pressure and daily precipitation amounts are needed. Observations of cloud and other weather phenomena are given in weather reports but are of somewhat limited use for climate purposes owing to their qualitative nature. As precipitation is episodic and can be very localized, high-resolution observations are needed to create an accurate picture. In addition, the frequency and intensity of precipitation are important because it does not rain or snow most of the time; at least hourly observations of the precipitation amounts are highly desirable. Satellite observations are a unique source of global information of such variables as temperature, wind and precipitation, but do not extend sufficiently far back in time to give a full historical perspective. Satellite observations also are vital for clouds and radiation at the top-of-atmosphere and in providing radiation budget information. Instrumental and palaeo-reconstructions of temperature and precipitation are essential to provide the long-term perspective.

The three-dimensional structure of the atmosphere determines the nature and movement of weather systems. In the troposphere and lower stratosphere, balloon-borne instruments combined with ground-tracking devices in a radiosonde network have traditionally measured temperature, water vapour and wind. Satellite measurements of radiances now complement these observations but require interpretation in geophysical terms to contribute to the climate record. Because natural modes of variability, such as El Niño and the North Atlantic Oscillation, alter atmospheric circulation and storm tracks, it is vital to determine and understand such processes as they can obscure climate change detection. Movement of aerosols and chemical species occurs in winds, and trapping of species in the stratospheric polar vortex under cold conditions can foster heterogeneous chemistry that can deplete the ozone layer. “Rainout” is a primary means of removing particulate matter from the atmosphere.

The ***ocean*** covers about 70% of the Earth’s surface. It is wet, fluid, and has high heat capacity. It stores and moves heat, fresh water, gases, and chemicals. Observations suggest large inter-decadal variations and trends in ocean heat content. Tracking the heat stored and the exchanges of heat, moisture, momentum and gas species with the atmosphere is vital for understanding and forecasting the evolution of climate variability and change. The ocean is the main reservoir for carbon and provides the thermal inertia of the climate system. It is likely to delay by 10 to 100 years the timing of the full response of the climate system to changes in forcing. Coupling between the atmosphere and ocean gives rise to the El Niño phenomenon, and hence to interannual variations in weather and climate around the world. Changes in El Niño as the climate changes may have substantial regional implications. Sea level and sea state are critical variables for low-lying regions. Sea-surface temperature is the most critical variable for the coupled atmosphere-ocean system. In addition to the surface atmospheric variables, others of note include sea-surface salinity, and partial pressure of carbon dioxide (*pCO_2*). Ocean colour is used to indicate biological activity. Observations of ocean currents, the thermohaline circulation and the three-dimensional structure of temperature and salinity are needed to determine the transport and storage of heat and carbon. Special attention is needed in coastal regions, and for boundary currents, narrow straits and shallow regions (choke points where flow is limited), biogeochemical variables, and primary productivity. Sea ice is important as an indicator of climate change as well as through its albedo feedback and its impact on polar ecosystems. Melting or forming sea ice affects salinity and hence density and ocean currents.

The ***terrestrial*** domain is characterized by relatively small heat capacity. The primary way it features in climate variability and human impacts is through changes in water storage and ground cover. Precipitation, evapotranspiration, ground water, runoff, stream flow, lake levels, and river discharge are all important ingredients in the hydrological cycle. Land has a wide variety of features, slopes, vegetation and soils, which affect water budgets, carbon-fluxes and albedo. It is covered by vegetation that is a mixture of natural and managed systems. Land use changes the characteristics of the land surface and thus can induce important local climate effects especially through changes in albedo, roughness and evapotranspiration. Evaporation from the land depends on moisture availability to the atmosphere and thus on vegetation and associated transpiration. Land may be covered by snow and ice on a seasonal basis, and it features glaciers, ice caps, and permafrost. Lakes may freeze. Major ice sheets have a huge heat capacity, but operate on long time scales as the primary heat exchange is through conduction. Snow and ice-albedo feedback come into play. As land-based ice melts it alters sea level. Disturbances to land cover (vegetation change, fire, disease and pests) have the capacity to alter climate and the ground (e.g., permafrost) but also respond to climate and thus provide feedbacks.

Goal 2. To monitor the forcing of the climate system, including both natural and anthropogenic contributions

The forcing fields of importance for climate variations on century time scales include variations in the TSI, volcanic aerosols, greenhouse gases and aerosols arising from human-produced emissions and changes in land use. The estimated radiative forcing from various anthropogenic origins (IPCC, 2001[4]) is shown in Figure 1.

Changes in the TSI can be tracked only from space, away from the influences of the atmosphere, and have been monitored only since 1979. Small changes due to the 11-year solar cycle are associated with much larger spectral changes, especially in the ultraviolet that may be amplified through effects on the ozone layer. Historical and palaeo-climate evidence indicate large changes in the sunspot cycle, and crude empirical estimates of associated changes in TSI are large enough to account for some changes in the climate prior to the twentieth century. Because absolute calibration of instruments is difficult, it is vital to have overlapping records from instruments on different satellites in order to create a continuous time series. Because of ozone effects, there is also a need to monitor spectral changes in solar radiation.

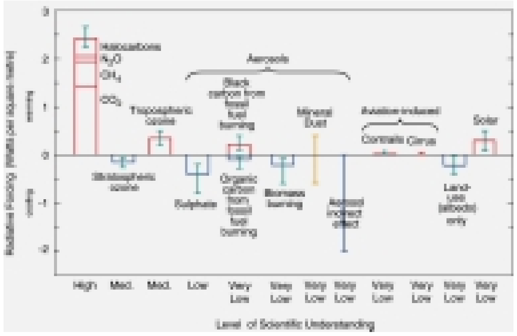

Figure 1. Estimated radiative forcing and uncertainty arising from human and other influences on the climate system (IPCC, 2001[4]).

Major **volcanic eruptions** eject gases and debris into the atmosphere, but most stay in the troposphere and have a limited lifetime since they are removed by precipitation. Of more concern for climate change are the substances injected into the stratosphere from the most explosive volcanic eruptions, where aerosols can remain for several years. Most often these result from sulphur dioxide that is oxidized to form sulphate. These aerosols scatter solar radiation and typically cause cooling through reflection of radiation back to space. However, they also cause warming through a greenhouse effect. Measurements following the Mount Pinatubo eruption in 1991 identified a local warming in the stratosphere but a global surface cooling of several tenths °C that lasted for about two years. It is important to be able to track such episodic events and characterize the nature and radiative properties of the aerosols.

Human activities change the vegetation and land surface, which alters the surface albedo, roughness and exchanges of moisture, gases and dust with the atmosphere. Such changes often have a strong seasonal cycle as crops are planted and harvested, and respond to climate variations, such as drought. Human-caused fires and disturbance are also important and affect aerosol and mineral dust loading of the atmosphere. Accordingly, it is important to track these changes and the feedbacks, and to determine their role in the evolving climate.

A major influence of humans on climate occurs through changes in the composition of the atmosphere (Figure 1). Of most concern are the emissions of long-lived **greenhouse gases**, such as carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFCs) and other minor trace species. Because they are greenhouse gases, they change the radiative balance of the planet and, if uncompensated by other factors, cause warming when their concentrations increase. As they are long-lived, they become globally distributed in a year or so, and continually increase in concentration. Accordingly, global concentrations can be tracked from a small number of surface stations. Of additional concern, however, is the tracking of the sources, recycling, and sinks of the greenhouse gases, and the monitoring of associated human emissions. There is therefore a growing need for detailed synoptic patterns of concentrations, both geographically and with height. For carbon dioxide, concentrations are influenced by photosynthesis in plants, which occurs during the day, so that large diurnal variations exist in the boundary layer.

Ozone is another important greenhouse gas. Its greater chemical reactivity means that its lifetime in the troposphere is of the order of months and therefore it is not uniformly distributed around the globe leading to a requirement for a higher density of monitoring stations. A major tropospheric source of ozone arises from human activities, including for example, emissions and oxidation of carbon monoxide. A natural ozone layer in the stratosphere is vital for protecting life at the surface from ultraviolet radiation but is influenced by human activities, notably emissions of CFCs that have contributed to the Antarctic ozone hole and stratospheric ozone depletion world-wide. Accordingly, it is important to know both the column amount of ozone and the vertical profile. Observations from both the ground and space have proven vital and complementary. Also of long-term concern is the steady build up of certain replacements for chlorofluorocarbons, which are chemically inert but radiatively active, and thus will contribute to a greenhouse effect.

In the troposphere, **aerosols** from both natural and human origins are important. They affect radiation through scattering and absorption, and modify the brightness and lifetime of clouds, and therefore precipitation. Unlike greenhouse gases, their lifetime is generally of order of a week as they are washed out of the atmosphere in precipitation, and hence they are regionally distributed. The sources, types and radiative properties of aerosols need to be better characterized. Because the aerosol radiative effects often depend on relative water vapour, their co-variability with atmospheric moisture is important.

Goal 3. To support the attribution of the causes of climate change

Attribution is the process of relating the observed changes in the climate state variables to the forcings, properly taking natural variability into account. It is important, within the context of the UNFCCC, that information be collected to provide means for understanding and properly attributing the causes of climate change. In addition to the need for observations of both forcings and state variables given in Goals 1 and 2, good models are required to be able to relate the expected change in state variables to the forcings. Interpretation depends on variables important for feedbacks, such as clouds, water vapour and sea-ice cover. Attribution may be assisted through numerical experiments to determine a "fingerprint" that can be sought in analysis of the variables.

Full account must be taken of the **natural variability** of the climate variables, and results depend strongly on the ability of the model in simulating the variability as well as the correct signal. Accordingly, it is vital to have independent, reliable estimates of variability from the palaeo-climate record as well as the instrumental record on multiple time scales. The observed record can give only the total variability, which arises from external forcings and internal processes involving interactions among climate system components such as the atmosphere and ocean. Isolation of the responses to natural as well as anthropogenic forcings is essential, as is consideration of possible non-linear interference among them.

Goal 4. To support the prediction of global climate change

Until now, IPCC projections of future climate have been based only on estimates of forcings from emissions scenarios. Recognition that regional climate change is occurring, for whatever reasons, has increased the need to make climate predictions that help plan adaptation. Predictions of climate require taking advantage of not only the forcings and their past history, as has been done in IPCC, but also the current state of the climate system. Further, assigning probabilities to future emissions scenarios would allow them to be incorporated into probabilistic predictions of future climate on various time horizons. Some predictability of climate is associated with knowledge of the current state as it slowly adjusts to changing forcings. Further predictability for up to several decades arises from the initial conditions. For predictions of a season to a year or so, the sea-surface temperatures, sea-ice extent and upper ocean heat content, soil moisture, snow cover and state of surface vegetation over land are all important. Such initial value predictions are already operational for forecasting El Niño and extensions to the global oceans are underway. On longer time scales, increased information throughout the ocean is essential. The mass, extent, thickness, and state of sea ice and snow cover are vital at high latitudes. In addition, data are needed on the recent forcings and probabilities of future forcings. Predictions necessarily involve ensembles of model runs that explore uncertainties in the initial state, the forcings, and the models. Special limited-term observations are needed to improve understanding of processes and thus improve models.

Goal 5. To project global climate change information down to regional and national scales

Impacts and adaptation will be apparent mostly on national and local scales. As a result, there is a special need for detailed local information about the same variables described in Goal 1. This detailed information enables construction of statistics on local weather including severe small-scale weather events, such as tornadoes and hurricanes, based on their relationships to circulation scales that can be predicted. Stream flow and flooding are other examples of vital importance to society, but which require more detailed information than available from global models. In some cases, downscaling may be possible using global and/or regional models, and detailed observations are needed for verifying results.

Goal 6. To characterize extreme events important in impact assessment and adaptation, and to assess risk and vulnerability

Data for properly characterizing extreme events are important for impact assessment (e.g., floods, disaster management), policy development and adaptation strategies. This characterization will often take the form of statistical estimates using many of the same variables as in Goal 1. Models for assessing risk and vulnerability to changes in extreme events and variability need to be based on high-quality data and process research. It is important that these data are gathered within the general framework of monitoring variability and change.

4. The System for Global Climate Observation

4.1 Strategy

The strategy for providing the climate data and products identified in Section 3 must be both technically and fiscally feasible now and for the future. While the strategy must be dependent on national efforts, success will be achieved only through internationally-coordinated action. The strategy must initially focus on the global nature of the requirements but at the same time, its data and products must also be relevant to regional and local requirements. In the case of the monitoring of extreme events, which can be inherently of a small scale and/or high frequency, the optimum strategy must enable global estimates of such phenomena.

The strategy for GCOS implementation depends upon close cooperation with many different organizations and agencies with complementary responsibilities, including the international observing programmes (the World Weather Watch Global Observing System (GOS) and the Global Atmosphere Watch (GAW) of the WMO; the Global Ocean Observing System (GOOS); and the Global Terrestrial Observing System (GTOS)) and their sponsors. These organizations, together with GCOS and other relevant bodies including the Space Agencies and the research programmes, form the Integrated Global Observing Strategy (IGOS) Partnership for the definition, development and implementation of an integrated global observing strategy. Each of the observing system partners is interested in observation for a wide range of users, not only climate. Therefore GCOS works with them to ensure that they are fully aware of the climate requirements and to ensure that those requirements are met.

4.2 Networks

The GCOS implementation strategy envisages five complementary types of network that will provide observations. These are:

- Comprehensive global observing networks including regional and national *in situ* networks as well as satellites, which provide observations at the detailed space and time scales required to fully describe the nature, variability and change of a specific climate variable;
- Baseline global observing networks, which involve a limited number of observations at selected locations that are globally distributed and provide long-term high-quality data records of key global climate variables, as well as calibration for the comprehensive networks;
- Reference networks, which provide highly-detailed and accurate observations at a few locations for calibration purposes;
- Research networks, which can provide estimates of the local variability of key variables to evaluate models and/or provide comprehensive data sets to understand climate processes; and
- Ecosystem networks, where a number of different variables are measured at several locations within a specific ecosystem and are used to characterize that ecosystem.

Although an ultimate goal, it is presently unrealistic to attempt to establish and operate networks at all five levels for all climate variables. ***Priority is currently given within GCOS to the establishment of key baseline networks making in situ observations, selected comprehensive networks many of which use satellite technology, a selected number of reference networks, and the long-term operation of a number of research networks.*** As the terrestrial ecosystem networks develop, more use will be made of them for climate monitoring.

4.3 Integration and Products

Making climate observations is a significant investment, and specialist knowledge is needed to exploit the raw measurements. It is therefore vital that all observations be used to the fullest extent possible. This requires that they be integrated into quality-controlled products that meet user needs, and be continually assessed as to their adequacy. This integration usually occurs on a variable-by-variable basis and on two time frames. The first occurs in real time or near-real-time for monitoring and prediction purposes and is vital for providing quality control and essential feedback to the observers. The second occurs in a delayed mode, where historical data are also incorporated, usually as part of an analysis or as part of ongoing research in the detection of climate variability and change.

The requirement for **high-quality climate products** means that quality-control and homogeneity issues must be considered at all stages in the process of data collection, data handling and product generation. Special care must be taken to provide data with a low bias, as well as small random errors. To ensure consistency and homogeneity of the data, some overlap of measurements must be maintained in the networks in order to provide the necessary cross-checks. The synthesis of satellite and *in situ* data also takes advantage of the unique characteristics of each as well as providing a sound basis for intercomparison and validation.

Data assimilation can add considerable value to global observing systems by combining diverse sets of observations with global numerical models to produce comprehensive and internally-consistent fields. The assimilation process comprises a sequence of steps in which observational and background information on the consistency and interrelationships of the data sets are combined with numerical models to produce an analysis of aspects of the instantaneous state of the atmosphere, ocean and land surface. The assimilated products thus combine the accuracy of the observations with known geological, chemical and physical consistency and provide the global coverage inherent in the models. The observations typically comprise sets of *in situ* and remotely sensed measurements, each set with its own accuracy and inhomogeneous data distribution. Analyses provide a complete specification of selected state variables (winds, temperatures, sea state and currents, atmospheric composition and so on) over the globe or a region, at a chosen spatial resolution. Essential background information comes from a short-range model forecast initiated from the preceding analysis in the sequence.

A **medium-term record of climate** can be obtained by accumulating a collection of analyses made each day to initiate numerical weather forecasts. However, the data assimilation systems used in routine forecasting are subject to frequent change as the systems are continually improved. This introduces inhomogeneity that limits their usefulness for studies of inter-annual and longer-term variations in climate. To overcome this, programmes of atmospheric re-analysis have been established in Europe, the USA and Japan, using modern data-assimilation systems to reprocess the observations taken over the past several decades. Such re-analysis products have found widespread application in studies of climate, basic atmospheric processes, ocean-model initialization and forcing, air quality, and numerical weather prediction itself. Diagnostic data produced during the assimilation process are essential to provide information on the overall quality of the analyses, including information on model biases, as well as to identify questionable data.

4.4 Network Components

While the specific components of any individual network will vary, there are a number of common elements that fit together to form an end-to-end system, an example of this for the GCOS baseline networks is shown in Figure 2.

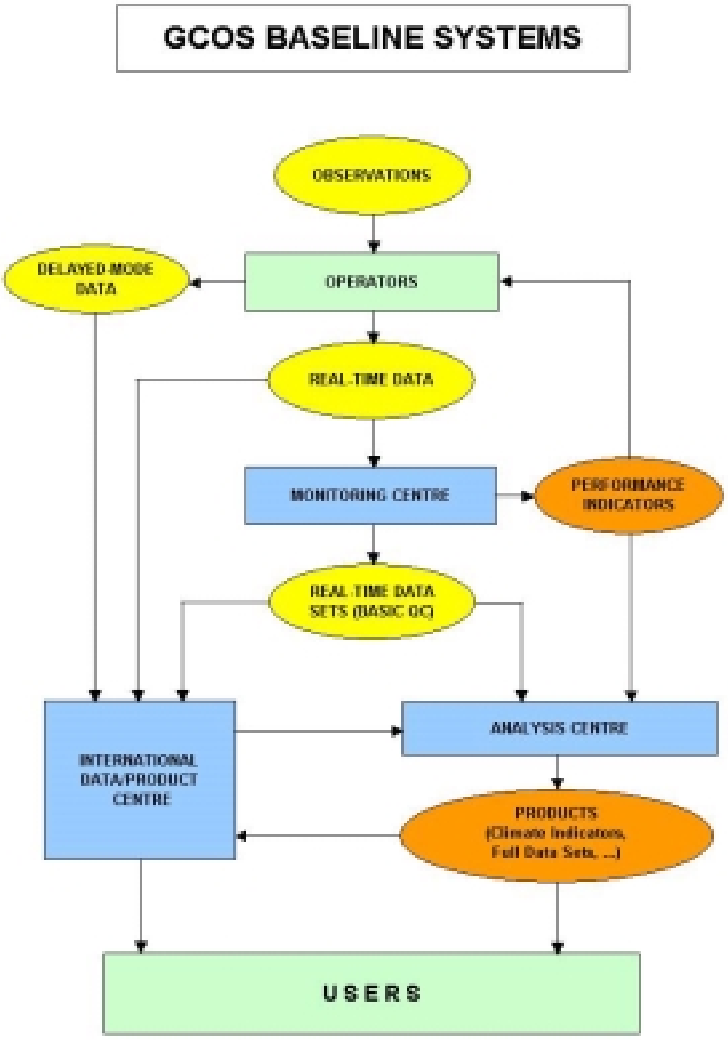

Figure 2. Schematic of the components of a typical GCOS baseline network.

Specific components include: the operators who collect the observations; the centres that monitor the international exchange of the observations, conduct quality assurance and produce information on the performance of the network; the analysis centres that integrate the observations into products for the various user communities; the international data centres that are responsible for the archiving of the observations and maintaining a permanent but accessible repository of the data for subsequent analysis; and the telecommunications systems that act as the glue to keep the system together. Also required are the standards and guidelines for taking observations, the communications protocols required to exchange the data, the data management and archiving procedures, and the regular evaluation of performance.

Finally, there are the integration and analysis centres that perform the four-dimensional data assimilation and re-analysis of many of the variables into comprehensive representations of the climate system.

The **failure of any one part of the system** leads directly to poorer-quality products and thereby reduces their value to the user.

4.5 Satellite Observation

One of the fundamental sources of observations for the climate system is **Earth observation satellites**. These satellites can be broadly categorized into three different types, each with its own specific characteristics.

Operational observing satellite systems have to date been employed primarily to provide necessary observations for weather forecasting and other short-term applications. These satellites are typically flown in a series of multiple identical spacecraft (including instruments). Calibration of instruments before launch and on orbit has usually not been adequate from a climate perspective, although the current efforts of the Space Agencies to improve calibration are very much welcomed and need to be continued. Historically, the satellite orbits were not properly maintained, as this was not a requirement for the weather community. This effectively changed the local observation time and thereby aliased the diurnal cycle onto trends and variability, creating significant problems from a climate perspective. Steps are now being taken to minimize this problem for future systems.

Research satellites have normally been flown as precursors to operational systems. This includes some of the latest-generation imaging and sounding instruments, as well as sensors for a number of other variables such as solar irradiance, ozone concentrations, stratospheric aerosols, and sea-surface topography. New research systems are being planned that may serve to begin records for other parameters (e.g., precipitation). The research satellites and instruments typically place greater attention on pre-launch and on-orbit calibration and maintaining the spacecraft orbits than has traditionally been the case for operational spacecraft. With satellites designed for research, there are no plans that would fill in gaps created by instrument and/or spacecraft failure thereby potentially limiting the value of their record from a climate perspective.

“One time” research satellites are designed to comprehensively characterize some process or component of the Earth system in a new way. The lead times associated with such satellites are typically shorter than that of the other types (~5 years). However, finite lifetimes and the absence of plans for overlap with successor instruments may significantly limit their use for climate monitoring. Nevertheless, most new global satellite environmental observations start with such experimental missions, and they should be looked at as an important and necessary step in the incorporation of new variables into the suite of global observations for climate study. It is also worth noting that some spacecraft in this category also can remain operating well beyond their planned lifetime, and in several cases have been used to provide information on interannual and even decadal observations, in essence turning them from “one time” research satellites into the “initial installment” of a series of research satellites as defined in the previous paragraph.

4.6 Implementation

Clearly, the implementation of an operational system involving some 46 variables, each with its own unique network and management organization, poses many scientific, technical and institutional challenges. Not the least of these is that the networks and systems were usually put in place for reasons other than climate. The GCOS approach to implementation therefore consists of the following:

- Identify the variables required for global monitoring of the climate system using the GCOS science panels that are jointly sponsored[12] with other organizations;
- Invite the intergovernmental and international agencies to adopt and publish observing standards and guidelines for the required climate variables and encourage their Members to implement the required networks, as done for example with the WMO Commission for Basic Systems (CBS) for the GSN and GUAN;
- Encourage the Technical Commissions of the intergovernmental agencies to adopt the GCOS Climate Monitoring Principles (Appendix 2) and standards and specifically to organize the climate networks, building wherever possible on existing observational activities;
- Inform national (e.g., National Meteorological and Hydrological Services) and regional organizations, through its sponsors, of the need for climate observations;
- Work with the international research programmes (WCRP, IGBP and IHDP) to establish observational needs and encourage the conduct of pilot projects;
- Work with the international research programmes to maintain key research networks and to assist in the transition of mature networks to full operational status;
- Invite and encourage centres to undertake performance monitoring and the development and preparation of analysis products on behalf of specific networks;
- Inform the Space Agencies of the climate observation requirements through both the WMO Consultative Meetings on High-Level Policy on Satellite Matters and the Committee on Earth Observation Satellites (CEOS) and work within the Integrated Global Observing Strategy (IGOS) Partnership to identify and establish strategies for integrated observing systems and products;
- Encourage national and regional planning and implementation of systematic observation of the climate system;
- Inform international aid and other appropriate funding agencies of the specific needs of developing countries and those countries with economies in transition for effective participation in global systematic observing programmes; and
- Contribute to the capacity-building activities of the GCOS Sponsors and assemble multi-party participation in the implementation of specific networks.

In following this implementation approach a number of priority aspects must be promoted.

First, one of the requirements that distinguish climate observations from many others is the absolute need for **homogeneous records** covering many decades and all parts of the globe. Integration of the climate variables cannot be done in any meaningful manner without all nations and organizations involved clearly adopting and implementing a set of basic observing principles. The GCOS Climate Monitoring Principles, articulated in Appendix 2, for both *in situ* and satellite observations, are of fundamental importance to climate applications and services of the GCOS Sponsors as well as the UNFCCC. It should be noted moreover that these principles by and large would be of benefit to any observing system.

Second, the requirement for information on trends and change makes **historical data as important as new observations**. Therefore activities that lead to the recovery and rehabilitation of historical observations and related metadata, including those from satellites, are vitally important to the whole community.

Third, the very nature of the global climate system is such **that both satellite and *in situ* observations are essential**. *In situ* observations provide the long-term historical record for most variables and serve a vital role in calibration. In some cases, such as the deep oceans, they are the only currently viable technology. At the same time, satellites provide a truly global view and are the only currently viable tool for some variables such as TSI and global estimates of albedo. A balance between the two approaches is essential - one cannot go forward at the expense of the other. It is for this reason that the GCOS has worked very closely with WMO/CBS, JCOMM and the IGOS-Partnership as a means for ensuring that the

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[12] The Atmospheric Observation Panel for Climate (co-sponsored with the World Climate Research Programme); the Ocean Observations Panel for Climate (co-sponsored with the Global Ocean Observing System and the World Climate Research Programme); the Terrestrial Observation Panel for Climate (co-sponsored with the Global Terrestrial Observing System and the Global Climate Observing System).

priority requirements for climate observations are fully integrated into the programmes for satellites as well as for *in situ* observations. As this integrated observation strategy develops it will require the redesign of *in situ* networks to be more responsive to satellite calibration and verification needs. There have been a number of encouraging strategies from the IGOS themes process over the past eighteen months, including those on oceans and carbon. Other important strategies under development include water and atmospheric chemistry.

Fourth, the **research community** for both *in situ* and satellite components must continue to play a vital role in the development and evaluation of operational observing systems to ensure that the understanding obtained from research networks and satellite missions is carried into the future and that new techniques are appropriately developed and adopted.

Lastly, the whole system is dependent upon **national contributions** of observations, people, resources and infrastructure. Bringing these all together within an effective international framework will ensure that the global climate observing system is more than just the sum of its individual parts.

5. Progress Since the First Adequacy Report

The First Adequacy Report in 1998 made a number of findings and proposed several recommendations to improve global observing systems for climate. This section contains a **brief review of some of the progres**s that has taken place since that first report. Overall there has been progress and improvement in the implementation of global observing systems for climate since the first report, especially in the use of satellite information and in the provision of some ocean observations. At the same time, the global terrestrial networks remain to be fully implemented; the ocean networks lack global coverage and commitment to sustained operation; and the atmospheric networks are not operating with the required global coverage and quality. Coordination and planning have improved in a number of nations and regions and there is significant potential for further improvements in the future. Specific progress towards meeting each of the findings and recommendations is summarized in Appendix 3.

One of the most significant issues identified in the previous report was the large volume of observations that were taken but that were unavailable to the scientific community for assessment and use in quantitative scientific studies. Some of the requested data sets have now been placed in the international data centres. However, in spite of the great visibility given to this issue in the previous report, **progress in completing the global database has been distressingly limited**. Major improvements in access to some climate data have been made by a few of the Parties and at some international data centres, but access remains limited for many data and for many Parties.

There has been **some progress in halting the decline of observations from *in situ* atmospheric network**s. However, there continue to be closures of sites that have long-term high-quality records. These closures jeopardize our ability to detect climate trends and climate change in many parts of the world. Vertical profiles of ozone in the upper troposphere and lower stratosphere in the southern subtropics have been enhanced giving the first-ever multi-year climatology of ozone profiles from the equator to 20 degrees south. Global observation of aerosol optical depth is now available.

The development of autonomous profiling floats and the initial deployments of the Argo project (that have reached the 25% point level with 742 out of 3,000 deployments) are **significant advances toward the global observation of oceanic heat and freshwater content**. The TAO/Triton and Pirata mooring arrays that observe variability in the equatorial Pacific and Atlantic have been maintained and two additional surface moorings now extend this coverage into the eastern Indian Ocean. Surface drifting buoy technology has improved and costs have been reduced. A global programme of full-depth repeat hydrographic sections including carbon and tracers has been designed and a number of sections are funded. The ship-of-opportunity XBT programme is developing and has support identified for about 65% of the target system. New ice surface height satellites will soon be reporting data. Geocentric location of some water level gauges, and some enhancement of the array has occurred; satellite altimeters have been launched and will operate until 2006 with the possibility of continuing operation into the future. There are a number of ocean surface $p\mathrm{CO}_2$ programmes operating on ships-of-opportunity and agreements have been made on data exchange and data set development.

The last four years have seen **substantial progress made by GTN-P** concerning near-surface measurements. GTN-G too has consolidated its network and identified gaps. A new Global Terrestrial Network for Hydrology (GTN-H) has been designed and implementation has begun. The number of FLUXNET sites making CO_2, energy and water flux measurement is growing, although not all sites make systematic meteorological observations, nor do they provide land-use land-cover histories.

The previous report identified issues associated with the use of satellites for long-term trend determination. **Recent improvements in calibration** (and the dissemination of this information), development of new sensors on Earth observation satellites and advances in remote-sensing science are beginning to allow new, quantitative approaches to data processing, and reprocessing. Examples of the latter include sea level from altimetry, improved atmospheric sounders and surface imagery, and continued ozone observations. Space Agencies and other organizations now provide observations for some key global terrestrial variables on an increasingly routine basis. Their involvement in the validation of global land cover and fire products derived from Earth observation satellites is noted and their further involvement in these activities is essential. The significant efforts at inter-calibration, algorithm tests, etc., should assure the adequacy of this set of observations for trend determination. Research into new sensors of potential benefit to climate has progressed. For example, the observations of precipitation over the tropical and sub-tropical regions has helped establish scientific understanding of climate in those regions and led to plans for a multi-national Global Precipitation Measurement (GPM) mission. This will extend coverage to all latitudes, provide some information on precipitation type, improve temporal resolution (to ~3 hours), and be done in a way that may facilitate its longer-term aspects. Other variables for which the first global measurements from satellite have recently begun or are planned for the near future include cloud and aerosol three-dimensional structure, carbon dioxide, soil moisture, and ocean salinity. The usefulness of such future satellite measurements will be dependent on the validation provided by surface-based and *in situ* measurement platforms.

However, for some variables, **potential gaps in the satellite record** may occur without appropriate steps being taken. For instance, the long-running observations of the Earth radiation budget may face a gap. The ocean surface winds that have been so successfully measured in the recent past could be impacted if a successor mission is not launched in time to provide an adequate overlap with the current instrument. The vertical profile of stratospheric aerosols made since 1984 may not be continued with comparable observational characteristics, which could complicate the estimation of climate forcing associated with any future large volcanic eruption. This matter is under active consideration by the Space Agencies. There is also a potential gap in solar irradiance measurements. The small solar cycle variation, the great difficulty associated with accurate metrology for space-based solar irradiance measurements, and the absolute reliance on space-based observations for this quantity make direct overlap between spacecraft for its measurement more important than for any other environmental variable observed from satellites.

The development of **integrated climate products** (using appropriate combinations of satellites and surface-based measurements) has shown significant progress since the last report. Global re-analyses of the atmosphere are being produced that synthesize all kinds of multi-variate data using four-dimensional data assimilation. The products contain a comprehensive amount of detail but lack full checks on the presence of model or instrument-induced biases. In the field of atmospheric aerosols, data from several satellites and the ground-based networks are being integrated as part of the Global Aerosol Climatology Project. Similarly, ocean colour observations from multiple spacecraft are being integrated with a very strict emphasis on inter-calibration of different sensors and algorithm intercomparison. Some longer-term integration activities have been continued, most notably the integration of cloud observations from multiple national polar and geostationary orbiting satellites through the International Satellite Cloud Climatology Project.

Planning and reporting activities on systematic observations have accelerated since the last report. Some nations have implemented national planning and coordination activities for climate observations.

The ocean climate *in situ* and satellite, research and sustained observing, communities have agreed on the design of an initial global ocean climate observing system. The WMO and IOC have formed the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) to oversee its implementation. In some countries, dialogue has been established between the ocean research and operational communities. In addition, international programme managers, observing system representatives and the Space Agencies have come together as part of the Integrated Global Observing Strategy (IGOS) Partnership for the development of strategic plans for observations. Strategic plans in the areas of oceans, water, and atmospheric composition have been developed to date. Regional planning workshops have been organized by GCOS in: 1) the Pacific Islands, 2) Eastern and Southern Africa, 3) Central America and the Caribbean, 4) East and Southeast Asia, and 5) Western and Central Africa. Regional action plans have been prepared for the first four regions and now require project funding for implementation.

6. Adequacy of the Networks

As noted earlier, the analysis of the networks will be provided according to the three domains.

6.1 Atmospheric Networks

Many of the atmospheric networks for GCOS are based on well-established systems. There has been some progress in implementing the baseline components for some of the essential atmospheric climate variables. There has also been some progress in the development of integrated products for climate purposes, particularly through re-analysis of data collected over the past few decades. However, much more effort is required to ensure that future climate observations are properly collected, processed and archived.

6.1.1 Adequacy of the Atmospheric Networks for Characterizing the State of the Global Climate System and its Variability

The atmospheric networks divide naturally into those variables measured at the surface and those measured in the upper atmosphere.

6.1.1(a) Surface

The key atmospheric variables required are surface air temperature (daily maximum and minimum), precipitation (type, frequency, intensity, amount), pressure, wind, water vapour, and surface radiation. The surface observing networks of the World Weather Watch (WWW) Global Observing System (GOS) provide the basis for a comprehensive network for all of these variables except surface radiation.

The **GCOS Surface Network (GSN)** contains about a quarter of the 4,000 stations within the WWW reference synoptic network. These stations have been selected on the basis of past performance and global representation to form a baseline network for climate purposes. The GSN has been specifically designed to determine the variability, including extremes, of surface air temperature over land at global, hemispheric and continental scales. In addition to estimating change and rates of change of surface temperature over decadal time scales, it is also used to make similar estimates for precipitation and pressure. The GSN also provides a mechanism for continued quality control and assessment of the record from the full surface network. The overall usefulness of the information from the GSN has been reduced because there are major regions of the globe for which few observations are available for the GSN (or the full WWW network), owing to lack of resources and/or training. These deficiencies are greatest in Africa and Central and South America. Moreover, according to the performance statistics from the network monitoring centres, only about one third of the stations have provided the GSN archive centre with the historical daily data required to determine the extremes of climate variability. The fundamental importance of the full operation of the baseline GSN in monitoring the long-term trends of air temperature, precipitation, and pressure over the land surface is reaffirmed. There is no baseline network for surface wind or water vapour over land.

FINDING: The problems with the observation and exchange of GSN data, which have been reported regularly over the past decade, require the urgent attention of nations. Many developing countries need assistance and capacity-building to resolve these problems.

Voluntary Observing Ships (VOS) have provided the majority of the historical record of conditions at the marine surface. As the character of merchant vessels and instrumentation has changed, inhomogeneities have been introduced into the record. The quality of daytime air temperature measurements is falling and requires improvement. Night-time air temperatures, after adjustment for changing deck heights and observing procedures, are better and are a valuable crosscheck for sea-surface temperatures. The historical record is especially sparse in many areas before the mid-twentieth century although the activity to create an International Comprehensive Ocean-Atmosphere Data Set (I-COADS) will assemble the best possible data for study of the historical record. High-quality data, and metadata about the VOS ships and their instrumentation, are being sought through the "VOSClim" programme in an effort to provide climate-quality data. The VOS data are sparse in high southern latitudes, off major shipping lanes and in parts of the tropics, and the overall number of observations is dropping. Therefore, knowledge of climate-quality ocean-surface conditions depends on the establishment and sustained operation of a composite network involving surface drifters, air-sea moorings and satellites in addition to improved VOS observations. Composite products incorporating all data sources are required.

FINDING: The support of maritime Parties is required for the implementation of the VOSClim programme to improve measurement of air temperature and water vapour over the oceans.

FINDING: There is an urgent need for the establishment of a composite marine-surface network involving VOS, surface-drifting buoys, air-sea moorings and satellites to make measurements of the surface atmospheric variables over the ocean. This is especially important for the high southern latitudes and other regions with few shipping routes.

Precipitation (type, frequency, intensity, and quantity) is a key variable for specifying the state of the climate system. It varies considerably in space and time and requires a high-density network to observe its variability and extremes on regional scales. Although data from over 40,000 stations have been delivered to the Global Precipitation Climatology Centre (GPCC), over 100,000 precipitation gauge stations are operated worldwide. The release of these data to the international data centres is essential for the improvement of analyses in areas of complex terrain and at high latitudes, and for better understanding of the water cycle. Daily and, if possible, hourly data are required for studies of extremes and precipitation characteristics.

The historical record of **precipitation over the oceans** has been primarily based on rain gauges on islands. There are many questions about the representativeness of this record as it offers very limited and biased coverage of the global ocean. The main source of data on the monthly amounts of precipitation over the oceans now comes from estimates made using various sensors on satellites. Specific satellite missions, such as the Tropical Rainfall Measurement Mission (TRMM), have started to resolve differences between estimates computed on the basis of data from different sensors and the various methods of computation. Large differences among infrared, passive microwave, and active radar sensors in several regions are being reduced. Proposed satellite missions, such as the Global Precipitation Measurement (GPM) mission, will improve spatial and temporal coverage. It is important to establish ocean reference sites to obtain the maximum benefit from the satellite observations and to ensure the creation of reliable composite rainfall products.

Measurements of **solid precipitation** are fraught with difficulty especially, for example, in cases of blowing snow. Further work is needed to develop adjustments for different kinds of gauges and corrections for under-catch, and to standardize measurements among nations. Development of techniques for remote sensing of solid precipitation is also desirable through such activities as the Dual-frequency Precipitation Radar (DPR).

FINDING: Global and regional estimates of precipitation and their variability can be significantly improved by nations routinely exchanging their current and historical observations with the international data centres.

FINDING: The remaining discrepancies among the different estimates of precipitation over the oceans from satellite observations need to be resolved and a reference network of ocean-surface precipitation stations established on key islands and moored buoys around the globe.

Surface air pressure is monitored adequately over most of the Earth's land surface. The analysis products are enhanced by the incorporation of wind fields through dynamical relationships in models. There has been an increase in the deployment of drifting buoys. However, the data coverage over some regions of the ocean, particularly in the southern hemisphere, and over Antarctica remains too sparse.

FINDING: Drifting buoys deployed in the southern oceans have ameliorated uncertainties in surface pressure fields, and should be continued in conjunction with sea-surface temperature measurements.

Surface wind at the air-sea interface is estimated accurately from the latest generation of wide-swath satellite scatterometers for wind speeds below about 25 m/s. While there are a number of current and planned missions providing this information there is no formal commitment to continue the operation of instruments of this level of capability for the long term. The changes made in the scatterometers used in each new generation of satellite have yielded an inhomogeneous record that can only be rectified by adhering to the GCOS Climate Monitoring Principles for satellites. The record of *in situ* surface wind over the ocean is also far from homogeneous, and efforts to improve the historical record being made through I-COADS, VOSClim and other projects need to be supported. Metadata on instruments sited at land stations and on ships should be obtained and maintained; and metadata specifying wind speed units require careful checks for accuracy.

FINDING: Satellite scatterometer observations measure ocean wind fields and will need to be continued as part of the operational global observing systems for climate.

Radiation, both total and its spectral composition, is an important component of the overall surface energy budget and needs to be monitored systematically. Basic surface radiation is measured at about 1,200 sites around the world as part of the GAW. The Baseline Surface Radiation Network (BSRN) of the World Climate Research Programme (WCRP) has established state-of-the-art measurement techniques for most surface radiation parameters. However, the BSRN is primarily a research network originally designed for satellite calibration, and it does not have full global coverage. Further effort in calibration and protocols must be devoted to this essential source of data.

FINDING: The BSRN provides high-quality measurements of radiation at the surface, and should be expanded and adequately supported.

Extending the length of the surface record is essential for the UNFCCC. Many observations of air temperature, precipitation, pressure, wind, and water vapour have been taken since about 1850. Those observations with a long record and of good quality need to be consolidated and updated in a homogeneous way, to support the estimation of regional and global indices and to allow more confident understanding of climate variability and change on decadal time scales.

On longer time scales, there is a requirement to synthesize the climate record using **paleoclimatic** data for the past 2,000 years with annual to decadal resolution. There is a particular lack of paleoclimatic data for the Southern Hemisphere.

FINDING: There should be further work on extending the climate record through data recovery and the collection and synthesis of high-resolution paleoclimatic data.

6.1.1(b) Upper Air

While observations of surface climate are essential, detailed information on the **three-dimensional** state of the atmosphere is necessary to ensure that we can understand and predict climate on all scales. The specific variables of interest are upper-air temperature, wind, water vapour, clouds and the Earth radiation budget. The radiosonde network of the WWW/GOS provides the basis of a comprehensive network for these variables.

The **GCOS Upper-Air Network (GUAN)** was identified as a baseline network of about 150 stations that have been selected from the full GOS upper-air network, on the basis of past performance and global representation, to form a baseline network for climate purposes. It is intended to provide reliable measurements of large-scale temperature variations for heights up to 5hPa in the free atmosphere for the detection of climate changes. The GUAN also provides a mechanism for continued quality control and assessment of the record from the full radiosonde network. However, according to the statistics from the network monitoring centres, the performance of nearly one third of the GUAN network has been poor, with failures to take and/or report observations, especially in those regions with limited resources, thereby potentially biasing the information obtained from the network. In addition, instrumental and procedural changes undertaken without due regard for the GCOS Climate Monitoring Principles continue to compromise the homogeneity of records. The fundamental importance of the full operation of the baseline GUAN in monitoring the changes in profiles of air temperature, water vapour, and wind is reaffirmed.

FINDING: There remains a significant problem with the availability of data from up to one third of both the GUAN and full radiosonde network, especially in the tropics. These problems are occurring either because observations are not being taken due to a lack of resources, or because data are not being exchanged.

The GUAN stations alone provide a very coarse representation of the **temperature profile** of the atmosphere and must be complemented by observations from satellites and the full radiosonde network of some 900 stations to obtain a global distribution. The "satellite temperature record" derived from specific radiance channels from the satellite-based Microwave Sounding Units (MSU) provides near-global coverage but suffers from difficulties in merging records across satellites due to changes in microwave channels and instruments, and changes and precession of orbits (and the resulting times of observations). This remains an active research matter.

FINDING: Inadequately-documented radiosonde performance, changes in types of sondes, and lack of overlap during these changes damage the continuity of the record and severely limit the utility of these observations for climate purposes. Adoption of the GCOS Climate Monitoring Principles for all of the GUAN, and to the greatest extent possible for the full radiosonde network, should be a high priority for the Parties.

FINDING: In order to continue the historical microwave radiance record, there is a need for homogeneous and continuous monitoring of specific radiances by satellite, with increased attention to the calibration of instrument and orbital characteristics.

Stratospheric temperatures respond to changes in ozone and carbon dioxide as well as natural variability associated with changes in water vapour, solar cycles and the quasi-biennial oscillation, for instance. Observations of recent large changes in the stratosphere have highlighted the need for continuing existing *in situ* and satellite observations in addition to further improvements. Substantial advances have been made in satellite soundings using microwave and infrared radiances, with increased spectral and spatial resolution, and improved methods of cloud clearing. These are especially useful for improving the analyses of upper-atmospheric temperature and water vapour. Experimental satellite results suggest that potentially very useful global estimates of the temperature profile in the upper troposphere and lower stratosphere are being obtained through the use of GPS receivers on polar-orbiting satellites. These retrievals measure a time-delay, due to refraction in the atmosphere, of an occultation, and hence have potentially higher accuracy and resolution than direct measurements of radiances. Although also potentially useful at lower levels in the atmosphere, the refractive index includes components from both temperature and water vapour, and hence is useful in data assimilation or as a combined index.

FINDING: GPS occultation measurements provide a promising new technology to retrieve profiles of atmospheric refractive index. GPS receivers could be incorporated on operational meteorological satellites to provide useful temperature estimates in the upper-troposphere and stratosphere.

The **larger radiosonde network** is also important in determining winds within the atmosphere. The number of daily soundings has declined by about 20% in the past decade alone. Tracking of sondes using GPS has led to improved accuracy of winds but at greater cost per sonde. Increased soundings from aircraft as they take off and land helps in some areas, but these are much less suitable for most climate purposes due to the limited heights that aircraft fly and lack of balanced geographical representation. Satellite-tracked cloud wind observations provide global coverage of winds at a few levels but inaccuracies continue to exist in the determinations of wind heights. There is also a lack of the consistency required for climate studies because of changes in computational methods.

For **water vapour**, radiosondes are generally not responsive at low temperatures (below about -20°C), thus limiting their accuracy, particularly in the upper troposphere. Therefore, the best prospects for future observations of the upper troposphere and for reconstruction of the recent past appear to come from reprocessing of satellite water vapour channels, and through four-dimensional data assimilation and re-analysis. The one single reliable record of upper-tropospheric and stratospheric water vapour (from Boulder, Colorado) is invaluable, but should be supplemented with a few other records around the globe, in particular a site in both the tropics and southern hemisphere, to create a reference network.

FINDING: A few reference sites should be established in key regions to provide high-quality upper-tropospheric and stratospheric observations of temperature and water vapour profiles based upon protocols used at Boulder, USA.

Over the oceans, passive microwave measurements provide measurement of **total column water vapour**. Comparable data over the land would aid water vapour analysis. In recent years, a number of countries have demonstrated the value of estimates of column water vapour derived from ground-based GPS receivers, but there is no international protocol for exchanging and archiving these data. Through international cooperation, these measurements should be extended across all land areas and the data should be freely exchanged and archived in international data centres.

FINDING: The column water vapour observations over land from ground-based GPS receivers should be exploited globally through international coordination.

Changes in cloud are the single biggest source of uncertainty in the sensitivity of climate models to changing greenhouse gases. There is an urgent need to better observe, understand and replicate in models all aspects of clouds, including their geographical coverage and distribution with height, their radiative properties, their ice and liquid water contents and particle sizes, as well as the role of aerosols in influencing these properties. Satellite-borne instruments have been used to measure radiation from the atmosphere and the International Satellite Cloud Climatology Project (ISCCP) has estimated cloud top height, optical thickness and other characteristics of clouds, but changes in satellites, instruments and channels, have led to discontinuities in the records. More advanced retrieval techniques are being explored on research satellites and are required to determine unambiguously the physical properties of clouds mentioned above.

FINDING: Clouds and water vapour provide the strongest and most uncertain feedbacks in the climate system. Priority should be given to the development of an effective strategy for monitoring these variables.

The **Earth Radiation Budget** (ERB) describes the overall balance between the incoming energy from the Sun and the outgoing thermal (longwave) and reflected (shortwave) energy from the Earth at the top of the atmosphere. It can only be measured from space. Because the stability of the instruments employed is often greater than the accuracy of the absolute calibration, it is vital to have overlapping records from instruments on different satellites in order to create a continuous time series with the highest relative accuracy. As a result, it is essential that there be no gap in the satellite programme for making these measurements. Continuous measurements with high spectral resolution, and with adequate spatial and temporal sampling, are needed to detect decadal changes in the spectrum of the greenhouse effect. This would facilitate the detection and attribution of the physical variables responsible for the changes.

FINDING: Satellite observation of the ERB must be continued without interruption and with strict adherence to the GCOS Climate Monitoring Principles. Measurements of solar irradiance as well as upwelling radiation are required. Continuous measurements with high spectral resolution, and with adequate spatial and temporal sampling, are needed to understand changes.

6.1.2 Adequacy of the Atmospheric Networks to Monitor the Forcing of the Climate System, Including Both Natural and Anthropogenic Contributions

The **monitoring of the forcing** of climate involves variables from natural sources including solar irradiance and volcanic aerosols. It also includes those anthropogenically-influenced atmospheric components of aerosols and the greenhouse gases including carbon dioxide, methane, ozone and other long-lived greenhouse gases[13]. The GAW currently has a network for determining the long-term trends in the meridional distribution of non-reactive greenhouse gases. Currently, the GAW participants are enhancing the network to determine the global distribution of these non-reactive greenhouse gases and to include the monitoring of certain short-lived greenhouse gases and aerosols.

Carbon dioxide is the most important of the greenhouse gases emitted by anthropogenic activities, and is currently monitored at about 100 ground-based sampling sites and 22 continuous monitoring stations around the world as part of the GAW. The adequacy and consistency of the measurements from a climate perspective can only be guaranteed through strict adherence to calibration and intercomparison protocols. For methane and CFCs, there are some outstanding issues in the development of calibration standards, which are currently being addressed by GAW and its partners. Satellite-based measurements of greenhouse gases will progress with the launch of new sensors that are in the research and development phase.

There is significant interest in the links between the **surface sources and sinks of greenhouse gases** and their influences on atmospheric concentrations. Therefore, there is a need to monitor the detailed regional and temporal distribution of the atmospheric concentrations of greenhouse gases, especially over the continents. This need can be met in part by expanding the coverage and capabilities of the continuous monitoring undertaken as part of the GAW global network and through atmospheric re-analysis that includes both *in situ* and satellite-based measurements of the various greenhouse gases.

FINDING: Continuous and homogeneous observations should be made of the spatial and temporal distribution of greenhouse gases including carbon dioxide to help determine sources and sinks. This should be accomplished through the continued support of current stations, the enhancement of the GAW global network in selected regions, and the advancement of appropriate satellite observations. These capabilities should be fully exploited by the development and implementation of atmospheric composition real-time analysis and re-analysis products.

Ozone is a key greenhouse gas, and also plays a role in filtering UV radiation from the sun. The monitoring of ozone depends upon complementary data from satellite and ground-based measurements. Although there has been substantial progress in the southern hemisphere subtropics, the *in situ* measurements are not well distributed and there are too few systematic measurements of the vertical

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[13] Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

profile of ozone from sondes. In addition, support for routine calibration and intercomparison of instruments is needed.

FINDING: There is a need for improved distribution and calibration of ground-based observations to support the use of satellite data for global monitoring of ozone.

Aerosols in the atmosphere have a significant influence on atmospheric temperatures. Measurements of surface and upper-air temperature following the Mount Pinatubo eruption in 1991 identified a warming in the stratosphere and a global cooling at the surface that lasted for about two years. The IPCC identified anthropogenic aerosols as the most uncertain climate forcing constituent. It is important to be able to track man-made and natural events and to characterize the nature and radiative properties of the associated aerosol. Anthropogenic emissions leading to aerosols strongly influence climate forcing, especially at the regional level. Aerosols including those from desert dust, soil dust, sea salt and biomass burning are also important on regional and global scales.

Comprehensive measurements of aerosols are available at a very limited number of sites, reflecting the difficulty in developing an effective and feasible observing strategy. The most extensive observation for aerosols is the optical depth measured by satellite and ground-based instruments. The latter are coordinated in part by GAW and its partners, including NASA/AERONET. In addition, routine vertical profiling of scattering from ground and satellite LIDARS is under development, as are more advanced satellite aerosol sensors. More measurements from aircraft and ground stations are needed. A concerted effort to integrate the available satellite and ground-based measurements of aerosol optical properties and to expand the above measurements has begun and is an important step in developing a system for global aerosol monitoring. The development and generation of consistent products combining the various sources of data are again essential. Furthermore, the physical and chemical composition of aerosols needs to be routinely monitored at a selected number of globally-distributed surface sites. Finally there should be a re-processing of past satellite observations using better calibration, cloud screening and aerosol microphysics to obtain a historical record.

FINDING: GAW, its partners (including the Space Agencies) and GCOS need to consolidate baseline measurements and further develop a strategy for obtaining continuous homogeneous observations to characterize the nature and radiative properties of aerosols.

6.1.3 Adequacy of the Atmospheric Networks to Support the Attribution of the Causes of Climate Change

Attribution is a process in which observed changes in the climate state variables are related to the climate forcing. Fundamentally, this is a problem of sorting out a known or suspected signal from the noise of natural variability. High-quality data on the forcing and variability of global climate are required for comparison with model simulations. In some cases this process involves numerical experiments to identify a "fingerprint" of the response to anthropogenic forcing in the climate state variables. Analysis of attribution has to date been limited by many factors, including uncertainties in anthropogenic aerosol forcing. Further uncertainties are due to the quality and relatively short length of the record of natural forcing, such as volcanic aerosol and solar irradiance. Also needed is a reliable estimate of natural variability on multiple time scales.

Paleoclimate data are used to estimate the forcings and variability that existed in earlier times. The emphasis should be on highly-resolved (better than annual where possible) reconstructions over the last two millennia in order to be able to address synchronicity of records and establish absolute time sequences that can be synthesized regionally and globally. For forcings, improved estimates are needed of the Total Solar Irradiance (TSI) and extent and radiative effects of aerosols from historic volcanic eruptions. It is highly desirable that models develop diagnostics, such as $\delta^{18}O$ from rainfall, for direct comparison with proxy records.

FINDING: Improved estimates of climate forcings and natural variability on multiple time scales based on the instrumental and paleoclimate reconstructions are needed.

6.1.4 Adequacy of the Atmospheric Networks to Support the Prediction of Future Changes of the Climate System

Previously, most **projections of future climate** have been based solely upon scenarios of future forcing fields, without concern about the current state of the climate system. However, projections on time scales of a few years to perhaps decades should also account properly for the initial state in order to generate ensembles of predictions. Therefore the accuracy of future predictions of climate change depends on the quality of the data used to develop and initialize the models; these data are the product of the networks described in the preceding sections. Projection of future climate change is also dependent upon the accuracy of the estimates of future forcing fields, including greenhouse gases and solar irradiance. For the most part these are not predictable and hence scenarios of possible and likely outcomes are constructed to allow model projections to be made. Improved historical data on these forcings and their causes are required in order to improve our capability to estimate future forcing scenarios. Owing to increases in greenhouse gases, the climate system is responding to a radiative imbalance at the top-of-atmosphere. Hence model predictions should take advantage of the existing information on the past and current forcings. Finally, the development of climate models requires specialized data sets acquired through limited-duration field campaigns (or process studies) conducted by the research community.

FINDING: There is a need for observations from specialized research studies to support improved understanding of processes and the development of models used for climate simulation and prediction. This is in addition to the need for on-going systematic observations of the climate system outlined in this Report.

6.1.5 Adequacy of the Atmospheric Networks to Project Global Climate Change Information Down to Regional and National Scales

All of the atmospheric variables described in preceding sections are also required for regional- and national-scale projections of climate. The key difference is that they are required at a much finer physical scale or resolution. The higher-density data enable the development of statistical relations for use with downscaling from global and/or regional model projections. However, for many regions of the world, an adequate past observational record does not exist, and prospects for improving observational coverage in the near future may be limited in most countries by the lack of adequate resources for observational systems.

FINDING: Many nations require additional financial resources to conduct observing programmes at the scale required for the development of statistical relations for use with downscaling from global and/or regional model projections.

6.1.6 Adequacy of the Atmospheric Networks to Characterize Extreme Events Important in Impact Assessment and Adaptation, and to Assess Risk and Vulnerability

The comments and findings of the preceding section are directly relevant to this goal but the emphasis on **extreme events** means that the data are required at a much finer temporal resolution. Even when the necessary daily or hourly observations are made at the local level they are often not exchanged or made available internationally for use in impact studies.

FINDING: Studies on regional impacts of, and vulnerability to, climate change, especially changes in extreme events require national and regional climate observing networks at a finer scale, in addition to the GCOS baseline networks. When requested for the purposes of impact studies and extreme events, daily and/or hourly observations of the climate variables should be provided to the appropriate international data centre.

There have been some coordinated efforts at the regional level involving developing countries to collate and **analyze the key variables** of precipitation, temperature and pressure for the development of trends in extreme climate events. However, there has been little analysis of surface water vapour, wind and radiation. It should be emphasized that there are not even well-defined baseline systems for these variables on a global scale.

The **lack of high-quality daily climate data** in many regions means that we cannot adequately characterize the regional nature of major flood and drought events. When smaller-scale but equally devastating events such as tornadoes, tropical storms and hailstorms are considered, there is a lack of consistency in the relatively few observations taken in different parts of the world. It is clear that a major and coordinated effort is required to establish the systems for monitoring extreme climate events in the future. These efforts are at a scale not currently addressed by the global observing systems for climate. Careful analysis of historical data and the experience of GCOS could provide guidance on the establishment of these systems, in addition to providing information on the past record of extreme events.

6.2 Ocean Networks

It has now been demonstrated that we can effectively observe climate changes in the ocean at global scales. Since the preparation of the First Adequacy Report the design of an initial ocean component of the global climate observing system has been agreed. The WMO and the IOC have established the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) to oversee implementation of most aspects of the ocean observing system for climate. In addition, the IGOS-Partners have adopted strategic guidance for an integrated approach to the provision of ocean observations following the preparation of the “Ocean Theme” Report. Despite this significant progress, ocean networks are not yet adequate to meet the specific needs of the UNFCCC for most variables and in most regions of the planet (and are particularly lacking in the southern hemisphere).

6.2.1 Adequacy of the Ocean Networks for Characterizing the State of the Global Climate System and its Variability

Historical data records suggest that the ocean is changing in ways that are broadly consistent with anthropogenic forcing. However, long regional records are few and global records are short, making interpretation difficult. There is so much variability in the ocean, ranging from the daily cycle and mesoscale eddies and storm-forced events to interannual events and decadal cycles (e.g., El Niño, the North Atlantic Oscillation and the Pacific Decadal Oscillation), that detection of climate change is a significant challenge. The shallow and shelf seas, which are the places where ocean climate change is directly felt by society, are even more difficult to observe than the open ocean. With few exceptions, existing observing efforts cannot provide data to adequately evaluate the skill of model climate change projections across the range of relevant questions.

In view of the wide variation in space and time scales, the community has agreed that an integrated, composite approach is necessary. The agreed initial ocean climate observing system recommendations include baseline and reference networks that enhance the comprehensive, global networks. They call for sustained support for existing proven activities, for enhancements of these to attain truly global coverage and for research efforts to develop new technologies and to guide the evolution of the initial system.

FINDING: The feasibility of observing climate changes in the global ocean has been demonstrated. Since the First Adequacy Report the ocean community has reached agreement on an initial integrated and composite system, developed new technologies, has established mechanisms to foster more effective international collaboration (including the JCOMM) and has begun the demonstration of community capability to generate ocean climate products (e.g., Global Ocean Data Assimilation Experiment (GODAE)).

The **initial composite system** is based on both surface and sub-surface networks. The surface network depends on satellite observations of several key variables together with accurate, globally-implemented *in situ* observations from a mix of sensors and platforms. *In situ* data provide essential satellite calibration information, accurate time series and an effective link with the historical record. For many of the variables of interest to the Parties they are the only source of information. The sub-surface network depends primarily on a mix of *in situ* observations but makes use of some satellite information. The mix and distribution of sensors will change over time as our knowledge and technology improve.

It has also been recognized that relatively long-term operation of some components of the observing system by the research community will be required. Support for research is required to develop the technologies needed to obtain sustained climate quality observations, to develop efficient and effective observing strategies, and to guide the overall evolution of the observing system. Pilot projects have been agreed as an appropriate approach to demonstrate effectiveness of new techniques. The community consensus includes agreement on an orderly staged approach from research to pilot projects on to sustained operations. This approach assumes that elements at present in need of research operation will become sufficiently robust to be transferred to operational entities. Successful operational implementation of the initial system will depend on sustained funding, on effective interaction with the research community and responsive management, to ensure that the quality of the products is maintained and that research can continue to improve the observing system.

FINDING: Research programmes are the primary source of funding for many elements of the present ocean climate observing system. Continuing strong involvement of the research community is needed. An orderly process to bring new technology into pilot project use and then sustained use in the ocean climate observing system has been agreed. Institutional encouragement and financial support is needed to ensure that this process results in the sustained operation of the agreed initial system.

6.2.1(a) Surface Ocean Networks

The **key variables** required to characterize the state of the climate and its variability at the ocean-surface are sea-surface temperature (SST), salinity, atmospheric pressure, winds, sea level, sea state, sea ice, ocean currents, and ocean colour (for biological productivity), as well as the air/sea exchange of water (precipitation, evaporation), momentum (wind stress), heat and gases, especially CO_2. Routine generation of global analyses as well as evaluation of key indices from these variables is required to meet the needs of the Parties.

The **surface ocean networks** for these variables consist of satellites and *in situ* observational components. Satellites can provide near-global coverage of SST, wind, sea level (from surface topography and gravity measurements), significant wave height and other sea-state characteristics, sea-ice extent and concentration and ocean colour. While both operational and research satellites provide valuable data sets for many of these parameters for climate purposes, environmental constraints and operating practices have to-date limited the accuracy, coverage, and homogeneity of a few of these data sets.

For **air-sea interaction variables**, the *in situ* observing system is comprised of the VOS network, surface buoys (moored and drifting) and various efforts within research programmes. The data produced are not all of the desired climate quality, are not fully homogeneous because of changes in location and measurement technology, and coverage varies because of logistical considerations and with the changing patterns of global shipping traffic. The participation of at least 200 merchant vessels in the VOSClim project is needed to improve the surface observations.

There has been good progress since the First Adequacy Report in developing *in situ* autonomous technology to provide high-quality surface data for some variables (e.g., temperature and pressure from drifting buoys). This approach has considerable benefits in terms of sampling in remote regions and cost effectiveness. In terms of the highest priority fields, the present network represents only around 50% of the full requirement, mostly because of weaknesses in coverage. In addition to the challenge of global coverage, there are challenges to develop robust and effective autonomous approaches for other key fields.

FINDING: The absence of global coverage and the lack of sufficient high-quality observations of the key variables remain the key weaknesses in the surface ocean network. For a few variables,

such as sea-surface temperature and mean sea-level pressure, cost-effective technologies are available to address this weakness. For other variables, considerable research and development are required.

Climate products depend critically on both *in situ* and satellite data inputs. However, only a few of the necessary *in situ* time-series stations, essential for eliminating biases and for trend identification in the satellite data, are in place. These are particularly critical for biogeochemical and air-sea flux products. Such products are also dependent on the development and application of new analysis techniques, including data assimilation, in order to make best use of each source of data.

FINDING: A sparse global array of surface reference moorings (29) can provide essential air-sea flux information for testing models and the evaluation of climate change projections. It also can provide needed platforms for development of new observing system sensors.

Sea-Surface Temperature (SST) is a primary variable and the challenges of its global characterization, to climate standards, illustrate the need for composite ocean surface networks. Near-global coverage of SST is provided by operational satellite sensors, but the utility of these data for climate is compromised by operational and environmental factors (e.g., clouds obscure the surface and bias retrievals; aerosols bias retrievals; sensor calibration) and the skin temperature sensed remotely is different from the near-surface (‘bulk’) temperature that comprises the historical record. Quality surface bulk temperature observations are needed to correct remotely sensed temperatures and maintain continuity with the historical record. Along the shipping lanes, VOS could provide the needed bulk data but too often their data are not of climate quality. Away from shipping lanes, surface drifters are the essential technology for global coverage and also can provide climate quality data. Observations from moorings provide the highest quality data and are the only source of data adequate for the detection of small long-term trends. Microwave measurements have provided an important new data stream, avoiding the problems associated with clouds and producing experimental products useful for climate. Thus climate quality analyses of SST require the global implementation of high accuracy *in situ* observing activities integrated with and complementing the operation of satellite sensors to climate standards.

FINDING: At present levels of coverage and operations, global analyses of SST are not adequate to meet all of the needs of the UNFCCC. However, global climate-accuracy SST analysis is achievable through enhanced global deployment of existing technology (1,250 surface drifters and 119 tropical moorings), with more than 200 ships participating in the VOSClim project and the improved operation of satellite sensors.

Ocean surface wind is a key variable for many ocean climate purposes. It is discussed in the atmospheric domain section (see Section 6.1.1(a)).

Sea-Surface Salinity (SSS) is important because it provides insight into changes in the planetary hydrological cycle, influences upper-ocean mixing (of heat and gases) and, in some regions, controls the formation of intermediate, deep and bottom waters. At present, climate-accuracy SSS measurements are obtained primarily through hydrographic survey efforts and some VOS and can meet only part of the requirements. Autonomous technology has been used on VOS and moorings, but accuracy between calibrations remains challenging. Microwave sensing of large amplitude SSS variability has been proven in concept, and several research satellite missions (e.g., SMOS and Aquarius) are planned in the next decade.

FINDING: At present, global knowledge of SSS is not adequate. Improvement in SSS analysis accuracy is limited by available technology. New satellite sensors hold promise of improved global coverage, although special *in situ* observing efforts will be needed to evaluate sustained sensor performance.

Sea-ice measurements are frequently made on the basis of specific research requirements. JCOMM does include a sea-ice activity focused on services but these are mainly focused on analyses and short-term forecasts of sea-ice conditions and not on the factors that are important for climate, such as sea-ice volume. Programmes such as the International Arctic Buoy Programme and the International Programme for Antarctic Buoys are primarily self-supporting research programmes. Sea-ice thickness measurements with upward looking sonar (ULS) are also carried out on a research basis, with the first formal grouping of ULS operators only now being discussed as part of the WCRP-CLIC project. Remote sensing provides routine estimates of sea-ice extent and coverage but there remain several uncertainties, particularly with relation to climate.

FINDING: Knowledge of sea-ice changes is not adequate. A sea-ice component of cryosphere research effort is ongoing. Recent satellite launches including ICESat, CryoSat and the AMSR-E instrument on Aqua will provide new remote ice measurements. *In situ* observing efforts and climate ice analysis and re-analysis are needed.

Sea level is important to all low-lying land regions including small-island states. Climate accuracy measurements are technically feasible and are made operationally in many locations. Global sea-level estimates are now being made by precision satellite altimetry missions, but require drift-correction with *in situ* gauges to obtain climate-accuracy. For climate change and long-term variability it is necessary to correct for land surface elevation changes. Geocentric location of water level gauges is possible via GPS or Doris techniques. In the absence of a commitment to sustained high-precision altimetry, a level of redundancy is required between the remote and *in situ* approaches.

FINDING: Present knowledge of global sea-level variability and change is not adequate. Monitoring of global sea level is technically feasible at present, but requires at minimum a global array of geocentrically-located high-accuracy water level gauges (86), continued operation of high-precision satellite altimetry and effective data exchange between nations.

There is great interest in changes in **ocean ecosystems**. At present only ocean colour observations can give any global insight into the variability of these systems. Remote sensing of ocean colour using satellites and airplanes is used to estimate surface chlorophyll (a proxy for phytoplankton biomass). While ocean colour satellite missions are planned for the next decade, in many regions we do not have a reliable way to relate ocean color even to chlorophyll-a. Improvements are needed and are in development within the research community. Enhanced sampling of surface-ocean colour variables from time-series stations and VOS lines could provide the high-quality data required for improvements.

FINDING: Knowledge of ocean ecosystem change is not adequate at present. Satellites provide global coverage of surface ocean colour, but the linkage between ocean colour and ecosystem variable remains limited. Research is underway to improve knowledge of the relationships between ocean colour and ecosystem variables, including chlorophyll-a. Enhanced *in situ* sampling of ocean colour and ecosystem variables is technically feasible.

6.2.1 (b) Sub-surface Ocean Networks

The **key variables** required to characterize the three-dimensional state of the climate of the oceans and their variability are temperature, salinity, ocean currents, ocean tracers, carbon, nutrients, and key ecosystem variables such as phytoplankton. Ocean dynamic-height, which is a derived quantity, and sea-level anomaly, which can be observed directly, are also important measures of the state of the sub-surface ocean circulation.

***In situ* networks** are the primary source for observations to fully characterize the three-dimensional structure of the ocean climate. Satellite altimetry indirectly gives important near-synoptic information on the spatial variability while satellite ocean colour data provides an indirect estimate of upper-ocean phytoplankton biomass.

Continuation of the **research vessel-based repeat section network** is required for measurement of full-depth ocean properties (temperature, salinity, carbon, nutrients and tracers). These observations, together with observations of boundary currents and overflows, are required for measuring variability and detecting any change in the global thermohaline circulation. There has been recent progress in international planning for repeat-survey work. Long-term commitment to a global survey programme is still inadequate.

The present logistical and technical difficulties of observing the deep ocean and its key climate variables most likely can be reduced via further technological innovation. Indirect acoustic methods and various semi-autonomous approaches, including underwater vehicles and new sensors, may offer solutions in the future.

FINDING: Measurements from the deep ocean are a critical contribution to characterizing ocean climate variability and change. At present the most effective approaches involve combinations of regular, deep ocean surveys and surface altimetry.

Repeat XBT lines provide characterization of important fine-scale ocean structures as well as heat and freshwater transports in the upper ocean. Time-series stations and moored buoy arrays provide critical characterization of the higher-frequency variability as well as opportunities to observe the co-variance of several of the key variables.

Recent technological developments (e.g., “Argo” floats) now permit global deployment of autonomous systems that will provide profiles of temperature and salinity in the upper ocean. Although substantial progress has been made, the global deployment remains incomplete and long-term commitments are still required.

All of the density data, together with accurate satellite and *in situ* sea-surface height information need to be assimilated to produce estimates of global sea-level variability and change.

FINDING: Systematic sampling of the global upper ocean is needed to fully characterize ocean climate variability. Global implementation of proven techniques remains to be accomplished. This will be addressed through implementation of the agreed upper-ocean network (specifically 3,000 Argo profiling floats, 41 repeat XBT lines, 29 surface reference moorings, 119 tropical surface moorings).

There are **many sources** of data from these networks, each with different error characteristics, as well as satellite data concerning surface variables. Therefore, the construction of ocean climate products should employ modern analysis techniques including multivariate ocean data assimilation. The current GODAE activity is an important pilot undertaking in this regard.

Efforts to develop **autonomous** monitoring systems for nutrients, carbon-system variables and other ecosystem variables are in their infancy. High-latitude monitoring systems are still in the research and development or pilot project stages.

In addition, the **shallow seas and coastal waters** that have shorter space and time scales pose particular technological challenges that require further research before full deployment.

6.2.2 Adequacy of the Ocean Networks to Monitor the Forcing of the Climate System, Including both Natural and Anthropogenic Contributions

The **oceans act as one of the important sinks** for atmospheric carbon dioxide. It is therefore essential to understand the process by which this occurs and to monitor carbon uptake by the oceans. The global ocean carbon survey of the 1990s has produced a baseline inventory of ocean carbon content (both natural and anthropogenic), and this inventory has proven to be a valuable input to understanding the present day global carbon budget. In addition, the development of realistic forcing scenarios for climate predictions requires an estimate of future ocean carbon uptake. A global network of carbon observations in the ocean interior is being developed based on a subset of the original global carbon survey lines, which will provide the data necessary to validate these estimates. Regular re-surveys will be conducted developed on this basis.

For shorter time scales and regional estimates of global carbon sources and sinks, the partial pressure of carbon dioxide at the surface (pCO_2) will make an important contribution. Present observational commitments are not sufficient for these purposes.

FINDING: Carbon cycle parameters should be measured at reference sites and full-depth carbon inventory surveys are needed to enable full interpretation of carbon cycle changes. Additional global pCO_2 measurements are required to document the decadal uptake by the oceans of anthropogenic CO_2. In addition to the full-depth surveys, present consensus requires implementation of 29 surface reference-moored buoys and at least 25 selected VOS. Further sensor development for autonomous pCO_2 and carbon system measurements is needed.

6.2.3 Adequacy of the Ocean Networks to Support the Attribution of the Causes of Climate Change

There are preliminary indications that **changes in heat content**, global patterns of temperature and salinity, global-average sea level, elements of the overturning circulation, and especially sea-ice extent are consistent with changes expected from climate change projections. A key issue is the rate of uptake of heat by the ocean in determining the response of the climate system to change. Considerable progress has been made on the basis of research observations with the largest uncertainties arising from inadequate global coverage and lack of reference sites and regularly repeated, high-quality measurements.

High-latitude regions pose particular difficulties due to the harsh environment and the presence of sea ice. Present autonomous technologies such as Argo floats are not suited to such regions. Such gaps in the ocean observational coverage are a concern because they introduce uncertainties when testing models and prevent a full understanding of ocean-ice interactions and detection of temperature and salinity changes. New technologies, including modified floats and acoustic techniques are being applied within research programmes. These considerations are also relevant to Section 6.2.1.

This foundation needs to be exploited through commitment to extensions of the instrumental record into the past, as well as future high-quality, comprehensive global networks. The commitment to global coverage is the most challenging and pressing need if we are to unambiguously attribute the causes of observed changes. Comprehensive global networks, including full depth trans-ocean sections, complemented by ocean baseline and reference measurements of full-depth ocean properties at time-series stations, time series of sea ice, and measurements of boundary currents and sill overflows are required.

FINDING: Proper attribution of the causes of ocean change requires a commitment to characterizing ocean variability (Section 6.2.1). Comprehensive and baseline networks, as well as reference stations can provide the needed information. Global coverage and long-term commitment are the most significant challenges.

6.2.4 Adequacy of the Ocean Networks to Provide the Observations Needed to Support the Prediction of Future Changes of the Climate System

The **Third Assessment Report** of the IPCC found that starting long coupled integrations from observations is important for a number of reasons, including simplification of the initialization procedure and reduction in the overhead for new coupled model integrations. In essence the impact is in the correction of systematic error and alleviation of drift rather than in the sense of initialization as used in weather prediction. There is no consensus as yet on the importance of initial conditions for forecasts or, perhaps more importantly, on the effect, if any, on model projections of uncertainty.

To the extent that the previous sub-sections have described the required comprehensive, baseline and reference networks, we have fully specified the data sets needed to support **climate change predictions**. For the products derived from the comprehensive system, the tests will usually be against derived products and not directly against the data, whereas the baseline and reference data will be suitable for direct comparisons. It will be important that analyses from related systems, such as operational ocean forecasts models and seasonal prediction ocean data assimilation systems are available to the climate change community. It is also important that climate change specific analyses, including those from ocean climate data assimilation models, be promoted. The need to validate the model representations of ocean processes is also critical, and this requires support for relevant process research.

Global ocean climatologies of temperature and salinity are the basic data set for model evaluation at present. Yet significant deficiencies limit their utility for regional evaluation and as initial conditions. The proposed enhancement to the observing system described above will permit the construction of dramatically better initial-condition and evaluation fields. These fields will be essential in the exploration of climate response to changing ocean conditions.

Confidence in the **regional aspects** of global projections of climate change is partly dependent on an evaluation of the skill of models to simulate observed ocean evolution on regional scales. Relevant regional data include observations of coastal sea level, sea-ice extent and coverage, temperature and boundary and coastal currents. It is important that model forecasts be evaluated against such observations. With few exceptions (see Section 6.2.3) we have inadequate data over most of the globe to evaluate model projections of changes in the global and regional ocean currents or heat transport and their exchange with the atmosphere and cryosphere. High-latitude waters and sea ice have been identified as particularly sensitive to climate change. Sea-ice extent, concentration and thickness data will thus be particularly helpful for testing climate model skill. Research remote-sensing instruments will provide valuable new information, but their observations must be compared and the results synthesized to provide better information about ice-volume changes.

FINDING: Ocean data and ocean climate analyses are important for supporting the testing of climate change models and evaluation of the ocean state/structure of predictions of future changes of the climate system. The global comprehensive networks together with baseline and reference networks as described previously can provide the needed information, with particular emphasis on three-dimensional analyses and climatologies and time series.

6.2.5 Adequacy of the Ocean Networks to Project Climate Change Information Down to Regional and National Scales

The **shelf and coastal seas** have smaller space and time scales than the deep-ocean. They respond to offshore (open-ocean) conditions, atmospheric conditions and to terrestrial inputs. Estimates of regional marine impacts of climate change in the shelf and coastal seas (e.g., coastal flooding associated with storm surges, ecosystem changes) will be dependent on information about the open-ocean to give the broader context, as well as on regional data sets and robust dynamical (or perhaps in some cases statistical) models. Only a few regions in the world have appropriate shelf- and coastal-seas observing systems.

Present regional projections of sea-level-rise patterns differ substantially among models. However, we do not have sufficient time series of global sea level either from satellite or *in situ* observations (see Section 6.2.1(a)) to evaluate the different model patterns and thus to estimate regional impacts.

Present models for projecting climate change information down to regional and national scales do not have strong dependencies upon the ocean network, except for sea-surface temperature. In the future we anticipate increased use of ocean models (and hence the need for data) as regional projections include the ocean domain and begin to address coastal issues. At present, the latter is done mostly through storm surge models.

6.2.6 Adequacy of the Ocean Networks to Characterize Extreme Events Important in Impact Assessment and Adaptation, and to Assess Risk and Vulnerability

The risk of damage from **extreme sea-level events** (storm surges) will change as a result of changing mean sea-level and/or changing meteorological forcing. Evaluating the frequency/intensity of such events requires high-frequency tide gauge data. These data exist for many, but not all, regions. However, many of the necessary data have not been submitted to international archives to allow regional assessments to be completed. In regions with very limited data, enhancements to the Global Sea level Observing System (GLOSS) network are required.

FINDING: Adequately characterizing extreme regional sea-level events requires that high frequency sea-level observations need to be taken and exchanged and historical data from tide gauges need to be provided to the international data centres. Capacity-building efforts in developing countries for undertaking local sea-level-change measurements can benefit the global system and foster needed regional enhancement.

There are other **extreme ocean events** that have been documented and attributed to natural variability that may have different manifestations under climate change. These include changes in sea temperature, changes in sea-ice extent and concentration, freshening and/or other effects resulting in abrupt changes in regional upwelling, among other things.

Ecosystem vulnerabilities to climate change, particularly extreme conditions, may be considerable, but data from previous periods are not adequate to provide projections of likely impacts. The coastal module of GOOS is developing standards, practices and recommendations for national and regional coastal networks.

FINDING: Obtaining full national and regional benefit from GCOS efforts will depend on the development of integrated regional and national observing systems and special products for shallow sea and coastal waters. National and regional participation in the GOOS Coastal Module provides one framework for coordinated development and operation of observing efforts in national waters.

6.3 Terrestrial Networks

The Terrestrial Observation Panel for Climate[14] has identified the need for observation of over 80 terrestrial variables to fully characterize the climate system. Descriptions of these can be found on the GCOS and GTOS web sites. At present, technical, economic and logistical (e.g., physical access) constraints make measurement of all these variables in baseline or comprehensive global networks impossible.

Many organizations make terrestrial observations, for a wide range of purposes. Various different measurement protocols are used, even for the same variable. The resulting lack of homogeneous observations limits our capacity to monitor the terrestrial changes relevant to climate and to investigate the causes of observed land-surface changes. Data are collected and/or processed by different organizations, leading to duplication of effort. Some duplication may be desirable as redundancy helps to guarantee the continuous availability of the required variables and allows cross-validation. Coordination among organizations and benchmarking of products are clearly needed to ensure unbroken homogeneous records are available.

FINDING: There is a requirement for the establishment of an international mechanism that would prepare and issue regulatory and guidance material relating to terrestrial observing systems and management of their data and associated products.

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[14] Jointly sponsored by GCOS and GTOS.

Though the terrestrial networks (other than those operating as part of the GSN) are the **least integrated component of the global climate observing system**, some progress is being made. Infrastructure to coordinate collection of data for key *in situ* variables is being developed and the Space Agencies now provide observations for some variables on an increasingly routine basis. Of the 80+ variables required, river discharge, water use, ground water, lake levels, snow-cover, glaciers and ice caps, permafrost and seasonally frozen ground, albedo, land cover, Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), Leaf Area Index (LAI), biomass and fire disturbance have been highlighted for early implementation because they are important to the UNFCCC, the technology to make adequate measurements is by-and-large proven, and an infrastructure exists that could provide the measurements operationally. The importance of the other 70-or-so variables, including soil physical properties, soil moisture and process-related CO_2 and water flux is recognized. Reference sites measuring such variables (e.g., FLUXNET) need to be sustained and strengthened, with a view to incorporating some of these additional variables into the Global Climate Observing System. For the terrestrial domain, in many cases there is no clear distinction between variables characterizing the state of the global climate system and those forcing the system. The division of variables among the following sections is therefore somewhat arbitrary.

6.3.1 Adequacy of the Terrestrial Networks for Characterizing the State of The Global Climate System and its Variability

Our capacities for global measurement of key variables describing fresh water in its liquid phase, such as river discharge, lakes, reservoirs and wetlands, groundwater and water use, are currently limited. Yet uncertainties in terrestrial water budgets were found by IPCC to be the largest uncertainty in understanding twentieth century sea-level rise.

River discharge is a highly-sensitive component of the water cycle. It is the only hydrological variable that integrates over a large area, i.e., the river basin. This makes river-discharge measurements particularly important for parameterizations used in global climate models, as these are currently unable to model the full details of the hydrology.

The volume of water in surface-storage units **(lakes, reservoirs and wetlands**) reflects both atmospheric (precipitation, evaporation-energy) and hydrological conditions (surface-water recharge, discharge and ground-water tables). If climate changes, then lakes and wetlands will reflect this promptly.

Approximately 30% of liquid fresh water occurs as **ground water**. Both recharge and discharge rates are affected by climate. Depletion of aquifers (ground-water mining) occurs where withdrawals exceed recharge. Use of groundwater for irrigation may change the regional water balance.

Despite the fact that approximately 85% of fresh water use goes for **irrigation**, and demand will increase as population grows, there are no global networks monitoring this important variable. Irrigation affects the climate system by changing regional water balances through increasing evapotranspiration, reducing river discharge, and changing land-surface variables such as albedo.

Many countries run national or regional observation programmes for river discharge, lakes, reservoirs and wetlands, groundwater and water use, yet this information is not exchanged because of the perceived (or real) commercial/security value of the data. Data are managed in a decentralized manner (e.g., river basins, federal states), in different sectors (e.g., water supply, energy generation) and stored in different computer systems. National data policies can restrict dissemination to international data centres. Observations in some parts of the world are declining, particularly in developing countries. The World Hydrological Cycle Observing System (WHYCOS), a capacity-building activity aimed at "bottom-up" implementation in developing countries, is attempting to reverse the decline. A new GCOS/GTOS Global Terrestrial Network for Hydrology (GTN-H) is designed to improve access to existing data and networks, and to provide coordination of near-real-time data collection. Only one component of GTN-H dealing with liquid fresh water is currently in place: the Global Runoff Data Centre (GRDC) in Germany, though the Netherlands government is considering the establishment of an International

Groundwater Resources Assessment Centre (IGRAC) and the State Hydrological Institute of St. Petersburg is proposing a global database on lakes and reservoirs.

FINDING: The Parties need to provide the observations identified by the GTN–H, in particular those on river discharge, lakes, reservoirs and wetlands, and groundwater, to the associated international data centres. In spite of repeated calls by the international community for free and unrestricted exchange of hydrological data, this still does not happen.

Snow is a key component of land-surface processes at higher latitudes and altitudes. It affects surface albedo and energy balance at global and regional scales, the mass-balance of glaciers, ice sheets and sea ice, governs freezing and thawing of the ground and affects soil moisture and runoff, thereby influencing water resources and plant growth.

Observations are obtained from *in situ* measurements and satellite mapping; these include extent, depth, and water-equivalent of the snow-cover. Snow-water-equivalent products derived from satellite data extending over some 25 years are available. *In situ* snow-cover data are collected by numerous agencies with differing goals; for example, snow depth is measured once daily at weather stations, though no central archive embracing all snow-cover observations exists. The high cost of maintaining surface networks is leading to their contraction and/or switching to automated measurement using different instrumentation. Satellite monitoring provides snow-cover extent at weekly intervals for the northern hemisphere and daily snow-cover extent for many countries.

FINDING: The contraction of *in situ* observations should be halted and there is an urgent need to develop optimal procedures to blend surface observations of snow with visible and microwave satellite data and related airborne measurements.

Glaciers and ice caps provide key variables for early detection of climate changes because their contraction indicates worldwide warming trends and historical-to-Holocene variability. Ice cap variables (movement of Antarctic ice streams, mass, area and thickness) are also needed to fully understand sea-level rises. Long-term mass-balance measurements provide direct signals of climate variability and change. They constitute the basis for developing coupled energy-balance/flow models for understanding complex feedback effects and for use in model validation. Satellite observations of polar ice caps, continental mountain glaciers and ice shelves are helping to establish the representativity of *in situ* measurements over time and provide a basis for regular inventory. Analysis of current and archived observations would provide trend information for the last two decades. Systematic *in situ* observations have been internationally coordinated for more than a century. The Global Terrestrial Network for Glaciers (GTN-G) is the coordinating body for these variables with data being analyzed and archived by the World Glacier Monitoring Service. The GTN-G reports that the number of *in situ* measurements is decreasing in Asia, the Americas and Africa and that the mass-balance network is deficient in the southern hemisphere, in arctic regions and in the high mountains of central Asia.

FINDING: Mass-balance measurements of glaciers and ice caps need to be re-initiated in Patagonia, New Zealand and Africa so that changing patterns can be monitored globally. Archived Earth observation data should be analyzed to determine trends over the last two decades. Observations should be provided to the World Glacier Monitoring Service.

The stability and distribution of **permafrost** depends on ground-surface temperature regimes. There is consistent evidence in the northern hemisphere of warming and thawing at the margins of the latitudinal and altitudinal limits of perennially-frozen ground. Variations in soil thaw and related soil moisture affect trace-gas emissions and sequestration as well as surface runoff. Heat-induced thaw penetration into the underlying ice-rich permafrost results in surface subsidence and accelerated erosion, thereby affecting infrastructure stability and water quality. Systematic climate-related permafrost monitoring is still being developed. The continuation of recently-established programmes and those that have been operating for a number of years is still uncertain, and no international resources are available for data management. In some instances data are withheld by the scientific community while awaiting formal publication. The

Global Terrestrial Network for Permafrost (GTN-P) provides coordination and has highlighted key measurement gaps.

FINDING: New temperature boreholes and *in situ* observations of active layer thickness need to be established in both hemispheres by the Parties at sites identified by the Permafrost Network with the observations provided to the Network's international data centre.

6.3.2 Adequacy of the Terrestrial Networks to Monitor the Forcing of the Climate System, Including both Natural and Anthropogenic Contributions

Surface **albedo** is both a forcing variable controlling the climate and a sensitive indicator of environmental degradation. Albedo varies in space and time as a result of both natural processes (e.g., changes in solar position, snowfall and vegetation growth) and human activities (e.g., forestry and agriculture).

Accurate estimates of land-surface albedo require simultaneous measurements of the spectral reflectance from a variety of directions. A very limited number of instruments have this capability. Daily-average surface albedo values have been derived experimentally from a single geostationary satellite, but could be obtained from all the current geostationary platforms to give near-global coverage. In addition, archived data from these instruments could be used to document the evolution of albedo during the last two decades. Mono-angular[15] multi-spectral sensors on polar-orbiting platforms usefully complement this potential monitoring system by providing better coverage of polar regions (especially important during summer). The accuracy of the estimates needs to be assessed, as they often rely on the accumulation of data over 2 weeks or more, during which atmospheric conditions may vary considerably.

Significant improvements in the accuracy and availability of land-surface albedo products can be expected from the synergistic use of sensors, though research is needed to resolve differences among the performance of various sensors, orbital characteristics, and differences among retrieval algorithms.

FINDING: There is a need to: (1) establish a benchmark for assessing land-surface albedo products, and (2) implement a system to retrieve land-surface albedo from existing geostationary platforms on a daily and global basis.

FINDING: Archived data from geostationary platforms should be reprocessed to form a global climatology of albedo for the entire period of available measurements.

Land cover describes the distribution of vegetation types and human use of the land for living space, agriculture and forestry. Natural vegetation distributions are in large part determined by regional climate, and their changes provide a way to monitor climate change. The spatial pattern of land cover is also critical information for determining the capacity of biodiversity to adapt to climate change. Land-cover changes also occur in response to changes in weather patterns and changes in land management/land use (e.g., conversion of forest to pasture or cropland). Changes in land cover force climate by modifying water and energy exchanges with the atmosphere, and by changing greenhouse gas and aerosol sources and sinks. Many climatically-relevant variables that are difficult to measure at a global scale (e.g., surface roughness) can be inferred reasonably well from vegetation type. Thus land cover can be a surrogate for other important climate variables.

Although land-cover change can be measured using data from Earth observation satellites, the currently available global land-cover data sets vary significantly, are of uncertain accuracy and use different land-cover-type characterization systems. Data are also provided from different sources and at different spatial resolutions. Whilst the efforts of some Space Agencies and other entities to produce global land-cover products are important steps towards more adequate measurement of this important variable, the lack of compatibility between the products means that there are significant difficulties in using them to measure and monitor climate-induced or anthropogenic changes in land cover.

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[15] Instruments that only provide a single-view angle for each pixel.

FINDING: An international body should advise on standards for the production of land-cover maps, specifically in terms of the resolution and land-type characterization to be employed.

FINDING: Existing land-cover data should be analyzed and/or reprocessed, wherever possible, to ensure the compatibility of maps produced for the last decade. New land-cover maps should be produced every five years.

FINDING: Historical land-use data sets could be significantly improved if more and better-documented inventory data sets were made available.

L**and cover** can change dramatically in a matter of days (loss of forest due to fire for example, or agricultural expansion) though change is more usually apparent on time scales of years. Vegetation has its own dynamics; the diurnal cycle of plant photosynthesis and respiration, growth, and differentiation with the seasons. Our capacity to monitor key variables quantifying these dynamics (Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), Leaf Area Index (LAI) and biomass) is improving.

FAPAR is a primary variable controlling the photosynthetic activity of plants, and therefore an indicator of the presence and productivity of vegetation and the intensity of the terrestrial carbon sink. FAPAR varies in space and time due to differences between species and ecosystems, weather and climate processes, and human activities. It is a key variable in the carbon cycle and thus in the assessment of greenhouse-gas forcing. Spatially-detailed descriptions of FAPAR provide information about carbon sinks and can help to verify the effectiveness of the Kyoto Protocol’s flexible-implementation mechanisms. Changes in FAPAR are also an indicator of desertification and the productivity of agricultural, forest and natural ecosystems.

FAPAR is not directly measurable, but is inferred from models describing the transfer of solar radiation in plant canopies, using remote-sensing observations as constraints. The generation of FAPAR products from space measurements has just commenced on a regular basis. Evaluation of the algorithms and products has started but requires more effort.

The amount of leaf material in an ecosystem is an important variable used in vegetation models (including those coupled to climate models), and is described by the LAI. LAI can be estimated by *in situ* measurements, while the retrieval of accurate estimates of LAI from space measurements is difficult. When the canopy cover is sparse, reflectance measurements are dominated by soil properties and the accuracy of the LAI is rather low. The regular production of global LAI estimates from space has recently commenced, but there are significant differences in the methods used. In addition, only LAI values up to 3 to 4 can be retrieved from Earth observation data. Above these values the measurements saturate, so for various parts of the globe (e.g., humid tropics) LAI can be measured only *in situ*, and these measurements are sparse. GCOS reference sites should address this inadequacy.

FINDING: Daily global FAPAR and LAI products should continue to be generated by Space Agencies and other entities and made widely available. The validation of these products, currently being undertaken by the Space Agencies and associated research programmes, should be continued.

FINDING: Reference sites making *in situ* observations of FAPAR and LAI are essential both for validation and to redress the intrinsic limitations in the satellite-derived measurements.

Biomass plays two major roles in the climate system. First, photosynthesis withdraws CO_2 from the atmosphere and stores it as biomass. Second, the quantity of biomass consumed by fire affects CO_2, other trace gases and aerosol emissions. Estimates of the imbalance between CO_2 emissions, the increase in atmospheric CO_2, and its absorption in the oceans, indicate a significant terrestrial sink that is attributed in large part to biomass production. However, the magnitude, stability, and regional and temporal variability of this sink are poorly known and are the subject of heated debate, particularly because of its relevance to the Kyoto Protocol. Long-term variations in biomass production for any given part of the globe may be associated with changing land-use practices, changing climate, nitrogen fertilization and the like. The balance among these terms is poorly understood on continental-to-global scales.

Only above-ground biomass is readily measurable as part of a global system, and most nations have schemes to estimate woody biomass through forest inventory (little is recorded on non-forest biomass, except through agricultural yield statistics). Such inventories differ greatly in definitions, standards and quality, and the development of an acceptable international standard will be a major challenge. However, technologies suitable for satellite deployment exist (low-frequency radar, canopy lidar) that would be able to provide global estimates of biomass at kilometric (or better) resolutions. The limitations of these technologies have not been fully explored, particularly with respect to the high values of biomass encountered in the tropics.

FINDING: Satellite missions capable of measuring global vegetation biomass are required.

The emissions of greenhouse gases and aerosols from **fires** are important climate forcing factors; fires also have a large influence on the storage and flux of carbon in the biosphere and atmosphere and can cause long-term changes in land cover. Fire events are difficult to predict, and virtually all terrestrial ecosystems are affected, so that continuous, global observations are required. Space-borne thermal and optical sensors can be used to determine the location of active fire events, the spatial extent of the burnt area and the location and size of smoke plumes and haze. Persistent cloud cover prevents detection of fires in some regions and little information can be obtained on ground fires occurring beneath forest canopies. Statistical corrections based on alternative sources of information, including *in situ* observations, can fill these gaps. *In situ* observations are also needed to validate measurements made from satellite observations.

A historical record of fire activity and burnt area could be prepared by reprocessing archived data from Earth observation satellites (1982 – 2003). The reprocessing would need to address known problems, such as directional effects, instrument calibration drifts and atmospheric correction.

FINDING: Space Agencies should continue to fly sensors capable of detecting burnt areas and active fires, and global burnt-area and active-fire products should continue to be produced. The quality of the various fire products should be established.

FINDING: Archived Earth observation data should be reprocessed to produce a consistent data set on fire disturbances and their trends.

Intensive local measurements are essential to support process studies as well as to provide validation of a number of the key variables described above. It is currently estimated that the terrestrial surface takes up about a quarter of the human-induced CO_2 emissions into the atmosphere. The rate of uptake varies greatly between years, has uncertain future dynamics, and the location of uptake is not known with better resolution than broad latitudinal bands.

FLUXNET is a global network of around one hundred CO_2, energy and water flux measurement towers that can help to resolve some of these uncertainties. Their main purpose at this time is the development and validation of the models used for regional extrapolation. Although the current distribution of sites does not adequately represent all major terrestrial ecosystems, the FLUXNET sites provide a good basis on which to develop a reference network making flux measurements and other co-located measurements.

FINDING: Continued support for the long-term operation of a representative set of terrestrial flux measurement towers (FLUXNET) is required. With adjustments to the distribution of sites to include under-represented ecosystems and an expansion to the range of co-located measurements, FLUXNET could form a reference network at some point in the future.

7. Common Elements

In the preceding chapter an analysis of the adequacy of the observing networks for meeting the requirements of the UNFCCC was undertaken on a variable-by-variable basis. During this analysis a number of clear common issues emerged. These common issues are more fully discussed in this section.

7.1 Earth Observation Satellites

Satellites now provide the single most important means of obtaining observations of the climate system from a near-global perspective and comparing the behaviour of different parts of the globe. A global climate record for the future critically depends upon a major satellite component, but for satellite data to contribute fully and effectively to the determination of long-term records, the system must be implemented and operated in an appropriate manner to ensure that these data are climatically accurate and homogeneous. To assist the Space Agencies, the GCOS Climate Monitoring Principles have been extended specifically for satellite observations, as documented in Appendix 2. Their implementation by the Space Agencies for operational spacecraft and systematic research spacecraft would greatly enhance the utility of satellite information and benefit the climate record. For “one time” research spacecraft, the principles of continuity obviously do not fully apply, but as many of the other principles as possible (e.g., those for rigorous pre-launch instrument characterization and calibration, on-board calibration, complementary surface-based observations, etc.) should be followed.

FINDING: Up to the present, operational satellites have not had climate observation as a priority objective and research missions were not planned to measure multi-decadal long-term trends. In consequence, satellite observations for most environmental variables have not met the accuracy and homogeneity requirements for climate. Some research satellites have been able to operate for long periods of time to provide data sets useful for long-term climate studies. The continuation of the attention being given by the Space Agencies to addressing the accuracy and homogeneity requirements for climate would significantly enhance the value of satellite observations to the global observing systems for climate.

FINDING: The Space Agencies need collectively to endorse and adopt policies that would implement the GCOS Climate Monitoring Principles for satellite observations contained in Appendix 2. Implementation priority is required for those variables with clear climate importance and without adequate *in situ* baseline support.

Key shortcomings and issues to be addressed through these principles to ensure the utility of satellite observations for climate monitoring are:

Continuity and homogeneity:

- Key observation series for climate monitoring often start with data from research satellites. Continued observations deemed essential by GCOS will require the support of the Parties and relevant Space Agencies to implement the future systems needed to ensure continuity of the record.
- New sensors arise from technological advances among other things, but can generate measurements that are different from earlier ones. Periods of overlap between old and new sensors or effective cross-calibration with other measurements are required to ensure the continuity of the climate record.
- Early observations in a series should be reprocessed in the light of advances in science and technology. There should be an expectation of reprocessing from the start and appropriate measures taken for archiving and access.

Orbit control:

- Detailed navigation information (position, velocity and attitude as a function of time) should accompany the data themselves.

- Wherever practicable and cost-effective, satellite orbital characteristics (e.g., local equator crossing time) should be stable. If platforms cannot be so controlled, knowledge of the orbital drift and decay is necessary for data interpretation.

Calibration:

- For climate purposes, satellite systems should include on-board calibration and information on the calibration should be made available as part of the metadata. Satellites that take advantage of techniques that are, to the first order, self-calibrating may be useful, e.g., occultation measurements. Calibration based on known external targets or underpinning flights remains important for calibrating sensors lacking adequate on-board capabilities and for validating the calibration of others.
- Cross-calibration among similar sensors is essential in support of long-term records.
- Absolute accuracy of calibration is very difficult to achieve; however, sensors often have excellent characteristics in terms of calibration stability that can be exploited with adequate overlap to establish trends.

Data interpretation and validation:

- Algorithms to retrieve geophysical variables evolve. It is therefore important to archive raw measurements, such as radiances, for use in their own right and future reprocessing.
- The error characteristics of geophysical variables should be fully characterized based on the known properties of the measurement and retrieval processes. In many cases, a mature theoretical framework exists to do this.
- Comparison against independent observations should be performed, primarily to verify that the satellite products have their expected error characteristics.
- State-of-the-art processing methods for the analysis and assimilation of data and the generation of high-level products should be used, along with the maintenance and distribution of portable and supported software packages.

Institutional issues:

- Cooperation among Space Agencies should continue to:
    - Provide complementary coverage of the full range of user requirements;
    - Avoid unnecessary duplication, whilst retaining planned redundancy;
    - Deliver global coverage (e.g., for data from geostationary platforms); and
    - Ensure cross-calibration of sensors.
- Parties should ensure the establishment of organizations capable of end-to-end operations to acquire, process and archive observations, and to make data and products accessible to users.
- The CEOS through IGOS should consider how best to meet the specific requirements of the climate system.

7.2 Integrated Climate Products

While observations of the climate variables are an essential pre-requisite, the users of the information generally require **analyzed outputs and products**. It is essential that there be analysis centres for all of the Essential Climate Variables that are responsible for the regular production of the required outputs. While the Parties are operating a number of such analysis centres for the atmospheric variables, many additional operational analyses are required for the oceanic and terrestrial variables. International coordination of these activities is essential. It is also important to recognize that alternative analysis approaches are required to ensure the accuracy of the various outputs for specific variables. At this point in time there are very few analysis centres that are integrating observations of a given variable using data from different networks.

FINDING: Additional analyses are required for most variables, especially for those in the oceanic and terrestrial domains.

Real-time data assimilation and re-analysis are increasingly powerful tools that have significant potential for integrating climate variables and providing a comprehensive picture of the climate system. These tools are essential to ensure that full benefit is obtained from the substantial investments made in space-based observing systems. Re-analysis also increases the benefit that is derived from continuing improvement of the historical data record.

The main focus and success of real-time data assimilation and re-analysis to date has been on short-term variability of the atmosphere rather than on studies of long-term climate trends. The latter places particular demands both on the re-analysis systems and on the observational data that they ingest. Ocean data assimilation and re-analysis is just now developing and terrestrial activities are in their infancy, due in part to a lack of historical data and limited institutional commitment.

The quality of current atmospheric re-analysis products depends on the distribution and accuracy of each type of observation used, on the realism of the background model, and on how well model and observational information are combined. Bias is a critical component of both observation and model error (and hence analysis error) for many climate applications. Observing systems have changed substantially over the past few decades, and spurious shifts in the climate deduced from re-analysis products can stem both from changes in observational coverage and from changes in the bias of observing systems. Changes in radiance bias from one satellite to the next in a series can be a particular problem, as can a major change of instrument type from one series of satellites to the next. Re-analysis quality also tends to be poorer for fields (such as precipitation) that are derived directly from background-model forecasts than for fields (such as temperature) that are controlled directly by observations. Because of such problems, it is important that re-analyses be available from independent producers, both to help users assess the reliability of the various types of product and to help the producers assess where and how to improve their systems.

Although the **quality of re-analyses is at present insufficient** for a number of climate applications, there are good reasons to be optimistic and there is an opportunity to develop improved procedures for climate re-analyses and thereby reveal long-term trends:

- Atmospheric re-analysis has recently produced trend estimates for near-surface and lower-stratospheric temperatures that compare well with standard climate estimates based on careful analysis of instrumental records alone;
- Re-analysis systems will improve as both data-assimilation systems and computational capacity improve; and
- Several key areas of data-assimilation development being undertaken for improvement and extension of numerical weather prediction are also key areas for climate application (handling of biases, representation of the hydrological cycle and land-surface and introduction of coupled ocean/atmosphere systems, for example).

Implementation of the **GCOS Climate Monitoring Principles** is an essential way of making re-analyses more useful for climate monitoring and research:

- The baseline observing systems will not only provide primary input data but will also improve specification of the biases and random errors of other observing systems;
- The reference measurements will be valuable for the validation of products and refinement of assimilation systems;
- The availability of observations from satellite systems that adhere to the GCOS Climate Monitoring Principles will reduce problems of the type experienced in the analysis of earlier satellite data; and
- Data archaeology (recovering synoptic observations from national weather records, for example) and data reprocessing (such as correction of radiosonde biases or re-derivation of cloud-tracked winds or establishing the error-characteristics of both modelled and observed data) will increase the reliance that can be placed on analyses of earlier periods.

A highly-promising additional application of data assimilation is the **analysis of variables related to atmospheric composition** and forcing of the climate system, such as non-reactive greenhouse gases, reactive gases, aerosols, land-surface characteristics and ocean colour. Good progress has been made already on the assimilation of ozone data, and new measurements from satellites are prompting initiatives covering other areas.

FINDING: A small number of re-analysis centres are required, with adequate staff and data processing, as part of an internationally-coordinated programme for the preparation of integrated climate products. The international re-analysis programme should give initial priority to: (a) extending current atmospheric re-analysis activities to meet requirements for monitoring climate variability and trends; (b) building on and extending ocean data-assimilation research activities such as GODAE to establish ocean re-analyses for the recent satellite era, and for longer if practicable; and (c) developing products relating to the composition and forcing of the climate system. The outputs of the re-analysis programme should be widely and easily available to the user community.

FINDING: An essential requirement for the effective conduct of re-analysis will be the provision of national holdings of historical data to the international data centres.

7.3 Historical Data Sets

Accurate records of past variations and changes are an essential part of interpreting and using new observations. Improvement of these historical records is dependent on adequate investment in data archaeology for the rehabilitation of data that are not presently accessible or are inadequately assessed for random errors and time-dependent biases. Three aspects of data archaeology are critical for putting new observations into a historical context or making effective use of the past records.

First, information must be compiled about how, where and when observations were made, i.e., **metadata.** Most instrumental observing systems as well as proxy data or data from non-instrumental sources, (e.g., biophysical or geochemical data such as tree rings, coral growth, dust layers) have not been designed to measure decadal and longer-term changes and variations. Understanding long-term changes requires a detailed knowledge of the location and environment in which an observation has been taken as well as changes to that environment. It also requires a detailed knowledge of when, how and why instruments were changed, as well as all aspects of the procedures followed in taking the observation. Such metadata have often not been recorded or the records themselves not been maintained in any accessible manner nor have such metadata been exchanged internationally and made available to the international data centres for archiving along with the data themselves. For example, metadata related to many of the characteristics of the instruments used to measure basic quantities such as temperature and precipitation are inadequate for many stations and the local environment around which the observations were made is usually not known. This makes interpretation of changes in the temperature and precipitation records difficult without substantial and costly research.

FINDING: Adequate metadata are essential for climate observations. In their absence exhaustive investigative research is required to find, compile, and integrate information on how, where and when observations were taken in order to effectively interpret the data.

Second, it is essential to **synthesize present observations with historical data** to obtain the most comprehensive spatial and long-term data sets. Considerable amounts of historical data are inaccessible because they are not available electronically or because countries have not made their data available for analyses, either as a matter of policy or due to a lack of resources. Illustrative examples include the daily maximum and minimum temperatures required to develop information on extreme events. Most countries collect the observations but, as described in IPCC, 2001[4], data are not available in the international data centres for over one third of the global landmass. In some cases where data are made available, they are not up to date, often by several years or even decades. The sparseness of historical ocean observations means that particular emphasis must be placed on data archaeology and rehabilitation of ship observations. These observations fall into two categories. First, those from the open ocean that are essential for extending and supplementing the observational data sets used to calculate global averages and variability, Second, there is an even larger and perhaps less homogeneous body of data from coastal seas that is crucial for evaluating climate impacts.

FINDING: At the present time scientists are struggling to address all aspects of data archaeology. This includes retrieving data inaccessible because the recording media are outdated, national data exchange is restricted, or resources are inadequate to make them easily accessible.

Third, once appropriate metadata and comprehensive data sets are assembled, a demanding task remains; **time-dependent biases within the data sets must be identified and corrected**. These biases arise because of changes in instrument, sampling times and frequencies, differences in spatial coverage, instrument drift, and other factors. If not identified and accounted for, they can lead to erroneous conclusions about temporal changes and variations. A difficult scientific challenge is to ascribe quantitative measures of uncertainty related to any adjustments or corrections made to the data sets.

FINDING: When historical climate observations from GCOS baseline networks have been digitized, quality controlled and homogenized, the rehabilitated data and their associated metadata should be available in international data centres.

7.4 Data Management and Stewardship

One of the most important activities to be undertaken is to ensure that high-quality data records are collected and retained for analysis and/or re-analysis by current and future generations of scientists. This essential but relatively low-profile activity is called data management and stewardship.

First, it is clear from the detailed network reviews that **the flow of real-time data** to the user community and to the international data centres for the variables contained in Appendix 1 is inadequate. This is especially true for many terrestrial-observing networks. Data policy, lack of resources and inadequately integrated data-system infrastructure are the primary causes. The latter are especially problematic in developing countries and countries with economies in transition.

FINDING: Users seeking information for global analyses often find access to large amounts of already-collected data unavailable for use because of national and international data policies.

Second, **access to very large data sets**, including some satellite data and model simulations, is becoming increasingly difficult for many users. This is compounded in developing countries with inadequate information technology infrastructure. Access to these data must be made more effective through the developments of derived products, as present data volumes exceed communication bandwidths and analysis-system capacity. It remains essential, however, that the original observations be archived for use in re-analysis.

FINDING: The rapidly-increasing volume of raw observations that must be saved and stored in an archive is such that the data are too often inaccessible to many users.

Third, the **preservation of the data for future** use requires facilities and infrastructure to ensure the long-term storage of the data. Once data are in electronic format, the data must be continually migrated to newer storage devices and access software in order to preserve the data for sustained future use. This practice of technological data stewardship is a requirement on the international data centres and the Space Agencies to ensure future data usage.

FINDING: At the present time, even large centres are barely keeping pace with the influx of new data. This is especially true when observing systems are put in place without adequate consideration of the technological data-stewardship requirements for data archive and access.

FINDING: Procedures for the storage and exchange of metadata need to be developed and implemented.

FINDING: International data centres and Space Agencies need to give high priority to making use of modern information and communication technology to ensure effective access and long-term migration, and thus ultimate preservation, of the rapidly-growing volumes of climate-related data.

Fourth, a key component of data management includes adequate **scientific stewardship of the data**. This includes timely quality-control of the observations by the monitoring centres and notification to observing system operators and managers of both random and systematic errors, so that corrective action can occur. An operational system is needed that can track, identify, and notify network managers and operators of observational irregularities, especially time-dependent biases, as close to near-real time as possible. Such feedback systems are currently not routine practices at monitoring and analysis centres. Equally important is the follow-up required by operators and managers who are responsible for implementing timely corrective measures. This is especially problematic in developing countries with less-than-adequate resources. Without adequate scientific data stewardship, biases often become apparent only after substantial investment in research related to the rehabilitation of the data record, e.g., data archaeology. Scientific data stewardship, therefore, is a cost-effective measure that minimizes the need for uncertain corrections at a later date.

FINDING: When problems in the observations and reporting of the observations are not identified and corrected as soon as possible, errors and biases accumulate in the data and the climate records can be irreparably damaged.

FINDING: International agencies, working with their technical commissions and the GCOS Secretariat, should address the inadequacies related to scientific data stewardship, including the introduction of adequate near-real-time observing system performance monitoring and monitoring for time-dependent biases.

7.5 Planning and Implementation

The needs of the UNFCCC for global climate observations and products can be addressed only if **plans are developed and then implemented** in a coordinated manner by national, regional and international organizations.

GCOS and its international partners have over the past decade developed and disseminated plans for the operation of individual networks for most of the key variables. It is essential that these **plans be extended to cover all of the variables** and address the integration of both *in situ* and satellite observations.

Regional planning and cooperation is increasing. The GCOS Sponsors currently undertake a number of regional planning and implementation activities and in response to the request of the UNFCCC the GCOS Regional Workshop Programme has supplemented these activities by undertaking planning workshops to resolve specific deficiencies in climate observing systems involving developing countries in a number of regions. This has the substantial benefit of sharing work across many partners with common interests and of learning from the experience of others.

FINDING: Efforts to enhance regional planning for the collection, processing and archiving of climate observations need to continue, as this shares the workload across many nations.

As noted in the Interim Report presented to the SBSTA in June of 2002, the **National Reports submitted by the Parties to the UNFCCC** clearly show that, with few exceptions, national efforts supporting climate-observing systems are poorly coordinated and planned. Almost all Parties reported that many governmental bodies, agencies and research institutes were involved with systematic observation of the climate system as well as there being different levels of internal governance. Only a very small number of Parties reported that they had instituted internal mechanisms to ensure the necessary coordination. A small number of Annex 1 Parties reported that they had either prepared or were preparing plans for systematic observation of climate as recommended by GCOS. All Parties need to recognize the benefits arising from the implementation of coordination mechanisms and the development of national plans for systematic observation of the climate system, and to adopt appropriate measures within their own jurisdictions.

A few **Parties reported that they had benefited** from the preparation of such plans. Some had allocated new financial resources to make specific improvements to their observing systems. Others had restructured their national networks to meet more directly the needs of the Convention.

FINDING: All nations require active national coordination and planning processes as well as plans for systematic climate observation.

FINDING: Reporting on systematic climate observation activities by the Parties as part of their national communications under the UNFCCC has been valuable in the planning and implementation of global observing systems for climate.

Observations of several climate-system variables are made in the context of research programmes or by Space Agencies whose primary mission is research and development, rather than as part of operational programmes. This is particularly so in the oceanic and terrestrial domains. Once methods are sufficiently mature to guarantee a sustained set of observations to known and acceptable levels of accuracy to their users, they need to be **translated into an operational observing system**. Although this transition has not been a natural process in national and organizational planning, recent progress involving the Space Agencies and some others has occurred and further improvements are encouraged. The operational system requires an organization with the institutional mandate. This may involve the transfer of responsibility from one organization to another and the issue of operational and continued research funding is always a major concern. It also implies sustained dialogue between the operational entities and the research community so that the operational arm may benefit from scientific advances.

FINDING: The transition of a research network or satellite observation into operational status requires the development and implementation of plans for: (i) an institution or organization to assume operational responsibility for making the observations and for their distribution, analysis, and archiving; (ii) sustained sources of funding; and (iii) a framework that provides for national commitment to continue to make the required observations.

For atmospheric and oceanographic observations, the actual implementation of the networks for the climate variables is undertaken by national entities under overall guidance from the technical commissions of the WMO and IOC. These technical commissions are responsible for meeting the needs of a variety of user groups of which climate is but one group. The GCOS Secretariat acts on behalf of the UNFCCC and other users in the climate community to ensure that these commissions are fully aware of all aspects of the requirements for climate observations and products. Conducting this activity requires a **dedicated staff** whose primary function is to ensure that climate products are being delivered to the user community with sufficient quality, and to work with the technical commissions and others to resolve deficiencies wherever they occur.

As noted earlier the Parties, through their specialized agencies, carry out the actual implementation and operation of the networks. The National Reports indicated that most of the developed countries were in a position to carry out programmes within their national boundaries. They were also able to assume responsibility for the operation of many of the monitoring and analysis functions on behalf of the global system. At the same time, it was quite clear that **most developing countries and many countries with economies in transition could not provide many of the essential *in situ* observations**; nor could they participate in the global activities by undertaking monitoring or analysis functions, except in a few cases.

FINDING: Multi-national funding mechanisms are required to support high-priority global observing systems for climate in developing countries and some countries with economies in transition. Support is needed for capacity-building, infrastructure issues and sustained operational activities.

8. Acknowledgements

This Report has been prepared under the direction of the Chairman of the GCOS Steering Committee, **Professor Paul Mason**, with the support of the GCOS Secretariat and the assistance of many organizations, institutions and individuals. Appreciation is extended to all who participated in the preparation of the Report, especially those most directly involved who are noted in Appendix 4. Special thanks are also due to those many individuals who took the time to review the draft materials and provided useful comments on its content. The direct financial support of Japan, the United States of America, the United Kingdom, and EUMETSAT is gratefully acknowledged; without that support this Report could not have been prepared.

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Appendix 1

Essential Climate Variables

This appendix contains a statement of the Essential Climate Variables that are required to support the work of the Convention and that are technically and economically feasible for systematic observation. It is these variables for which international exchange is required for both current and historical observations. Additional variables required for research purposes are not included in this listing. Additional information and specification of these variables is contained in the annex to this document. It is emphasized that the ordering within the listing is simply for convenience and is not an indicator of relative priority.

1. Atmospheric Variables

The following essential atmospheric variables are required over land, sea and ice:

1.1 Surface

Air temperature
Precipitation
Air pressure
Surface radiation budget
Wind speed and direction
Water vapour

1.2 Upper-air

Earth radiation budget (including solar irradiance)
Upper-air temperature (including MSU radiances)
Wind speed and direction
Water vapour
Cloud properties

1.3 Composition

Carbon dioxide
Methane
Ozone
Other long-lived greenhouse gases[16]
Aerosol properties

2. Oceanic Variables

2.1 Surface

Sea-surface temperature
Sea-surface salinity
Sea level
Sea state
Sea ice

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[16] Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

Current
Ocean colour (for biological activity)
Carbon dioxide partial pressure

2.2 Sub-surface

Temperature
Salinity
Current
Nutrients
Carbon
Ocean tracers
Phytoplankton

3. Terrestrial Variables

River discharge
Water use
Ground water
Lake levels
Snow cover
Glaciers and ice caps
Permafrost and seasonally-frozen ground
Albedo
Land cover (including vegetation type)
Fraction of absorbed photosynthetically active radiation (FAPAR)
Leaf area index (LAI)
Biomass
Fire disturbance

Appendix 2

GCOS Climate Monitoring Principles

Effective monitoring systems for climate should adhere to the following principles[17]*:*

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.

2. A suitable period of overlap for new and old observing systems should be required.

3. The results of calibration, validation and data homogeneity assessments, and assessments of algorithm changes, should be treated with the same care as data.

4. A capacity to routinely assess the quality and homogeneity of data on extreme events, including high-resolution data and related descriptive information, should be ensured.

5. Consideration of environmental climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.

6. Uninterrupted station operations and observing systems should be maintained.

7. A high priority should be given to additional observations in data-poor regions and regions sensitive to change.

8. Long-term requirements should be specified to network designers, operators and instrument engineers at the outset of new system design and implementation.

9. The carefully-planned conversion of research observing systems to long-term operations should be promoted.

10. Data management systems that facilitate access, use and interpretation should be included as essential elements of climate monitoring systems.

Furthermore, 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; and
(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:

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

12. 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.

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[17] *The ten basic principles were adopted by the Conference of the Parties to the UN Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November 1999.*

13. Continuity of satellite measurements (i.e., elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured.

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

15. On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored.

16. Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate.

17. 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.

18. 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 de-commissioned satellites.

19. Complementary *in situ* baseline observations for satellite measurements should be maintained through appropriate activities and cooperation.

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

Appendix 3

Specific Progress Since The First Adequacy Report

This appendix contains a short analysis of the progress made during the past four years in addressing the specific recommendations and findings contained in the First Adequacy Report submitted to COP-4 in November of 1998.

Recommendation 1. *Each Party should undertake programmes of systematic observations including the preparation of specific national plans, based on the overall plans formulated by GCOS and its partner programmes. The national plans should contain commitments to undertake specific implementation actions and be tabled and reviewed at regular intervals at COP sessions.*

Progress:

As noted in the GCOS Interim Report[18] to SBSTA-16, thirteen Annex 1 Parties reported to the UNFCCC on their national activities with respect to global observations of the climate system. Seven have adopted internal coordination mechanisms with three preparing national policy. Four have clearly identified national focal points. Only two of the Parties reported having prepared and published a specific national plan. Non-Annex 1 Parties have yet to prepare and publish such plans.

Recommendation 2. *Parties should exchange, with other nations and with appropriate international organizations, those data required to meet climate objectives and the needs of the FCCC. They should take active steps to eliminate any internal barriers to such exchange.*

Progress:

The European Union has made changes to improve access to climate data. In addition, Parties have commenced the submission of daily data to the World Data Centres. On the whole, this remains one of the two or three major outstanding issues with limited progress.

Recommendation 3. *Parties should actively support capacity development to enable countries to collect and utilize observations to meet local and regional needs. The capacity building programmes of appropriate international organizations could assist countries to acquire and use climate information. If necessary, Parties should reconsider the priorities of funding mechanisms which support the FCCC.*

Progress:

GCOS Sponsors and partners as well as other international and intergovernmental organizations currently undertake activities aimed specifically at capacity-building related to systematic observations that have been beneficial for climate. In response to a request from the UNFCCC, the GCOS Regional Workshop Programme has supplemented these activities by undertaking planning workshops to resolve specific deficiencies in climate observing systems involving developing countries in a number of regions. Using funds from the Global Environment Facility (GEF) and a number of other sponsors[19], regional planning workshops have been held in: 1) the Pacific Islands (Apia, Samoa), 2) Eastern and Southern Africa (Kisumu, Kenya), 3) Central America and the Caribbean (San José, Costa Rica), 4) East and Southeast Asia (Singapore), and 5) Western and Central Africa (Niamey, Niger). Regional action plans have been prepared for the first four regions and now require project funding for implementation. Some non-Annex 1 Parties have reported receiving financial and other support for their observing activities related to upper-air observations, as well as to sea level and data management. The GEF, WMO, UNEP and several Parties have provided some resources toward the development of regional action plans for addressing deficiencies in the observing systems in developing countries.

Recommendation 4. *Countries should support national meteorological observing systems and particularly ensure that the stations identified as elements of the GCOS networks based on the WWW and GAW are fully operational and that best practices are maintained. Support should be provided to*

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[18] GCOS-79, October 2002.

[19] To date: Australia, Canada, China, France, Japan, U.K., U.S.A.; IOC, OAS, UNEP, WMO.

assist countries as needed. The number of stations in the observing networks for atmospheric constituents including ozone, and aerosols when formulated, should be increased. Satellite missions to observe and quantify atmospheric constituents should continue.

Progress:

The decline of some of the comprehensive networks in the WWW noted in the First Adequacy Report has been to a large extent arrested in the recent past due to the concerted efforts of a number of operators and agencies. This applies also to the GSN and GUAN, although performance remains at unacceptably low levels and concerns remain regarding the loss of stations with long records in these networks. Several Parties have enhanced the availability of their *in situ* observations of the atmosphere in recent years. In addition, a number of satellites have been launched with instruments that are potentially relevant to climate (e.g., scatterometers for ocean winds, aerosol optical depth over oceans), and there is an increasing cooperation among Space Agencies and users through the IGOS.

Recommendation 5. *Countries should actively support national ocean observing systems and particularly ensure that the elements of the GCOS and GOOS networks in support of ocean climate observations are implemented to the degree possible. Support should be provided to increase the number of surface observations, particularly in remote locations, and to establish and maintain reference stations and repeat sections. Current satellite missions to observe sea-surface elevation, wind stress, and temperatures should be continued.*

Progress:

Since publication of the First Adequacy Report there has been progress relative to the Findings and Recommendations on ocean observing systems. The ocean climate *in situ* and satellite communities, for both research and sustained observations, have agreed on the design of an initial global ocean climate observing system. The WMO and IOC have formed the Joint Technical Commission for Oceanography and Marine Meteorology. The VOSClim project to improve VOS marine surface data quality has been established; climate-quality data from ocean surface reference site moorings have been demonstrated; two AOPC/OOPC Working Groups have been established (SST/Sea-Ice, and Surface Pressure); two surface moorings have been located in the eastern tropical Indian Ocean and the TAO/Triton and Pirata arrays have been maintained; surface drifting buoy technology has improved and costs have been reduced. An international group has proposed a sparse global array of moored reference sites and several are in operation. New ice-monitoring satellites will soon be reporting data and sea ice is a topic of study by the cryospheric research community. Geocentric location of some sea-level gauges, and some enhancement of the array, has occurred; Topex/Poseidon continues and Jason-1 has been launched and is expected to operate until 2006. The Argo profiling float has been developed and implementation of a global array has begun. A global full-depth repeat section hydrography programme including carbon and tracers has been designed and a number of sections are funded. Technology-development and research use of ocean biogeochemistry sensors continues. There are a number of ocean surface $p\mathrm{CO}_2$ programmes operating on ships-of-opportunity and agreements have been made on data exchange and data set development; new marine carbon research is underway. In some countries dialogue has been established between the ocean research and operational communities.

Recommendation 6. *Countries should actively support national terrestrial networks and in particular the various observational programmes to collect, exchange and preserve terrestrial variables according to GCOS and GTOS climate priorities. Specific support is required to secure and distribute relevant hydrosphere and cryosphere observations. Ecosystem networks addressing climate impact should be coordinated to provide global and regional databases. There is a particular need to encourage the transition from research to operational status of many of the terrestrial networks. Strong encouragement and financial support, if appropriate, should be given to developing countries to enable them to collect observations in support of warning systems in connection with extreme events exacerbated by climate change, vulnerability and impacts studies, and national and regional sustainable development efforts.*

Progress:

Most Annex 1 Parties conduct terrestrial observational programmes, but these are often made to address regional problems or for national resources management, rather than for long-term climate monitoring. Responsibilities for data collection vary and as a result data are widely scattered. Many organizations make terrestrial observations, for a wide range of purposes. Various different measurement protocols are used, even for the same variable. The resulting lack of homogeneous observations limits our capacity to monitor the terrestrial changes relevant to climate and to investigate the causes of observed land-surface changes. Coordination among organizations and benchmarking of products requires an intergovernmental organization with a mandate to prepare regulatory and guidance material relating to terrestrial observing systems, data management and services.

The non-Annex 1 Parties have no significant terrestrial activities. Progress has been noted in their involvement in the validation of global land cover and fire products derived from Earth observation satellites but there is no systematic involvement in these exercises.

Most relevant Parties are involved in the Glacier (GTN-G) and Permafrost (GTN-P) networks. The last four years have seen substantial progress made by GTN-P concerning near-surface measurements. GTN-G too has consolidated its network, but inadequate observations are made on Patagonian, New Zealand and African glaciers. A new Global Terrestrial Network for Hydrology (GTN-H) has been designed and implementation has begun. FLUXNET making CO_2, energy and water flux measurement is growing, now numbering over 100 sites.

Finding 1. *The importance of global comprehensive data sets for isolating the important signals of climate variability and for minimizing the uncertainty attached to estimates of climate change should be recognized and acknowledged. Observations with a long uninterrupted record should be given special consideration, as should programmes of data rehabilitation and restoration.*
Progress:
Some comprehensive networks within the WWW appear to be stabilizing due to the concerted efforts of a number of operators and agencies. Concerns remain about the loss of stations with long climate records. Several Parties have enhanced the availability of their *in situ* observations of the atmosphere. Limited progress has occurred with data rehabilitation and restoration.

Finding 2. *It is essential to adhere to and promote observing methods and principles that emphasize and value data quality, continuity and homogeneous, long-term records. The need for special care in the handling of satellite data must be recognized.*
Progress:
The GCOS Climate Monitoring Principles have been accepted by the UNFCCC and are being expanded specifically to include satellite observations. Almost all of the Parties have reported that the Principles are extremely important but will take time to implement. There are a number of examples where it is clear that the organizations involved are adopting the principles as they make adjustments in their operations, e.g., reconciliation of atmospheric temperatures.

Finding 3. *Composite systems including both satellite and ground-based elements are required to address climate observational requirements. The concept of an Integrated Global Observing Strategy should be supported to facilitate the implementation of long-term observational programmes.*
Progress:
The importance of the composite system is increasingly recognized by all of the contributing parties. A number of satellite missions with direct relevance to climate have been undertaken. The Space Agencies are increasing their attention to the unique requirements associated with climate long-term climate observations. The IGOS Partnership has undertaken a major review of how to address the requirements in a number of areas and prepared integrated strategies for the oceans and carbon.

Finding 4. *Data assimilation methods and re-analyses of past climate data using skilled models are important strategic techniques for characterizing and understanding climate variability and change, and in guiding observing system development.*
Progress:
There has been progress in our capability to reprocess data sets related to the basic climate state, in re-analysis as well as some individual data sets, such as surface temperature. Research into assimilation and re-analysis involving ocean and atmospheric chemical data is underway.

Finding 5. *When observing systems developed for climate research programmes have the potential to meet a critical need for long-term monitoring their use for this purpose should be carefully evaluated and when appropriate, plans should be developed to effect a transition from research to operational support.*

Progress:

In many countries there is serious attention being given to address the transition of research networks into operations. This process is being effectively addressed within the satellite community.

Finding 6. *Countries should ensure that national meteorological stations identified as elements of the GCOS Upper-Air Network (GUAN) are fully operational and adhere to best practices. Implementation of the components of a composite network is essential for the future. In order to meet this objective, financial assistance should be made available when necessary for developing countries.*

Progress:

There has been progress in establishing the infrastructure to monitor the receipt of GUAN data at GCOS Monitoring Centres. However, the overall performance of the network remains poor, with only about 75% of stations providing data routinely in the required CLIMAT TEMP format. Few soundings achieve the required altitude of 5hPa. There remains a need for financial assistance for the support of GUAN stations in some developing countries, especially in the tropics. Some funding has recently been made available by individual Parties and the concept of a voluntary donor fund is being investigated.

Finding 7. *In view of the importance of satellite data time series for global climate monitoring, satellite agencies should be urged to give high priority to long-term data continuity in conformance with climate observing requirements and principles.*

Progress:

In recent years, many satellites have been launched with instruments that are relevant to climate process studies (e.g., scatterometers for ocean winds). The Space Agencies have acknowledged that the long-term monitoring requirement for climate places special requirements on both instruments and operations. In addition there is a clear willingness to initiate the implementation of the GCOS Climate Monitoring Principles for specific missions.

Finding 8. *Countries should ensure that the stations identified as elements of the GCOS Surface Network (GSN) are fully operational and adhere to best practices. Implementation of the GSN is essential for global issues but, in most cases, additional stations will be needed to address regional/national issues. Financial assistance should be made available to developing countries where required.*

Progress:

There has been progress in establishing the infrastructure to monitor the receipt of GSN data at GCOS Monitoring Centres. However, only about 65% of stations routinely provide monthly reports, and requested daily historical data from only about 30% of stations have been provided to the GCOS Archive Centre. There remains a need for financial assistance for the support of GSN stations in some developing countries. Some funding has recently been made available by individual Parties and the concept of a voluntary donor fund is being investigated.

Finding 9. *Nations should continue to improve their observing systems for clouds and precipitation. Countries should ensure their ground-based and satellite information is provided for global and regional syntheses*.

Progress:

Precipitation data present major problems, including the poor availability of data over land areas and the continuing need to further refine algorithms for retrieving precipitation over the oceans beyond the progress made to date. Specific satellite missions have started to resolve differences among precipitation estimates computed from data from different sensors. There remains a need to develop systems to provide continuous and homogeneous monitoring of rain structure and cloud properties from satellites and the surface.

Finding 10. *Support is needed for GAW to expand its global network, to increase observations in the upper-atmosphere, and to incorporate atmospheric aerosol measurements.*

Progress:

Dedicated satellite missions have been initiated to observe carbon dioxide (e.g., OCO, GOSAT); also the opportunity exists to capitalize on other satellite missions (e.g., AIRS on Aqua, TES on Aura). Aerosol information is being pulled together through the Global Aerosol Climatology Project. There remains a need to develop a satellite and surface-based system, involving GAW sites, that provides data relevant to the spatial and temporal distribution of emissions of aerosols and greenhouse gases, especially carbon dioxide. The addition of ozone sonde stations in the southern hemisphere (SHADOZ) has greatly enhanced the GAW Global Network. The global column ozone network is in danger of losing calibration if routine instrument intercomparisons are not maintained. Elements of a global aerosol optical-depth monitoring network are emerging but need coordination and focus.

Finding 11. *Support should be provided for the creation of a joint body for oceanography and marine meteorology (JCOMM), as proposed by the IOC and WMO, to implement and maintain the ocean observing system.*
Progress:
The JCOMM has been established to coordinate IOC and WMO marine observing efforts. It first met in 2001, and a number of working subgroups have met since then.

Finding 12. *Nations and responsible agencies should support a range of measures to improve the quality, continuity and long-term stability of the surface marine observation networks relevant to climate.*
Progress:
TAO/Triton and Pirata mooring programmes have been continued. Preliminary extension of moored buoy programmes into the eastern Indian Ocean has occurred. Surface drifter array has decayed. VOS fleet has declined, as has the quality-control process. Efforts continue to improve understanding of errors in VOS observations and to establish a core of high-quality ship-based observations.

Finding 13. *Responsible national agencies should support the establishment of ocean climate reference sites to obtain data for calibrating models and satellites.*
Progress:
An array of reference sites has been designed and two sites, representing about 10% of the array, have been established in the North Atlantic and South Pacific.

Finding 14. *Noting the importance of measurements from the ice-covered regions of the ocean and, consistent with the emphasis on global homogeneity, national agencies should endeavour to maintain the Arctic programme and implement an enhanced programme for the Antarctic. For ice extent it is recommended that better documentation of the data stream be provided.*
Progress:
The WCRP has established a Climate and Cryosphere programme that covers the ice-covered regions of both hemispheres. Ice drifters continue to be deployed. Several satellites (e.g., ICESat, and also the AMSR instrument on Aqua and ADEOS-II) have recently been launched that have enhanced monitoring capabilities for ice-covered regions.

Finding 15. *Increased national participation is required to implement GLOSS plans for measuring sea-level change and to ensure long-term continuity of the surface network. In addition, satellite altimetry for climate change and programmes for geodetic positioning should be supported.*
Progress:
New GLOSS stations are being established and some existing sites are being enhanced. Roughly 2/3 of the desired network is operating. The Topex-Poseidon mission for altimetry has been extended and JASON-1 has been launched. JASON-2 has been approved.

Finding 16. *Support is required for the programme to enhance the observing system for the global oceans, which emphasizes need for sampling to greater depth (1,500-2,000 meters) in data sparse regions. Both temperature and salinity profiles are needed.*
Progress:
The Argo pilot programme of profiling floats has been established and at the end of March 2003, 25% of the target array is reporting. Present commitments indicate that the complete array will be achieved by 2006. The ship-of-opportunity XBT programme of high-density and frequently repeated lines is developing but support is only available for about 65% of the target system.

Finding 17. *A programme of deep, trans-ocean sections, at locations and frequencies to be determined, is needed to monitor heat, freshwater and carbon circulation in the ocean.*
Progress:
A global re-survey programme is under development based on the sections occupied during the 1990's. Some sections have already been re-occupied and others are funded and planned. These sections will measure physical/chemical properties and ocean carbon parameters to the highest quality and throughout the ocean.

Finding 18. *The implementation and maintenance of time-series stations to provide high-quality, climate records and to calibrate and validate ocean carbon-cycle models and satellite ocean colour instruments are required.*
Progress:
Progress in the deployment of moored biogeochemical systems continues and a few multidisciplinary time-series sites continue to be sustained. Satellite ocean colour instruments were launched; MODIS aboard Terra and Aqua, MERIS aboard ENVISAT and GLI aboard ADEOS-II.

Finding 19. *Observations are required of the exchange of carbon across the air-sea interface. Available techniques include underway sampling and fixed buoys. Research is needed to better characterize the process of carbon uptake.*
Progress:
Planning for a global volunteer and research vessel $p\mathrm{CO}_2$ observing system is in an advanced stage. Research efforts are being planned as part of the IGBP's Surface Ocean Lower Atmosphere (SOLAS) project.

Finding 20. *Current international implementation mechanisms for terrestrial observations should be reviewed by the relevant international bodies. Changes necessary to ensure the maintenance and improvement of climate-related terrestrial observations should be enacted.*
Progress:
No progress. Remains an outstanding priority issue.

Finding 21. *Support should be provided for the implementation of more reliable procedures of land use and land cover change. Space Agencies should be encouraged to ensure the acquisition and exchange of appropriate fine and medium resolution data on a regular basis.*
Progress:
There are now several instantaneous assessments of land cover based on data collected by Earth observation satellites (research missions). Some land-cover products are being produced on a routine basis by Space Agencies. There are two data sets describing historical changes in land cover, based on combining remotely-sensed data, inventory data and historical land-use information.

Finding 22. *The GAW global flask sample network and centralized calibrated isotopic analysis should be supported as well as the plans for the long-term CO_2 flux tower network. Space agencies should acquire and exchange well-calibrated satellite data, based on consistent overpass times for monitoring terrestrial primary* productivity.
Progress:
There are now over 100 FLUXNET towers measuring CO_2, energy and water flux, although not all sites make systematic meteorological observations, nor do they provide land-use land-cover histories. Their physical situation (away from disturbance, urban areas, etc.) also limits the sites' representativeness and gaps remain, especially in the tropics and the non-Annex 1 countries. Progress is being made on pre- and post-launch instrument calibration by the Space Agencies. The improvements in calibration (and the dissemination of this information) have allowed new, quantitative approaches to data processing and reprocessing. Examples include processing of data from the latest generation of Earth observation satellites to yield quantitative measurements of Fraction of Absorbed Photosynthetically Active Radiation (FAPAR); global gridded datasets of FAPAR and also Leaf Area Index (LAI) are being produced to support the monitoring of terrestrial primary productivity.

Finding 23. *An operational integrated global observation system capable of providing timely information on fires and their impacts, based on current and planned satellite systems, should be established.*

Progress:

Global burnt-area data sets are currently being produced on a routine basis by some Space Agencies and other organizations. Data sets documenting active fires are in development.

Finding 24. *It is urgent to address the inadequacies of the hydrological network and in particular the timely exchange of data for the discharge of major rivers and other hydrological variables.*

Progress:

A Global Terrestrial Network for Hydrology (GTN-H) was established in 2001 to coordinate and oversee the climate aspects of hydrology. Associated with this there is one operating international data centre for river discharge (GRDC). Two additional centres (for ground water and lakes) are in early stages of development. Three organizations have compiled meta-databases on lakes and reservoirs. One global map of irrigated areas has been compiled. Data exchange remains a fundamental problem.

Finding 25. *Glacier and ice sheet mass-balance surveys should continue using surface, aerial, and satellite techniques. Geographically representative glaciers should be added to the plans for the future. Countries with data should consider preserving their records in accessible formats and media and contributing them to archives for future use.*

Progress:

The Global Terrestrial Network on Glaciers (GTN-G) has been established and now acts as a key coordinating body to help feed data to the World Glacier Monitoring Service (WGMS). Movement of Antarctic ice streams, mass, area and thickness need improved monitoring, and measurements need to be re-initiated in Patagonia, New Zealand and Africa.

Finding 26. *The collection of permafrost observations should continue. Existing data should be rescued and made widely accessible to further the understanding of the impacts of climate change and to allow assessments of the socio-economic impacts of these changes.*

Progress:

The Global Terrestrial Network on Permafrost (GTN-P) has been established. It involves several hundred boreholes, mostly in the Northern Hemisphere, and over 100 active layer sites, mostly in the Arctic. Metadata and data compilation has been initiated for the permafrost thermal monitoring component of GTN-P. Active layer observations contributing to the Circumpolar Active Layer Monitoring (CALM) component of GTN-P have been compiled over the last decade and a summary of analysis of initial results was recently published. The network is still largely research oriented rather than operational. Funding is still lacking to make the transition from research to operational networks. Institutional mandates are required to facilitate this transition.

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Appendix 4

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Appendix 5

Acronyms And Abbreviations

ADEOS-II	ADVANCED EARTH OBSERVING SATELLITE-II
AERONET	AEROSOL ROBOTIC NETWORK
AIRS	ATMOSPHERIC INFRARED SOUNDER
AMSR-E	ADVANCED MICROWAVE SCANNING RADIOMETER-EOS, NASA
AOPC	ATMOSPHERIC OBSERVATION PANEL FOR CLIMATE
AQUA	NASA MISSION TO STUDY THE EARTH'S WATER CYCLE
ARGO	GLOBAL ARRAY OF PROFILING FLOATS
BSRN	BASELINE SURFACE RADIATION NETWORK
CALM	CIRCUMPOLAR ACTIVE LAYER MONITORING
CBS	COMMISSION FOR BASIC SYSTEMS (WMO)
CEOS	COMMITTEE ON EARTH OBSERVATION SATELLITES
CLIC	CLIMATE AND CRYOSPHERE (WCRP)
CLIMAT	REPORT OF MONTHLY MEANS AND TOTALS FROM A WWW LAND STATION
COP	CONFERENCE OF THE PARTIES (TO UNFCCC)
CryoSat	CRYOSPHERE SATELLITE
DPR	DUAL-FREQUENCY PRECIPITATION RADAR
ENVISAT	ENVIRONMENTAL SATELLITE (ESA)
ERB	EARTH RADIATION BUDGET
ESA	EUROPEAN SPACE AGENCY
EUMETSAT	EUROPEAN ORGANISATION FOR THE EXPLOITATION OF METEOROLOGICAL SATELLITES
FAO	FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
FAPAR	FRACTION OF ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION
FLUXNET	FLUX AND ENERGY EXCHANGE NETWORK (GTOS)
GAW	GLOBAL ATMOSPHERE WATCH (WMO)
GCM	GLOBAL CLIMATE (ALSO GENERAL CIRCULATION) MODEL
GCOS	GLOBAL CLIMATE OBSERVING SYSTEM
GEF	GLOBAL ENVIRONMENT FACILITY
GLI	GLOBAL IMAGER
GLOSS	GLOBAL SEA LEVEL OBSERVING SYSTEM
GODAE	GLOBAL OCEAN DATA ASSIMILATION EXPERIMENT
GOOS	GLOBAL OCEAN OBSERVING SYSTEM
GOS	GLOBAL OBSERVING SYSTEM (WMO)
GOSAT	GREENHOUSE GAS OBSERVING SATELLITE
GPCC	GLOBAL PRECIPITATION CLIMATOLOGY CENTRE
GPS	GLOBAL POSITIONING SYSTEM
GRDC	GLOBAL RUNOFF DATA CENTRE
GSN	GCOS SURFACE NETWORK
GTN	GLOBAL TERRESTRIAL NETWORK
GTN-G	GLOBAL TERRESTRIAL NETWORK FOR GLACIERS
GTN-H	GLOBAL TERRESTRIAL NETWORK FOR HYDROLOGY
GTN-P	GLOBAL TERRESTRIAL NETWORK FOR PERMAFROST
GTOS	GLOBAL TERRESTRIAL OBSERVING SYSTEM
GUAN	GCOS UPPER-AIR NETWORK
ICESat	ICE, CLOUD AND LAND ELEVATION SATELLITE
I-COADS	INTERNATIONAL COMPREHENSIVE OCEAN-ATMOSPHERE DATA SET
ICSU	INTERNATIONAL COUNCIL FOR SCIENCE
IGBP	INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAMME
IGOS	INTEGRATED GLOBAL OBSERVING STRATEGY
IGRAC	INTERNATIONAL GROUNDWATER RESOURCES ASSESSMENT CENTRE

IHDP	INTERNATIONAL HUMAN DIMENSIONS PROGRAMME ON GLOBAL ENVIRONMENTAL CHANGE
IOC	INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (OF UNESCO)
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
JASON	OCEANOGRAPHY MISSION TO STUDY GLOBAL OCEAN CIRCULATION (POST-TOPEX/POSEIDON)
JCOMM	JOINT TECHNICAL COMMISSION FOR OCEANOGRAPHY AND MARINE METEOROLOGY
LAI	LEAF AREA INDEX
LIDAR	LIGHT DETECTION AND RANGING
MERIS	MEDIUM RESOLUTION IMAGING SPECTROMETER
MODIS	MODERATE RESOLUTION IMAGING SPECTRORADIOMETER
MSU	MICROWAVE SOUNDING UNIT
NASA	NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (US)
NASDA	NATIONAL SPACE DEVELOPMENT AGENCY (JAPAN)
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (US)
OCO	ORBITING CARBON OBSERVATORY
OOPC	OCEAN OBSERVATIONS PANEL FOR CLIMATE
PIRATA	PILOT RESEARCH MOORED ARRAY IN THE TROPICAL ATLANTIC
SBSTA	SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE (UNFCCC/COP)
SHADOZ	SOUTHERN HEMISPHERE ADDITIONAL OZONESONDES
SMOS	SOIL MOISTURE AND OCEAN SALINITY
SSS	SEA-SURFACE SALINITY
SST	SEA-SURFACE TEMPERATURE
TAO	TROPICAL ATMOSPHERE-OCEAN ARRAY
TES	THERMAL EMISSION SPECTROMETER
TOPC	TERRESTRIAL OBSERVATION PANEL FOR CLIMATE
TRITON	TRIANGLE TRANS-OCEAN BUOY NETWORK
TSI	TOTAL SOLAR IRRADIANCE
ULS	UPWARD LOOKING SONAR
UNEP	UNITED NATIONS ENVIRONMENT PROGRAMME
UNESCO	UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
UNFCCC	UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE
VOS	V OLUNTARY OBSERVING SHIP
VOSClim	VOLUNTARY OBSERVING SHIPS CLIMATOLOGY PROGRAMME
WCRP	WORLD CLIMATE RESEARCH PROGRAMME
WGMS	WORLD GLACIER MONITORING SERVICE
WHYCOS	WORLD HYDROLOGICAL CYCLE OBSERVING SYSTEM
WMO	WORLD METEOROLOGICAL ORGANIZATION
WWW	WORLD WEATHER WATCH (WMO)
XBT	EXPENDABLE BATHYTHERMOGRAPH

LIST OF GCOS PUBLICATIONS*

GCOS-1 (WMO/TD-No. 493)	Report of the first session of the Joint Scientific and Technical Committee for GCOS (Geneva, Switzerland, April 13-15, 1992)
GCOS-2 (WMO/TD-No. 551)	Report of the second session of the Joint Scientific and Technical Committee for GCOS (Washington DC, USA, January 11-14, 1993)
GCOS-3 (WMO/TD-No. 590)	Report of the third session of the Joint Scientific and Technical Committee for GCOS (Abingdon, UK, November 1-3,1993)
GCOS-4 (WMO/TD-No. 637)	Report of the fourth session of the Joint Scientific and Technical Committee for GCOS (Hamburg, Germany, September 19-22, 1994)
GCOS-5 (WMO/TD-No. 639)	Report of the GCOS Data System Task Group (Offenbach, Germany, March 22-25, 1994)
GCOS-6 (WMO/TD-No. 640)	Report of the GCOS Atmospheric Observation Panel, first session (Hamburg, Germany, April 25-28, 1994)
GCOS-7 (WMO/TD No. 641)	Report of the GCOS Space-based Observation Task Group (Darmstadt, Germany, May 3-6, 1994)
GCOS-8 (WMO/TD No. 642) (UNEP/EAP.MR/94-9)	Report of the GCOS/GTOS Terrestrial Observation Panel, first session (Arlington, VA, USA, June 28-30, 1994)
GCOS-9 (WMO/TD-No. 643)	Report of the GCOS Working Group on Socio-economic Benefits, first session (Washington DC, USA, August 1-3, 1994)
GCOS-10 (WMO/TD-No. 666)	Summary of the GCOS Plan, Version 1.0, April 1995
GCOS-11 (WMO/TD-No. 673)	Report of the GCOS Data and Information Management Panel, first session (Washington DC, USA, February 7-10, 1995)
GCOS-12 (WMO/TD-No. 674)	The Socio-economic Benefits of Climate Forecasts: Literature Review and Recommendations (Report prepared by the GCOS Working Group on Socio-economic Benefits), April 1995
GCOS-13 (WMO/TD-No. 677)	GCOS Data and Information Management Plan, Version 1.0, April 1995
GCOS-14 (WMO/TD-No. 681)	Plan for the Global Climate Observing System (GCOS), Version 1.0, May 1995
GCOS-15 (WMO/TD-No. 684)	GCOS Plan for Space-based Observations, Version 1.0, June 1995
GCOS-16 (WMO/TD-No. 685)	GCOS Guide to Satellite Instruments for Climate, June 1995
GCOS-17 (WMO/TD-No. 696)	Report of the GCOS Atmospheric Observation Panel, second session (Tokyo, Japan, March 20-23, 1995)

*GCOS publications may be accessed through the GCOS World Wide Web site at:
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GCOS-18 (WMO/TD-No. 697) (UNEP/EAP.MR/95-10)	Report of the GCOS/GTOS Terrestrial Observation Panel, second session (London, UK, April 19-21, 1995)
GCOS-19 (WMO/TD-No. 709)	Report of the GCOS Data Centre Implementation/Co-ordination Meeting (Offenbach, Germany, June 27-29, 1995)
GCOS-20 (WMO/TD-No. 720)	GCOS Observation Programme for Atmospheric Constituents: Background, Status and Action Plan, September 1995
GCOS-21 (WMO/TD-No. 721) (UNEP/EAP.TR/95-07)	GCOS/GTOS Plan for Terrestrial Climate-related Observations, version 1.0, November 1995
GCOS-22 (WMO/TD-No. 722)	Report of the fifth session of the Joint Scientific and Technical Committee for GCOS (Hakone, Japan, October 16-19, 1995)
GCOS-23 (WMO/TD-No. 754) (UNEP/DEIA/MR.96-6) (FAO GTOS-1)	Report of the GCOS/GTOS Terrestrial Observation Panel for Climate, third session (Cape Town, South Africa, March 19-22, 1996)
GCOS-24 (WMO/TD-No. 768) (UNESCO/IOC)	Report of the Joint GCOS/GOOS/WCRP Ocean Observations Panel for Climate, first session (Miami, Florida, USA, March 25-27, 1996)
GCOS-25 (WMO/TD-No. 765) (UNEP/DEIA/MR.96-5)	Report of the GCOS Data and Information Management Panel, second session (Ottawa, Ontario, Canada, May 14-17, 1996)
GCOS-26 (WMO/TD-No. 766)	Report of the Joint CCl/CBS Expert Meeting on the GCOS Surface Network (Norwich, UK, March 25-27, 1996)
GCOS-27 (WMO/TD-No. 772) (UNEP/DEIA/MR.96-7)	Report of the Expert Meeting on Hydrological Data for Global Observing Systems (Geneva, Switzerland, April 29-May 1, 1996)
GCOS-28 (WMO/TD-No. 793) (UNEP/DEIA/MR.97-3)	*In Situ* Observations for the Global Observing Systems (Geneva, Switzerland, September 10-13, 1996)
GCOS-29 (WMO/TD-No. 794) (UNEP/DEIA/MR.97-4)	Report of the Global Observing Systems Space Panel, second session (Geneva, Switzerland, October 16-18, 1996)
GCOS-30 (WMO/TD-No. 795)	Report of the sixth session of the Joint Scientific and Technical Committee for GCOS (Victoria, British Columbia, Canada, October 28-November 1, 1996)
GCOS-31 (WMO/TD-No. 803)	Proceedings of the fifth meeting of the TAO Implementation Panel (TIP-5) (Goa, India, November 18-21, 1996)

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http://www.wmo.ch/web/gcos/gcoshome.html

GCOS-32 (WMO/TD-No. 796)	GCOS/GTOS Plan for Terrestrial Climate-related Observations, version 2.0, June 1997
GCOS-33 (WMO/TD-No. 798)	GHOST - Global Hierarchical Observing Strategy, March 1997
GCOS-34 (WMO/TD-No. 799)	Initial Selection of a GCOS Surface Network, February 1997
GCOS-35 (WMO/TD-No. 839)	Report of the second Joint CCl/CBS Meeting on the GCOS Surface Network (De Bilt, The Netherlands, June 25-27, 1997)
GCOS-36 (WMO/TD-No. 844) (UNESCO/IOC)	Report of the Joint GCOS/GOOS/WCRP Ocean Observations Panel for Climate, second session (Cape Town, South Africa, February 11-13, 1997)
GCOS-37 (WMO/TD-No. 845) (GOOS-10) & (GTOS-9)	Report of the Global Observing Systems Space Panel, third session (Paris, France, May 27-30, 1997)
GCOS-38 (WMO/TD-846) (GTOS-10)	Report of the Meeting of Experts on Ecological Networks (Guernica, Spain, June 17-20, 1997)
GCOS-39 (WMO/TD-No. 847) (GOOS-11) & (GTOS-11) (UNEP/DEIA/MR.97-8)	Report of the GCOS/GOOS/GTOS Joint Data and Information Management Panel, third session (Tokyo, Japan, July 15-18, 1997)
GCOS-40 (WMO/TD-No. 848)	Report of the GCOS/WCRP Atmospheric Observation Panel for Climate, third session (Reading, UK, August 19-22, 1997)
GCOS-41 (WMO/TD-No. 849) (GOOS-33)	Report of the Joint GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC) Ocean Climate Time-Series Workshop, (Baltimore, MD, USA, March 18-20, 1997)
GCOS-42 (WMO/TD-No. 857)	Report of the seventh session of the Joint Scientific and Technical Committee for GCOS (Eindhoven, The Netherlands, September 22-26, 1997)
GCOS-43a (GOOS-36)	TAO Implementation Panel, sixth session (Reading, U.K., November 4-6, 1997)
GCOS-43b (GOOS-55)	International Sea Level Workshop (Honolulu, Hawaii, USA, June 10-11, 1997)
GCOS-44 (GOOS-61)	Report of the Joint GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC), third session (Grasse, France, April 6-8, 1998)
GCOS-45 (WMO/TD-No. 922) (GOOS-58) & (GTOS-16) (UNEP/DEIA/MR.98-6)	Report of the Joint Meeting of the GCOS/WCRP Atmospheric Observation Panel for Climate and the GCOS/GOOS/GTOS Joint Data and Information Management Panel, fourth session (Honolulu, Hawaii, USA, April 28-May 1, 1998)

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GCOS-46 (GTOS-15)	Report of the GCOS/GTOS Terrestrial Observation Panel for Climate, fourth session (Corvallis, USA, May 26-29, 1998)
GCOS-47 (WMO/TD-No. 941) (GOOS-67) (GTOS-20)	Report of the Global Observing Systems Space Panel, fourth session, (College Park, Maryland, USA, October 22-23, 1998)
GCOS-48	Report on the Adequacy of the Global Climate Observing Systems (United Nations Framework Convention on Climate Change, November 2-13 1998, Buenos Aires, Argentina)
GCOS-49 (GOOS-64)	Implementation of Global Ocean Observations for GOOS/GCOS, first session (Sydney, Australia, March 4-7, 1998)
GCOS-50 (GOOS-65)	Implementation of Global Ocean Observations for GOOS/GCOS, second session (Paris, France, November 30, 1998)
GCOS-51 (GOOS-66)	Global Ocean Observations for GOOS/GCOS: An Action Plan for Existing Bodies and Mechanisms
GCOS-52 (GOOS-68)	TAO Implementation Panel, 7th Session (Abidjan, Ivory Coast, November 11-13, 1998)
GCOS-53 (WMO/TD-No. 958)	GCOS Surface Network (GSN) Monitoring Centre Implementation Meeting (Offenbach, Germany, January 19-20, 1999)
GCOS-54 (WMO/TD-No. 953)	Report of the eighth session of the WMO-IOC-UNEP-ICSU Steering Committee for GCOS (Geneva, Switzerland, February 9-12, 1999)
GCOS-55	Report of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC), fifth session (Silver Spring, MD, USA, April 20-23, 1999)
GCOS-56 (GOOS-75)	Special Report of the Joint GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC), fourth session (May 17, 1999); The CLIVAR Upper Ocean Panel (UOP), fourth session (May 21, 1999); A Joint Planning Meeting of the OOPC and the UOP for the OCEANOBS99 Conference (Woods Hole, MA, USA, May 18-20, 1999)
GCOS-57 (WMO/TD-No. 978) (GOOS-79)	Report of the OOPC/AOPC Workshop on Global Sea Surface Temperature Data Sets (Palisades, N.Y., USA, November 2-4, 1998)
GCOS-58 (GOOS-71)	Report of the 6th Session of the IOC Group of Experts on the Global Sea Level Climate Observing System (GLOSS)
GCOS-59 (GTOS-22)	Report of the GCOS/GTOS Terrestrial Observation Panel for Climate, fifth session (Birmingham, UK, July 27-30, 1999)
GCOS-60 (WMO/TD-No. 1004) (GOOS-70)	GCOS/GOOS/GTOS Joint Data and Information Management Plan, Version 1.0, May 2000

GCOS-61 (WMO/TD-No. 1031)	Report of the ninth session of the WMO-IOC-UNEP-ICSU Steering Committee for GCOS (Beijing, China, September 12-14, 2000)
GCOS-62 (WMO/TD-No. 1038)	Report of the Pacific Islands Regional Implementation Workshop on Improving Global Climate Observing Systems (Apia, Samoa, August 14-15, 2000)
GCOS-63 (WMO/TD-No. 1047) (GTOS-26)	Establishment of a Global Hydrological Observation Network for Climate. Report of the GCOS/GTOS/HWRP Expert Meeting (Geisenheim, Germany, June 26-30, 2000)
GCOS-64 (GOOS-107)	Report of the eighth session of the TAO Implementation Panel (TIP-8) (St. Raphael, France, October 15, 1999)
GCOS-65 (WMO/TD-No. 1055)	Report of the sixth session of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC) (Geneva, Switzerland, April 10-13, 2000)
GCOS-66 (GOOS-108)	Report of the ninth session of the TAO Implementation Panel (TIP-9) (Perth, Australia, November 16-17, 2000)
GCOS-67 (WMO/TD-No. 1072)	GCOS Implementation Strategy: Implementing GCOS in the New Millennium
GCOS-68 (WMO/TD-No. 1093)	Report of the seventh session of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC) (Geneva, Switzerland, April 30-3 May, 2001)
GCOS-69 (GOOS-98)	Report of the fifth session of the Joint GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC), Bergen, Norway, June 20-23, 2000.
GCOS-70 (GOOS-113)	Report of the sixth session of the Joint GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC), Melbourne, Australia, May 2-5, 2001
GCOS-71 (WMO/TD-No. 1099) (GTOS-29)	Report of the GCOS/GTOS/HWRP Expert Meeting on the Implementation of a Global Terrestrial Network - Hydrology (GTN-H), Koblenz, Germany, June 21-22, 2001
GCOS-72 (GOOS-95)	Report of the 7th Session of the IOC Group of Experts on the Global Sea Level Observing System (GLOSS), Honolulu, April 26-27, 2001
GCOS-73 (WMO/TD-No. 1106)	Manual on the GCOS Surface and Upper-Air Networks: GSN and GUAN, April 2002
GCOS-74 (WMO/TD-No. 1109)	Report of the GCOS Regional Workshop for Eastern and Southern Africa on Improving Observing Systems for Climate, Kisumu, Kenya, October 3-5, 2001
GCOS-75 (WMO/TD-No. 1124)	Summary Report of the tenth session of the WMO-IOC-UNEP-ICSU Steering Committee for GCOS, Farnham, UK, April 15-19, 2002
GCOS-76 (WMO/TD-No. 1125)	Report of the eighth session of the GCOS/WCRP Atmospheric Observation Panel for Climate (AOPC), Wokingham, UK, May 20-24, 2002

GCOS-77 (GOOS-122)	International Workshop for Review of the Tropical Moored Buoy Network, September 10-12, 2001, Seattle, Washington, USA. Workshop Report
GCOS-78 (WMO/TD-No. 1126)	Report of the GCOS Regional Workshop for Central America and the Caribbean. "Observing Climate from Weather Extremes to Coral Reefs", San José, Costa Rica, March 19-21, 2002 (disponible también en español)
GCOS-79 (WMO/TD-No. 1133)	Interim Report to the Sixteenth Session of the Subsidiary Body for Scientific and Technological Advice of the UNFCCC by the Global Climate Observing System, Bonn, Germany, June 5-14, 2002
GCOS-80 (WMO/TD-No.1140)	Report of the GCOS Regional Workshop for East and Southeast Asia on Improving Observing Systems for Climate, Singapore, September 16-18, 2002
GCOS-81 (GOOS-124)	Seventh Session of the Joint GCOS-GOOS-WCRP Ocean Obervations Panel for Climate (OOPC), Kiel, Germany, June 5-8, 2002
GCOS-82 (WMO/TD-No.1143)	The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC

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