5 October 2006

ENGLISH ONLY

UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

SUBSIDIARY BODY FOR SCIENTIFIC AND TECHNOLOGICAL ADVICE
Twenty-fifth session
Nairobi, 6–14 November 2006

Item 6 of the provisional agenda
Research and systematic observation

Report on a coordinated response from space agencies involved in global observations to the needs expressed in the Global Climate Observing System implementation plan

Submission from the United States of America on behalf of the Committee on Earth Observation Satellites

1. The Conference of the Parties (COP), by its decision 5/CP.10, invited Parties that support space agencies involved in global observations to request these agencies to provide a coordinated response to the needs expressed in the Global Climate Observing System (GCOS) implementation plan.

2. The Subsidiary Body for Scientific and Technological Advice (SBSTA), at its twenty-third session (FCCC/SBSTA/2005/10, para. 92), welcomed and accepted the offer from the Committee on Earth Observation Satellites (CEOS), on behalf of the Parties supporting space agencies involved in global observations, to provide a detailed report to the SBSTA, at its twenty-fifth session, on a coordinated response to the needs expressed in the GCOS implementation plan. This document contains the above-mentioned report from the United States of America on behalf of the CEOS.

3. In accordance with the procedure for miscellaneous documents, this document is reproduced[*] in the language in which it was received from the CEOS and without formal editing.

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FCCC/SBSTA/2006/MISC.14

GE.06-64421

Satellite Observation of the Climate System

The Committee on Earth Observation Satellites (CEOS) Response to the Global Climate Observing System (GCOS) Implementation Plan (IP)

Developed by CEOS and submitted to the United Nations Framework Convention on Climate Change (UNFCCC) Subsidiary Body on Scientific and Technical Advice (SBSTA) on behalf of CEOS by the United States of America (USA) delegation

TABLE OF CONTENTS

EXECUTIVE SUMMARY 4

1. INTRODUCTION 6

1.1 Purpose of the Report 6
1.2 Background 6

2. SATELLITE OBSERVATIONS FOR CLIMATE 7

2.1 GCOS Principles, Requirements, and Recommendations 7
2.2 Current Framework for Provision of Satellite Earth Observations 8

3. CEOS RESPONSE BY DOMAIN TO THE GCOS IP 9

3.1 Atmospheric Domain Response and Corresponding Actions 9
3.2 Oceanic Domain Response and Corresponding Actions 14
3.3 Terrestrial Domain Response and Corresponding Actions 18

4. ACTIONS RELATED TO THE GCOS CROSS-CUTTING NEEDS 20

4.1 Engagement of Climate Needs 20
4.2 Specific Cross-Cutting Needs Raised by GCOS 21

5. THE WAY FORWARD 25

6. ACKNOWLEDGEMENTS 27

Appendix 1: CEOS Actions in Response to the GCOS IP 28

Appendix 2: Atmospheric Domain—ECV Analysis 32

Appendix 3: Oceanic Domain—ECV Analysis 36

Appendix 4: Terrestrial Domain—ECV Analysis 39

Appendix 5: Importance of Consistent Calibration and Validation 47

Appendix 6: The Committee on Earth Observation Satellites 48

Appendix 7: Glossary of Abbreviations and Acronyms 49

Appendix 8: Contributors to this Report 53

EXECUTIVE SUMMARY

At the tenth Conference of the Parties (COP-10) to the United Nations Framework Convention on Climate Change (UNFCCC), the Parties that support space agencies were invited to provide a response to the needs expressed in the Global Climate Observing System (GCOS) Implementation Plan (IP).[1] The Committee on Earth Observation Satellites (CEOS), as the primary international forum for coordination of space-based Earth observations, agreed to respond. At COP-11, an initial document was submitted that outlined the approach CEOS would take in responding to the GCOS requirements.

This report provides a response by CEOS regarding the adequacy of past, present, and future satellite measurements in support of GCOS. It specifically responds to the UNFCCC needs for satellite observations as detailed in the GCOS IP and its Satellite Supplement.[2] Responding to these needs represents a unique opportunity for space agencies to review the way in which multi-agency cooperation on climate-related observations is prioritised, agreed, funded, implemented, and monitored. In this report, CEOS identifies what can be achieved by better coordination of existing and future capabilities as well as those improvements that require additional resources and/or mandates beyond the present capacity of space agencies. This report is intended to initiate action and assist the Parties in advising and commenting on the planning actions within the agencies.

The GCOS IP notes that satellites provide a vital means of obtaining observations of the climate system from a global perspective, and that a detailed global climate record for the future will not be possible without a major, sustained, satellite component. It further notes that 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 the data are climatically accurate and homogeneous. To this end, the GCOS Climate Monitoring Principles (GCMPs) call for continuity of observations, calibration and validation of observations, access to data, and research and development.

Although almost all Earth-observing satellite systems were not specifically designed for climate monitoring, space agency efforts have initiated a remarkably comprehensive climate data record that is forming the basis for better understanding the Earth's climate system. Much has been accomplished, but clearly, more remains to be done. Significant gaps remain in measurement capabilities and their continuity.

CEOS agencies operate satellites that collect data from three domains—atmospheric, oceanic, and terrestrial—necessary to establish key Earth system parameters, the so-called Essential Climate Variables (ECVs), required to meet the needs of the Parties to the UNFCCC. For each domain, CEOS has validated the satellite component of the GCOS IP and responded with detailed analyses and corresponding actions (presented in Sections 3 and 4 and listed in the first appendix) that fall into the following six key categories:

1. ensuring continuity of climate-relevant satellite measurements (13 actions);
2. taking a systematic approach to generating fundamental climate data records (FCDRs) (11 actions);
3. preserving climate data records (4 actions);
4. ensuring access to climate data products (10 actions);
5. coordinating international communities and interaction with users (10 actions); and
6. addressing future measurement needs (11 actions).

[1] Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, GCOS-92, October 2004 (WMO/TD No. 1219)

[2] Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS-92)", GCOS-107, September 2006 (WMO/TD No. 1338)

In addition to working to improve climate-related products, CEOS has identified opportunities for meeting the additional requirements by reprocessing historical data collections, improving data continuity, and moving measurements from research to operations. CEOS agencies recognize the need to ensure adequate retrieval, processing, archiving, and provision of historical satellite data and will investigate methods for doing so.

While recognising that different nations and agencies may pursue different thrusts and respond to diverse priorities, CEOS has launched an initiative to develop guidelines and criteria for agencies to implement groups, or "constellations," of satellites and their associated ground support systems. These Constellations will work in a coordinated manner to address a specific set of goals including the actions of this report. It is anticipated that CEOS Constellations will be used to enable more cost-effective missions and allow valuable contributions from a wide range of parties.

In the nearly 15 years since the UNFCCC was adopted, government recognition and public awareness of global climate change has increased substantially. GCOS, in consultation with its partners, has developed a credible plan that, if implemented, will lead to a much-improved understanding of climate change. Additionally, with the advent of the Global Earth Observation System of Systems (GEOSS), more attention has been given to the nine Societal Benefit Areas (SBAs), including that of climate. CEOS appreciates that meeting the UNFCCC climate needs described by GCOS would also contribute significantly to most, if not all, of the other SBAs. CEOS additionally recognises that not all Parties are able to fully benefit from access to satellite products and will give priority to improving such access.

Within this context, CEOS proposes the following way forward:

1. The Parties are invited to note the many wide-ranging and challenging actions identified in this report. CEOS agencies will work with their governing bodies to secure the additional resources that are required to meet the UNFCCC needs.

2. CEOS will work with GCOS to continue to strengthen the communication and cooperation that has led to the extremely productive dialogue in recent years.

3. CEOS notes the encouragement of past UNFCCC decisions and welcomes feedback from the Parties on the CEOS response to the GCOS IP. CEOS also understands the importance of reporting to the UNFCCC on systematic observations and progress, and, if requested by the Parties, would be willing to do so.

In conclusion, CEOS recognizes that both satellite and *in situ* data are required to better monitor, characterize, and predict changes in the Earth system. While *in situ* measurements will remain essential and largely measure what cannot be measured from satellites, Earth-observation satellites are the only realistic means to obtain the necessary global coverage, and with well-calibrated measurements will become the single most important contribution to global observations for climate.

Satellite Observation of the Climate System

The Committee on Earth Observation Satellites (CEOS) Response to the Global Climate Observing System (GCOS) Implementation Plan (IP)

1. INTRODUCTION

1.1 Purpose of the Report

This report provides a response by the Committee on Earth Observation Satellites (CEOS) regarding the adequacy of past, present, and future satellite measurements in support of the Global Climate Observing System (GCOS). It specifically responds to the United Nations Framework Convention on Climate Change (UNFCCC) needs for satellite observations as detailed in the GCOS Implementation Plan (IP).[3] Responding to these needs represents a unique opportunity for space agencies to review the way in which multi-agency cooperation on climate-related observations is prioritised, agreed, funded, implemented, and monitored. In this report, CEOS identifies what can be achieved by better coordination of existing and future capabilities as well as those improvements that require additional resources and/or mandates beyond the present capacity of space agencies. This report is intended to initiate action and assist the Parties in advising and commenting on the planning actions within the agencies.

1.2 Background

At the tenth Conference of the Parties (COP-10) to the UNFCCC, held in December 2004, the Parties that support space agencies were invited (Decision 5/CP.10) to respond to the needs expressed in the GCOS IP. CEOS, as the primary international forum for coordination of space-based Earth observations, agreed to respond. At COP-11, on behalf of CEOS, the Argentine delegation submitted an initial document that outlined the approach CEOS would take in responding to the GCOS requirements.

Concurrently, CEOS requested that GCOS provide additional detail on the nature of the requirements for systematic, satellite-based observations set out in the GCOS IP. This was provided in the form of the GCOS document entitled *Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS-92)"*.[4] Recognising that GCOS represents the systematic observational needs of the Parties to the UNFCCC, the Intergovernmental Panel on Climate Change (IPCC), and also the needs of the World Climate Research Programme (WCRP), CEOS, through this report, is formally responding to the GCOS IP.

Through CEOS, space agencies worldwide are able to provide a concerted response to the requirements for satellite and associated data as described by the GCOS IP on behalf of the climate community. CEOS agencies also note that these same requirements represent those of the Group on Earth Observations (GEO) "Climate" Societal Benefit Area (SBA). In accord with the needs of the UNFCCC for systematic observation, the climate SBA is cross-cutting and therefore includes many elements required in the other SBAs. CEOS is a Participating Organisation in GEO and has pledged its support in coordinating the provision of satellite observations for all nine of the SBAs. In

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[3] Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, GCOS-92, October 2004 (WMO/TD No. 1219)

[4] Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS-92)", GCOS-107, September 2006 (WMO/TD No. 1338). Both the GCOS IP (GCOS-92) and the Satellite Supplement (GCOS-107) are accessible at http://www.wmo.int/web/gcos/gcoshome.html.

undertaking this coordination, a major goal for CEOS is to maximize synergy of observation needs on multiple temporal and spatial scales.

2. SATELLITE OBSERVATIONS FOR CLIMATE

The GCOS IP notes that satellites provide a vital means of obtaining observations of the climate system from a global perspective, and that a detailed global climate record for the future will not be possible without a major, sustained, satellite component.

Space agencies provide the basic satellite observations—Fundamental Climate Data Records (FCDRs)[5]—needed to monitor global climate change. In turn, the end-user products for the Essential Climate Variables (ECVs) are generated by a range of interested communities through a variety of approaches that link satellite observation data with *in situ* data and other information through assimilation into models and other products. Table 1 shows, by domain, those ECVs that are dependent upon, or significantly benefit from, satellite observations. Relations among ECVs and FCDRs and other additional details are discussed in Section 3 and in Appendices 2, 3, and 4, respectively.

Table 1: ECVs Largely Dependent upon Satellite Observations

Domain	Essential Climate Variables (ECVs)
Atmospheric	Surface wind speed and direction, upper-air temperature, water vapour, clouds, precipitation, Earth Radiation Budget (ERB) , ozone, aerosols, carbon dioxide and other greenhouse gases, upper-air winds
Oceanic	Sea ice, sea level, sea surface temperature, ocean colour, sea state, salinity
Terrestrial	Lakes, glaciers and ice caps/sheets, snow cover, surface albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (fAPAR), leaf area index (LAI), biomass, fire disturbance, soil moisture

2.1 GCOS Principles, Requirements, and Recommendations

For the observations mentioned above to yield the required FCDRs, the contributing satellite programmes must be implemented and operated using a range of criteria to meet the GCOS Climate Monitoring Principles (GCMPs), as adopted by COP. In November 2003, CEOS adopted the GCMPs, but it is evident that individual space agencies have not systematically applied these principles to their satellite programmes. There presently exists no process for identifying, prioritizing, and implementing cross-agency actions to ensure that user community needs are satisfied—with the exception of meteorology, where the Coordination Group for Meteorological Satellites (CGMS) plays an important role. This situation should and will be corrected (see Section 4).

[5] The term "Fundamental Climate Data Record" (FCDR) is used to denote a long-term data record, involving a series of instruments, with potentially changing measurement approaches, but with overlaps and calibrations sufficient to allow the generation of homogeneous products providing a measure of the intended variable that is accurate and stable enough for climate monitoring. FCDRs include the ancillary data used to calibrate them. For "one-off" research spacecraft, the principles of continuity obviously do not 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.

Taken as a whole, the GCMPs[6] call for continuity, calibration and validation, accessibility, and research and development (R&D). The GCMPs have important implications for the way satellite Earth observations are provided; specifically:

- **continuity of observations**—continuity of key observations must be guaranteed by one or more countries or regions undertaking to ensure a series of missions capable of supplying the necessary measurements well into the future without gaps in temporal or spatial coverage;
- **calibration and validation**—careful attention must be paid to the calibration, validation, and intercomparison of the different satellite-based sensors, and to overlap in successive missions, in creating a single climate variable record in order for satellite observations to satisfy the requirements for homogeneity, stability, and accuracy;
- **ensured access to data—**access to data must be guaranteed and data need to be archived with comprehensive metadata and most readily accessible arrangements; and
- **research and development**—space technology has demonstrated its potential to overcome limitations of techniques for climate-quality measurements. Space agencies must strengthen their R&D efforts to improve measurements of ECVs and to create reliable climate data records.

Specific recommendations from GCOS that emerged from these principles are to ensure:

- attention to the needs identified in this report related to the planning, initiation, and continuity of satellite missions that are needed to provide satellite climate data records;
- a systematic approach in applying, to the greatest extent possible, the GCMPs for the generation of satellite climate data records, recognizing in particular the need for overlap in missions, and for *in situ* measurement for calibration and validation purposes;
- long-term custody of present and future satellite climate data records and their associated metadata, and open access to these records;
- generation of, and access to, products based on the satellite climate data records;
- wide and ongoing interaction among the international scientific, operational, and end-user communities that will enable effective feedback mechanisms and continuing advice on observation and product needs; and
- the sustaining of active research satellite programmes that address challenging measurement needs and that allow capabilities to advance and be more cost effective.

2.2 Current Framework for Provision of Satellite Earth Observations

The development and operation of space vehicles, launchers, and instruments are highly technical endeavours and are generally delegated by national governments to specialised space agencies. A typical space agency has responsibility for overseeing all aspects of the space activities of its host national or regional government. Applications of Earth-observation satellite programmes are typically numerous and diverse, including, but not limited to, studies of climate, environmental issues, agriculture, meteorology, and natural disasters.

In broad terms, CEOS membership comprises two kinds of space agencies:

- **research agencies**, which typically undertake cutting-edge R&D activities, often involving "one-off" Earth-observation missions intended to demonstrate a technical concept of measurement capability in support of well-identified science objectives; and
- **operational agencies**, which are funded by governments to make continuous and time-critical observations, ensuring that there are no temporal or spatial gaps in coverage. A limited number of space agencies fall into this operational category.

[6] The GCMPs were the subject of a report authored by George Ohring and others entitled "Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop" (*Bulletin of the American Meteorological Society,* vol. 86, no. 9, p. 1304). GCOS has used this report in a review of the climate requirements noted in the World Meteorological Organization (WMO)/CEOS database of satellite requirements. The report, also used and referenced by GCOS in its Satellite Supplement (GCOS-107) to the GCOS IP, represents the best available detailed assessment of the ability of current observing systems to meet the GCMPs.

To date, issues such as data and mission continuity, overlap, and cross-calibration have been undertaken by research agencies on a "best efforts" basis. While a typical mission involves considerable effort dedicated to these activities, and the funding agencies are mindful of the need to follow the GCMPs to the greatest extent possible, there remains a need to ensure that this happens systematically. In recent years, agencies have endeavoured to ensure continuity of some key measurements (*e.g.*, ocean surface altimetry) that have become established as near-operational within some user communities. This remains, however, the exception rather than the rule for research-oriented space agencies, which are neither mandated nor funded to provide operational services.

In contrast to research-focused satellite programmes, the satellite programmes of operational agencies have many of the characteristics required by GCOS for climate applications, such as sustained, overlapping, and coordinated coverage. Although recognition of the need to transition research satellites that provide observations required by the GCOS IP into operational systems is growing, constructing such a migration path in the planning for current and future systems remains difficult.

Despite the utility of satellite Earth observations for climate, it also should be understood that there is presently no overall strategy across nations for a comprehensive design of these systems. Most contributing missions were neither intended nor optimised for climate purposes. Therefore, gaps and needed improvements have been identified to realise the ambitions expressed in the GCOS IP. Sections 3 and 4 discuss these challenges and present corresponding actions.

Concurrently, CEOS has undertaken an effort to develop guidelines and criteria for agencies to implement groups, *i.e.*, "constellations," of satellites that can work in a coordinated manner to accomplish a specific goal or set of goals. Rather than trying to cover the whole spectrum of observational needs, the Constellations effort seeks to ensure that cooperatively, space agencies will in the future provide space-based observations that satisfy the key, relevant, user-community requirements and maximise opportunities for measurement continuity. CEOS, in cooperation with CGMS as appropriate, will accelerate the definition of the CEOS Constellations concept and work with GCOS to test the process by addressing one or more of the most crucial FCDRs, thus ensuring that the Constellation criteria address the GCMPs.

3. CEOS RESPONSE BY DOMAIN TO THE GCOS IP

The global observing system for climate requires observations from all domains—atmospheric, oceanic, and terrestrial—that are subsequently transformed via integration and analysis into products and information. In this section, domain-specific responses as to the adequacy for climate purposes of information derived from current and planned space systems, together with proposed actions to address inadequacies, are discussed. Additional details specific to all relevant ECVs and FCDRs in the atmospheric, oceanic, and terrestrial domains are presented in Appendices 2, 3, and 4, respectively. These appendices identify many issues requiring attention that the following high-level summaries do not include. It should be noted that the following proposed actions are in addition to the ongoing actions of space agencies that are helping to meet the goals of the GCOS IP.

3.1 Atmospheric Domain Response and Corresponding Actions

Atmospheric observation from space has evolved significantly over the past few decades, thanks in part to new capabilities offered by high spectral resolution infrared sounders, Global Positioning System (GPS) radio occultations (RO), microwave scatterometry, solar occultations, limb-viewing microwave measurements, visible and ultraviolet imagers, cloud radar, and lidar (light detection and ranging). Some of these research capabilities are being transitioned to operational missions such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the polar-orbiting Meteorological Operational (MetOp) satellites; other capabilities are not yet being transitioned in this way, but need to be. Although research instruments have demonstrated an observing capability for a number of ECVs, additional sustained calibration and validation of the FCDRs, further development and improvement of algorithms, and more algorithm processing and reprocessing are needed. Many Earth-observing systems currently in operation were not specifically designed for climate monitoring; hence, extremely careful data analysis must be performed to reduce systematic biases for more demanding climate applications, such as determining climate trends.

The current GCOS IP provides, at a high level, critical requirements for CEOS space agencies to address inadequacies in the acquisition and utilisation of satellite data necessary to contribute fully and effectively to a detailed and long-term global climate record. CEOS also agrees with the GCOS IP and its supplement, GCOS-107, that there are outstanding issues requiring research, including: monitoring of water vapour; understanding the 3-dimensional character of clouds and their relation to atmospheric circulation and dynamics; monitoring of the composition and distribution of aerosols; estimation of surface wind speed and direction; improved accuracy in the estimation of high temporal resolution precipitation amount and type (especially over the oceans and at high latitudes); synthesis of quality-assured greenhouse gas and ozone data; and development of consistent, unbiased, homogeneous reanalysis products for all ECVs. Table 2 provides an overview of the needs for products and sustained satellite data records for the atmospheric domain.

Table 2: Overview of Products – Atmospheric Domain

Essential Climate Variables (ECVs)/ Global Products requiring Satellite Observations	**Fundamental Climate Data Records (FCDRs) required for Product Generation (from past, current and future missions)**
Surface Wind Speed and Direction Surface vector winds analyses, particularly from reanalysis	Passive microwave radiances and scatterometry
Upper-air Temperature Homogenized upper-air temperature analyses: Extended Microwave Sounding Unit (MSU)-equivalent temperature record; New record for upper-troposphere and lower-stratosphere temperature using data from radio occultation; Temperature analyses obtained from reanalyses	Passive microwave radiances; GPS radio occultation; High-spectral resolution infrared (IR) radiances for use in reanalysis
Water Vapour Total column water vapour over the ocean and over land; Tropospheric and lower-stratospheric profiles of water vapour	Passive microwave imagery; Ultraviolet/visible (UV/VIS) imagery; IR imagery and soundings in the 6.7 µm band; Microwave soundings in the 183 GHz band
Cloud Properties Cloud radiative properties (initially key International Satellite Cloud Climatology Product (ISCCP) products)	VIS/IR imagery; IR and microwave soundings
Precipitation Improved estimates of precipitation, both as derived from specific satellite instruments and as provided by composite products	Passive microwave radiances; High-frequency geostationary IR measurements; Active radar (for calibration)
Earth Radiation Budget (ERB) Top-of-atmosphere ERB on a continuous basis	Broadband radiances; Spectrally-resolved solar irradiances; Geostationary multi-spectral imagery
Ozone Profiles and total column of ozone	UV/VIS and IR/microwave radiances
Aerosol Properties Aerosol optical depth and other aerosol properties	VIS/near infrared (NIR)/short-wave infrared (SWIR) radiances
Carbon Dioxide, Methane, and other Greenhouse Gases Distribution of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), of sufficient quality to estimate regional sources and sinks	NIR/IR radiances
Upper-air Wind Upper-air wind analyses, particularly from reanalysis	VIS/IR imagery; Doppler wind light detection and ranging (lidar)
Atmospheric Reanalyses	Key FCDRs and products identified in this report, and other data of value to the analyses

(Adapted from: Table 2, GCOS-107, p. vii)

As to the current status of space observations for the atmospheric domain ECVs, surface winds are measured adequately by scatterometers, although gaps in coverage persist; additionally, passive measurements have not been proven. For upper atmospheric temperature, tropospheric trend estimates are barely adequate but RO data may help. Total column water vapour is adequate but profiles are not—combined radiometric and RO measurements may offer hope. Cloud products are barely adequate for large-scale spatial structure, regional variability (El Niño Southern Oscillation (ENSO)), and model validation; they are inadequate for monitoring climate change. Precipitation records have major biases in month-to-month variations over broad areas; solid precipitation is poorly measured. Ozone total column provides gross change and fluctuations, but profile information has limited resolution and lacks continuity. Adequate aerosol measurements are beginning to be demonstrated, but there are neither long-term holdings nor adequate plans to acquire them. Greenhouse gas measurements have not been adequate, but there are promising plans to demonstrate new capabilities. Reanalysis programs have been started, but need inter-calibrated measurements to investigate trends.

In addition to the use of the operational meteorological satellite system, it is of vital importance to obtain sustained climate quality measurements of critical climate forcing and response variables. The following measurements are of basic importance to obtaining a sustained climate benchmark:

- GPS occultation measurements for precise monitoring of upper tropospheric and lower stratospheric temperatures;
- total solar irradiance measurements for monitoring variations in solar forcing of the Earth's climate;
- Earth Radiation Budget (ERB) measurements of the total longwave radiation emitted and total solar radiation reflected back to space by the Earth-atmosphere system;
- absolute, spectrally resolved measurements of radiance emitted and reflected by the Earth to space for information on variations in both climate forcings and responses and to calibrate the operational meteorological satellite sensors;
- a self-calibrating Stratospheric Aerosol and Gas Experiment (SAGE)-type instrument for upper-tropospheric and stratospheric ozone, volcanic aerosols, water vapour, and other minor atmospheric constituents; and
- a high-precision scanning multi-spectral polarimeter for tropospheric aerosol measurements.

Some of these instruments were planned for flight on NPOESS, but are now on hold. Specific shortfalls include:

- ozone profiling capability (without solar occultation and Ozone Mapping and Profiler Suite (OMPS) limb-scanner);
- capability to measure aerosol particle composition and shape/size (without Atmosphere Polarimeter Sensor (APS)); and
- more than twice-daily scatterometer sea surface wind measurements (exclusively relying on mid-A.M. Advanced Scatterometer (ASCAT)).

Provision for such measurements must be re-planned and CEOS will ensure that attention is given to these needs.

Currently, specific data gaps in the atmospheric domain of the climate observing system that are imminent include:

- Tropical Rainfall Measuring Mission (TRMM) follow-on (F/O), Global Precipitation Measurement (GPM) unlikely to fill gap;
- ERB-like measurements after 2020 (last Clouds and the Earth's Radiant Energy (CERES) goes on NPOESS C1);
- adequate RO measurement coverage after Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC);

- polar atmospheric motion vectors after Moderate Resolution Imaging Spectroradiometer (MODIS) (~2010); and
- atmospheric motion vectors from lidar after the Advanced Dynamics Mission (ADM) Aeolus demonstration, which starts in 2007.

To meet the challenges of observations for climate in the atmospheric domain, CEOS puts forth the following actions in response to GCOS recommendations:

Surface Winds: ensure two-satellite measurement of surface wind speed and direction.

Sea surface winds have been estimated with passive microwave radiometers and active scatterometers since the late 1980s. The absence of measurements from both A.M. and P.M. polar orbiters has created gaps in the coverage. Moreover, the capability of passive microwave sensors to make scatterometer quality measurements of surface winds still needs review. Passive microwave radiometers with a full polarimetric capability can provide both wind speed and wind direction simultaneously, but the direction retrieval becomes less accurate under light wind conditions, compared to scatterometers.

Action A-1: In 2007 CEOS agencies will review the capability of passive microwave sensors to make scatterometer-quality measurements and will work to ensure A.M. and P.M. satellite coverage of surface wind speed and direction by 2015.

Upper-Air Temperature and Upper-Air Moisture: ensure the continuity of radio occultation measurements.

Infrared (High Resolution Infrared Radiation Sounder (HIRS)) and microwave sounders (Microwave Sounding Unit (MSU) and Advanced Microwave Sounding Unit (AMSU)) have been providing atmospheric profiles for almost thirty years. Trend analyses in the stratosphere and troposphere have been elusive. Recent advances with high spectral resolution infrared (Atmospheric Infrared Sounder (AIRS)) and RO measurements (Coral Health and Monitoring Program (CHAMP) and COSMIC) offer hope for improvement. Moreover, the complementary aspects of radiometric and geometric measurements offer new opportunities for more accurate upper-air determinations of temperature and moisture. Thus, planning for the continuity of the record of RO measurements is needed.

Action A-2: CEOS will strive to ensure continuity of GPS RO measurements with, at a minimum, the spatial and temporal coverage established by COSMIC by 2011. CEOS will continue efforts in 2007 to exploit the complementary aspects of radiometric and geometric upper-air determinations of temperature and moisture.

Clouds: utilize Cloudsat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) records for validating multispectral measurements of cloud properties.

Accurate measurement of cloud properties has proven to be exceedingly difficult. The WCRP International Satellite Cloud Climatology Project (ISCCP) has developed a continuous record of infrared and visible radiances since 1983 utilizing both geostationary and polar orbiting satellite data, but the record suffers from heterogeneities. Combining multispectral measurements from both imagers and sounders offers promise for improved cloud records and the research missions, Cloudsat/CALIPSO, are providing validation opportunities.

Action A-3: CEOS will support in 2007 investigations of cloud properties and cloud trends from combined satellite imager plus sounder measurements of clouds (with horizontal as well as vertical information) using Cloudsat/CALIPSO for validation.

Precipitation: ensure continuity of precipitation measurements.

Precipitation measurements from space remain a major challenge. Infrared measurements are obscured by clouds and microwave measurements lack the needed temporal and spatial resolution. Major biases and month-to-month variations over broad areas exist in different satellite-derived precipitation fields. In addition, measurement of solid precipitation remains to be addressed. Recently improved measurements have been demonstrated, but future plans remain unclear. A TRMM F/O mission must be arranged as soon as possible to mitigate the likely data gap in these unique measurements.

Action A-4: CEOS agencies will ensure continued improvements to precipitation determinations demonstrated by TRMM and planned by GPM in 2010. The Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA) will lead a CEOS study team to establish, by 2007, the basis for a future Global Precipitation Constellation.

Earth Radiation Budget (ERB): promote the development of continuous, calibrated, absolute, spectrally resolved ERB measurements.

The past multi-satellite record of ERB measurements suffers from an absence of absolute calibration. It is recognized that development of absolute spectrally resolved measurements is needed to provide information on variations in both climate forcings and responses and to calibrate the operational meteorological satellite sensors. In addition, there is the likelihood of a measurements gap after 2020; the recent change in NPOESS plans for climate-relevant measurements call for coordinated re-planning efforts.

Action A-5: CEOS will plan by 2011 to make absolute, spectrally resolved measurements of radiance emitted and reflected by the Earth to space for information on variations in both climate forcings and responses.

Action A-6: CEOS agencies will participate in re-planning, by 2007, the Earth Radiation Budget Sensor (ERBS) removed from the planned payload of NPOESS.

Action A-7: CEOS agencies will participate in re-planning, by 2007, the Total Solar Irradiance Sensor (TSIS) removed from the planned payload of NPOESS.

Ozone: ensure continuity of ozone measurements.

Measurements from the Total Ozone Mapping Spectrometer (TOMS) and the Solar Backscatter Ultraviolet (SBUV) have provided an adequate record of gross change and fluctuation of total column ozone since the late 1970s. Shorter term records from research instruments are providing opportunities for valuable inter-calibration. Reprocessing of data sets with improved algorithms is planned to overcome instrument biases. Profiles of ozone were to be addressed by the NPOESS OMPS, but that instrument has been removed from the payload manifest. Furthermore, the discontinuation of solar occultation measurements will profoundly impact one of the FCDR pillars of ozone assessments.

Action A-8: CEOS agencies will participate in re-planning, by 2007, the OMPS limb instrument removed from the planned payload of NPOESS.

Aerosols: ensure calibrated, space-based aerosol measurements.

Advanced Very High Resolution Radiometer (AVHRR) records of aerosol optical depths suffer from the absence of onboard visible calibration. No operational aerosol instruments measuring particle composition and size/shape have been flown to date and efforts should be made to rectify this. It is recognized that the aerosol measurements from APS are no longer likely and that some re-planning must occur. Finally, operational active sensing lidar (*e.g.*, CALIPSO) from satellites should be considered.

Action A-9: CEOS agencies will participate in re-planning, by 2007, the APS instrument removed from the planned payload of NPOESS.

Greenhouse Gases: ensure continuity of greenhouse gas measurements.

The characterization of greenhouse gases and their sources and sinks has begun to emerge from measurements by research instruments on the Environmental Satellite (Envisat) and the Earth Observing System (EOS) satellites Terra, Aqua, and Aura. The advent of high spectral resolution infrared measurements (AIRS, Infrared Atmospheric Sounding Interferometer (IASI), and Cross track Infrared Sounder (CrIS)) is offering the promise of some sustained greenhouse gas measurements (CO_2, CH_4, and others). Moreover, when integrated with future measurements from atmospheric chemistry missions planned for the next 5 to 7 years, such as the Orbiting Carbon Observatory (OCO), the promise is even greater. However, the demonstrations of potential future operational measurements are neither complemented by plans for operational implementation nor any R&D follow-on.

Action A-10: CEOS agencies will participate in planning, by 2011, the operational follow-on to current chemistry missions and those planned for the next 5 to 7 years.

Upper-Atmospheric Winds: ensure continuity of upper-atmospheric wind measurements. Atmospheric motion vectors inferred from time sequences of geostationary satellite measurements (GOES, Meteosat, and GMS) have been recently supplemented by the addition of water vapour winds from polar orbiters (MODIS). Repeated reprocessing of these wind measurements is necessary in order to reduce wind-speed biases and spurious trends in the operational products. Plans need to be made to continue the polar-orbiting wind measurements. In addition, the promise of lidar measurements of atmospheric motions must be explored and incorporated into future plans.

Action A-11: CEOS agencies will commit in 2007 to reprocessing the geostationary satellite data for use in reanalyses projects before the end of the decade.
Action A-12: CEOS will determine options by 2010 for continuing improvements to wind determinations demonstrated by MODIS and to be demonstrated by ADM Aeolus.

3.2 Oceanic Domain Response and Corresponding Actions

Ocean observation from space has reached a high level of maturity in the past few years through a series of experimental, research-oriented, dedicated missions and instruments. These missions and instruments were purpose-built, most frequently with a focus on the climate-ocean relationship. As a result, there is an almost one-to-one correspondence between ECVs and FCDRs in the oceanic domain (Table 3).

Table 3: Overview of Products – Oceanic Domain

Essential Climate Variables (ECVs)/ Global Products requiring Satellite Observations	Fundamental Climate Data Records (FCDRs) required for Product Generation (from past, current and future missions)
Sea Ice Sea-ice concentration	Microwave and visible imagery
Sea Level Sea level and variability of its global mean	Altimetry
Sea Surface Temperature Sea surface temperature	Single and multi-view IR and microwave imagery
Ocean Colour Ocean colour and oceanic chlorophyll-a concentration derived from ocean colour	Multi-spectral VIS imagery
Sea State Wave height and other measures of sea state (wave direction, wavelength, time period)	Altimetry
Ocean Salinity Research toward the measurement of changes in sea-surface salinity	Microwave radiances
Ocean Reanalyses Utilizing altimeter and ocean surface satellite measurements	Key FCDRs and products identified in this report, and other data of value to the analyses

(Adapted from: Table 3, GCOS-107, p. vii)

Some FCDRs are available from satellite measurements undertaken since the early 1980s; many others were obtained in the 1990s. Remote sensing of oceans is obviously limited by the opacity of water to electromagnetic radiation. As oceans cannot be profiled from space, all remotely-sensed ocean data represent superficial (temperature, topography, colour, ice cover) characteristics. At best, sea surface height—as measured by high-accuracy altimeters—gives access to the ocean pressure gradient along the vertical, from which the ocean large-scale velocity field can be derived under specific assumptions.

After having long been an open space for competition and conquest, ocean observation is now becoming a domain for collaboration and partnership. No one nation can reasonably provide a single global observing system to meet all needs for ocean and climate data. In 1997, the Global Ocean Data Assimilation Experiment (GODAE) concept emerged from discussions of the Ocean Observation Panel for Climate (OOPC) with CEOS in the context of the then-proposed Integrated Global Observing Strategy (IGOS). Building on the demonstrated strengths of ocean observation from space, the concept was developed in the belief that attracting the resources necessary for an adequate, long-term, global ocean observing system for ocean monitoring depends upon a clear demonstration of the feasibility and value of such a system. The GODAE vision was that of "a global system of observations, communications, modelling, and assimilation that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community".[7] With GODAE, progress in ocean observation and its application to climate monitoring and studies has been greatly enhanced.

Space-based ocean observations for climate are currently at a crossroads: unless additional urgent actions in response to relevant GCOS requirements are taken, only observations for the sea surface temperature ECV will be adequate in the next six years. The level of observation for all other ocean ECVs will be marginal (sea ice, sea state) or even inadequate (sea level, ocean colour) within and beyond that timeframe. It should be noted, however, that new research missions are planned that will provide the first-ever measurements of sea surface salinity, an emerging ECV.

To meet the challenges of observations for climate in the oceanic domain, CEOS puts forth the following actions in response to GCOS recommendations:

Sea Ice: sustain appropriate microwave and visible imagery measurements and ensure consolidation of existing sea ice products.

Past provisions of sea ice FCDRs include microwave brightness temperatures and retrieved sea ice concentration/extent from various sensors since 1978, and provide clear opportunities for reprocessing. Microwave brightness temperatures are currently being continuously provided by several sensors and forthcoming missions. There is a potential gap of high-resolution ice observation. VIS/IR data records with moderate resolution are also provided by a number of existing and planned missions. NASA's Quick Scatterometer mission (QuikSCAT) is the only mission (already beyond nominal lifetime) that is currently providing continuous σ_0 data records. The European Organization for the Exploitation for Meteorological Satellites' (EUMETSAT) MetOp/ASCAT (to be launched in 2006) will improve this situation.

Action O-1: CEOS agencies will examine their respective plans to maintain provision of microwave brightness temperatures and visible/infrared radiances for the sea ice ECV.
Action O-2: Relevant CEOS space agencies will consult with the science community on appropriate retrieval algorithms of passive microwave observation for reprocessing sea ice products. Norway has expressed interest in committing to operational production of a global sea ice ECV (an initiative by the Norwegian Meteorological Institute, and coordinated by the Norwegian Space Center). The European Space Agency (ESA) is currently reprocessing the relevant ERS and Envisat archives to complement Canada's Radarsat in the context of WCRP's Climate and the Cryosphere (CLiC) core project.
Action O-3: New space-based measurements and products, including ice thickness and ice drift, will be considered by CEOS agencies as part of their future research missions.

[7] Global Ocean Data Assimilation Experiment – Strategic Plan, GODAE Report No. 6, GODAE International Project Office, Bureau of Meteorology, Melbourne, Australia, 2001.

<u>Sea Level</u>: ensure continuity of high-accuracy altimetry measurements.

A series of dedicated high-accuracy altimetry missions has been operated continuously since 1992 (Ocean Topography Experiment (TOPEX)/Poseidon, then Jason-1), and complemented for geographical coverage by the polar-orbiting European Remote Sensing satellite (ERS)-1, ERS-2, Envisat, and Geosat F/O; this continuity will be secured (though with little chance of overlap with Jason-1) with the planned launch of Jason-2 in mid-2008. Beyond this, however, there is currently no firm plan. The time series of dedicated high-accuracy altimetry missions must be continued beyond 2012 and complemented by other altimeter data from polar-orbiting platforms.

<u>Action O-4</u>: The National Oceanic and Atmospheric Administration (NOAA) and EUMETSAT will lead a CEOS study team to establish, by 2007, the basis for a future Ocean Surface Topography Constellation that satisfies the threshold requirements for the sea level ECV (and those of the sea state ECV).[8] This will include consideration of a future Jason-3 mission and requirements for new altimeter technologies to improve spatial resolution and extend observations in coastal regions (and over lakes and rivers for the lakes ECV).

<u>Action O-5</u>: The Centre National d'Etudes Spatiales (CNES) and the Indian Space Research Organization (ISRO) will cooperate on a new polar-orbiting altimeter aimed at filling a potential data gap beyond 2008. ESA and the European Union (EU) will lead planning for Sentinel-3 carrying an altimeter to complement spatial/temporal coverage of the sea level (and sea state) ECVs (and possibly sea ice extent and thickness, river, and lake level with the altimeter operating in Synthetic Aperture Radar (SAR) mode beyond 2012).

<u>Sea Surface Temperature</u>: ensure continuity of sea surface temperature measurements.

The continuity of the 4-km-resolution global product must be maintained through adequate instruments onboard operational weather satellites and its quality must be enhanced through high-precision sensors onboard other Earth-observation missions. Sea surface temperature (SST) ECV time series have been supplied with the NOAA AVHRR instruments for almost 30 years (AVHRR-1 on NOAA-6 was launched on June 27, 1979), and complemented by the high-precision ESA Along Track Scanning Radiometer (ATSR) series since July 1991. The AVHRR A.M. orbit observations will be continued with EUMETSAT's MetOp series (first satellite to be launched in 2006) until 2019. P.M. orbit continuity may be broken if NPOESS/ Visible Infrared Imager/Radiometer Suite (VIIRS) does not overlap current NOAA series operations. Microwave radiometers provide all-weather observations of SST (*e.g.*, JAXA's Advanced Microwave Scanning Radiometer-EOS (AMSR-E), and ISRO's Multi-frequency Scanning Microwave Radiometer (MSMR) onboard Oceansat-1 and -2). A gap in microwave observations of SST may happen beyond 2012 after the termination of the Conical Scanning Microwave Imager/Sounder (CMIS) on NPOESS.

<u>Action O-6:</u> An ATSR-like instrument is planned on ESA's Sentinel 3, presently scheduled for launch in 2012. JAXA will lead planning for Global Change Observation Mission-Water (GCOM-W) and GCOM-C (Climate) to maintain continuity of the sea surface temperature ECV.

<u>Action O-7:</u> CEOS agencies will examine their respective plans to maintain provision of microwave brightness temperatures for the sea surface temperature ECV.

<u>Action O-8:</u> Relevant CEOS agencies will examine their respective plans to maintain continuity of a 10-km-resolution sea surface temperature data sets global product.

<u>Action O-9:</u> CEOS agencies will cooperate to support the combination of all existing sea surface temperature data sets into a global FCDR.

<u>Ocean Colour</u>: ensure continuity of ocean colour measurements.

[8] The CEOS Ocean Surface Topography Constellation study will address some of the requirements for the sea state ECV that can be derived from altimeter data.

The ocean colour FCDR started with NASA's MODIS operations on Terra in February 2000, followed closely by ESA's Medium Resolution Imaging Spectrometer (MERIS) on Envisat, NASA's MODIS on Aqua, CNES's Parasol, and JAXA's Advanced Visible and Near Infrared Radiometer (AVNIR). All these missions are currently running in parallel. The continuity of the 25-km-resolution global product must be maintained through adequate instruments onboard polar-orbiting platforms. Degradation is expected beyond 2007, with only one secured mission left.

Action O-10: ISRO will lead planning of Oceansat-2, ESA and the EU of Sentinel-3, and JAXA of GCOM-C, which are all new missions planned to carry an ocean colour sensor.
Action O-11: Relevant CEOS agencies will examine their respective plans to maintain continuity of the 25-km-resolution ocean colour global product.
Action O-12: CEOS agencies will cooperate to support the combination of all existing ocean colour data sets into a global FCDR.
Action O-13: In consultation with GCOS and the relevant user communities, CEOS agencies will explore the means to secure, by 2011, continuity of the 1-km-resolution global ocean colour product needed to fulfil the target GCOS requirements.

Sea State: ensure continuity of altimetry and SAR measurements useful to derive the sea state ECV.

Altimetry and SAR measurements useful for sea state measures (wave height, direction, wavelength, and time period) have been continuously available since 1991 and will be maintained in the future, particularly with the NASA/CNES/NOAA/EUMETSAT's Jason-2 and ESA's Sentinel-3. Sea state records exist from ESA's ERS-1, ERS-2 and Envisat, NASA/CNES' TOPEX/Poseidon and Jason-1, and the U.S. Navy's Geosat Follow On (GFO), but no consolidated data product has ever been produced. New altimeter (wide-swath) and SAR technologies are needed to advance retrieval of near-shore sea state parameters.

Action O-14: CEOS agencies will cooperate with the user community to support efforts aimed at building on the decade-long satellite sea state records and making a comprehensive use of future altimeter- and SAR-bearing missions.

Ocean Salinity: ensure continuity of sea surface salinity measurements.

New research missions must demonstrate capabilities and pave the way to future continuous, climate-quality data records. Ocean salinity is emerging as an important new research product. To date, there has been no contribution from space-based observations to this variable. ESA and NASA/Comisión Nacional de Actividades Espaciales (CONAE) plan to fly demonstrator missions (Soil Moisture and Ocean Salinity (SMOS) and Aquarius/SAC-D) for salinity measurements.

Action O-15: ESA will fly SMOS in 2007 to demonstrate measurement of the sea surface salinity (and soil moisture) ECV; NASA/CONAE will fly Aquarius/SAC-D in 2009 to demonstrate measurement of the sea surface salinity ECV.
Action O-16: CEOS agencies will cooperate in developing future plans for an Ocean Salinity Constellation.

Ocean Reanalysis: ensure the optimal utilisation of data already collected for all ocean ECVs.

For all ocean ECVs, reprocessing of past data sets must be undertaken at regular intervals and their utilisation for ocean reanalysis must be facilitated through framework agreements between CEOS agencies and reanalysis centres.

Action O-17: CEOS agencies will undertake planning for reprocessing past data to improve FCDRs and legacy databases (*e.g.*, AVHRR Pathfinder, ATSR, Sea Level Pathfinder, and the sea ice ECV) in close coordination and partnership with existing advisory groups and reanalysis centres. All Level 2 data products for use in reanalysis should be properly accompanied by estimates of their uncertainty.

Action O-18: **CEOS, through its Working Group on Calibration and Validation (WGCV) and in the context of developing standards for on-going missions and for the Constellations, will recommend best practices for pre-launch and onboard calibration of ocean sensors and for validation of space-based ocean observations with *in situ* sensors, including the establishment and maintenance of calibration and validation sites and networks. This will facilitate the combination of data from different sources and enable the establishment of global data sets and long-term series.**
Action O-19: **CEOS agencies, in cooperation with other partners, will support planning for a follow-on to GODAE by 2007.**

3.3 Terrestrial Domain Response and Corresponding Actions

Considerable improvements in the quality of terrestrial products derived from Earth-observation systems have been achieved, especially since 2000. Recent advances mean that satellite data can be used to systematically characterize many aspects of the hydrosphere, cryosphere, and biosphere. Considerable effort and technical complexity, however, are involved in generating most terrestrial products since FCDRs derived from a variety of satellite missions over a considerable period of time are required to generate many of the individual terrestrial ECVs (Table 4).

Table 4: Overview of Products – Terrestrial Domain

Essential Climate Variables (ECVs)/ Global Products requiring Satellite Observations	Fundamental Climate Data Records (FCDRs) required for Product Generation (from past, current and future missions)
Lakes Maps of lakes; lake levels; and surface temperatures of lakes in the Global Terrestrial Network for Lakes	VIS/NIR imagery, and radar imagery; Altimetry; High-resolution IR imagery
Glaciers and Ice Caps Maps of the areas covered by glaciers other than ice sheets; Ice sheet elevation changes for mass balance determination	High-resolution VIS/NIR/SWIR optical imagery; Altimetry
Snow Cover Snow areal extent	Moderate-resolution VIS/NIR/IR and passive microwave imagery
Albedo Directional hemispherical (black sky) albedo	Multi-spectral and broadband imagery
Land Cover Moderate-resolution maps of land cover type; High-resolution maps of land cover type, for the detection of land cover change	Moderate-resolution multi-spectral VIS/NIR imagery; High-resolution multi-spectral VIS/NIR imagery
Fraction of absorbed photosynthetically active radiation (fAPAR) Maps of fAPAR	VIS/NIR imagery
Leaf area index (LAI) Maps of LAI	VIS/NIR imagery
Biomass Research toward global, above-ground, forest biomass and forest biomass change	L-band / P-band Synthetic Aperture Radar (SAR); Laser altimetry
Fire Disturbance Burnt area, supplemented by active fire maps and fire radiated power	VIS/NIR/SWIR/thermal infrared (TIR) moderate-resolution multi-spectral imagery
Soil Moisture Research toward global near-surface soil moisture map (up to 10-cm soil depth)	Active and passive microwave

(Adapted from: Table 4, GCOS-107, p. viii)

Presently, GCOS requirements are met globally for snow areal extent, land surface temperature, burnt area, and active fires. The requirements are marginally met for mapping lake area, lake level, lake surface temperature, glacier area, updates of glacier area, ice sheet elevation, surface albedo, land cover type, fraction of absorbed photosynthetically active radiation (fAPAR), leaf area index (LAI), fire radiated power, and soil moisture. Threshold requirements are met regionally on a research basis for land cover change, historical land cover change, and biomass. While there has been a strong trend toward improved adequacy of terrestrial products, there are opportunities for meeting additional requirements by reprocessing historical data collections, improving data continuity, and moving from research to operations. Since there is no current standardization of product quality, there is a need for coordinated, ongoing intercomparisons of products, as well as calibration/validation using reference *in situ* networks of FCDRs and resulting products. The CEOS WGCV is already sponsoring such intercomparisons with fAPAR and LAI, but this kind of effort needs to be extended considerably.

CEOS recognizes the need to emphasize retrieval, processing, archiving, and provision of historical satellite data (*e.g*., Landsat and AVHRR) for generating ECVs. Archiving of FCDRs at their original temporal and spatial resolution also is required to support future reprocessing. Current plans for satellite missions are satisfactory for attaining continuity for 250- to 1000-m resolution FCDRs and the potential for reprocessing corresponding historical data is realistic. Continuity of 10- to 30-m resolution FCDRs is essential for a number of ECVs; CEOS will strive to establish workable strategies for producing FCDRs that will meet requirements that are currently not being filled satisfactorily. It must be noted, however, that since additional R&D is needed for several of the terrestrial products, the necessary FCDRs do not guarantee adequate ECVs—they only provide the potential to produce the ECVs.

Calibration and validation of terrestrial products using *in situ* observations, supported by higher-resolution satellite data, are essential to evaluate and characterize ECVs. Thus, an increased emphasis on coordinated *in situ* observation networks for supporting ECVs is essential. Data integration techniques are very important but under-developed in the terrestrial domain. Such techniques are needed to integrate data from multiple satellites as well as from *in situ* data. This integration will allow for the refinement of data products from space observations and improve long-term records. CEOS will encourage its agencies to support research and operational implementation in this area. With appropriate emphasis on archival issues, data continuity, product intercomparisons, and validation efforts, the potential for achieving the GCOS requirements is high, provided appropriate resources are made available.

CEOS believes that the continuity of pertinent space-based observations is the primary challenge in meeting the requirements for the GCOS terrestrial ECVs. This continuity includes a connection to historical Landsat and AVHRR data (to ensure long-term data homogeneity) and assurances that there will not be a data gap in Landsat-class data. In addition, non-optical data such as from lidar and P-band sensors have the potential to address GCOS terrestrial requirements. Although some requirements call for breaking new technical ground, there are recent successes (*e.g*., creating a prototype global albedo product from geostationary satellites) that give cause for optimism in meeting the challenge.

To meet the challenges of observations for climate in the terrestrial domain, CEOS puts forth the following actions in response to GCOS recommendations:

Land Cover and Glaciers: ensure the continuity of terrestrial climate monitoring to monitor land cover and glacier change and to improve the ECVs derived from them.

The current gap of Landsat-class data needs to be addressed using one of several approaches currently being investigated by CEOS agencies. Research efforts need to be directed toward the extraction of the ECVs from this fine-resolution record.

Action T-1: CEOS agencies will determine which alternative approach best fills the current Landsat-class data gap and will explore the potential of integrating high-resolution data from multiple platforms (*e.g*., China-Brazil Earth Resources Satellite (CBERS), Indian Remote Sensing (IRS) satellite, Landsat, Satellite Pour l'Observation de la Terre (SPOT), and others) based on the results of a CEOS study team led by the United States Geological Survey (USGS) that will establish, by 2007, the basis for a future Land-Surface Imaging Constellation.

Action T-2: CEOS agencies will assess the feasibility of generating global historic and continuing ECVs at fine resolutions for land cover and glacier change.

Snow, Albedo, Land Cover, fAPAR, LAI, and Fire: improve the continuity of terrestrial climate monitoring through enhancements of the moderate-resolution historical record.

AVHRR data reprocessing must be undertaken to ensure a consistent data set to fulfil historical fAPAR, LAI, burned area, active fires, land cover, land surface temperature, and snow area requirements. Reprocessed AVHRR data also potentially will contribute to historical albedo.

Action T-3: CEOS (led by USGS and NOAA), in cooperation with relevant stakeholders, will explore the feasibility, by 2007, of retrieving and reprocessing the 1-km AVHRR data record from various centralized archives (NOAA and High Resolution Picture Transmission (HRPT) stations).

Action T-4: CEOS will work to enhance the quality of the FCDRs and the ECVs generated from the AVHRR record to meet threshold requirements.

Biomass and Soil Moisture: ensure the continuity of terrestrial climate monitoring to meet threshold requirements for biomass and soil moisture ECVs.

CEOS recognizes that current algorithms and planned satellite missions do not adequately meet the needs for some ECVs required by GCOS. A lidar or P-band sensor capable of retrieving biomass globally (and avoiding the saturation issue) may be able to achieve GCOS threshold requirements in the long term.

Action T-5: CEOS agencies will undertake research to support satellite technology development, such as lidar or P-band sensors, that are capable of retrieving biomass and LAI globally that meet GCOS requirements. CEOS agencies will also support research to improve algorithms that do not currently meet GCOS threshold requirements. New satellite technology and algorithms should be available by 2015.

Albedo, fAPAR, and LAI: develop new multi-angle observation technologies at moderate resolution (250-m to 1-km) for albedo, fAPAR, and LAI.

CEOS recognizes that current and planned missions are only marginally adequate for meeting the requirements for three ECVs: albedo, fAPAR, and LAI. Multi-angle observations and new algorithms are necessary to derive these ECVs.

Action T-6: CEOS will assess the feasibility of collecting operational multi-angle observations. Research will be carried out by CEOS agencies to improve radiation transfer schemes for albedo and fAPAR, especially under cloudy conditions.

4. ACTIONS RELATED TO THE GCOS CROSS-CUTTING NEEDS

4.1 Engagement of Climate Needs

While most of the GCOS IP requirements for satellite-based products are framed in terms of actions for space agencies that are specific to one of the atmospheric, oceanic, or terrestrial domains, the GCOS IP also puts forward a generic, all-embracing action ascribed to those "parties operating satellite systems" (C10):[9]

GCOS IP – Action C10: Ensure continuity and overlap of key satellite sensors; recording and archiving of all satellite metadata; maintaining currently adopted data formats for all archived data; providing data service systems that ensure accessibility; undertaking reprocessing of all data relevant to climate for inclusion in integrated climate analyses and reanalyses.

[9] GCOS-92, p. 25

In view of this generic action, and in the context of GEO, CEOS members will consider approaches to engaging the following needs and actions:

Effective institutional arrangements

The success of CGMS in advancing cooperation among space agencies involved in the provision of observations for meteorology is testament to the need for specificity of purpose in framing cooperative ventures. Many space agencies participate in both CEOS and CGMS, but more coordination between the two groups is needed. CEOS has spent considerable time reorienting and restructuring its efforts over the last two years in order to improve implementation effectiveness. In particular, CEOS will:

- endeavour to improve the communication between CEOS and CGMS; and,
- affirm the assignment of responsibility for coordination of meteorological satellite issues to CGMS and the support provided by the WMO for that purpose.

Action C-1: CEOS will review the prevailing institutional arrangements in place for the planning and implementation of cooperative efforts by space agencies in the domain of climate (among others) by 2007. In particular CEOS agencies will review the ways to improve coordination of future remote sensing tasks that address the upcoming space-based measurement challenges, so as to avoid duplication of efforts while taking cooperation between the international partners to a higher level.

Working in coordination with GEO

CEOS is a Participating Organisation of GEO and has pledged its support in coordinating the provision of satellite observations for GEO. Additionally, many of the governments with CEOS agencies are Member States of GEO. GEO was established to raise political awareness of, and increase political support for, Earth observations and their benefits for a range of SBAs, and to implement the Global Earth Observation System of Systems (GEOSS). CEOS will keep GEO informed of the relevant actions and progress arising from its cooperation with GCOS so that all the SBAs will benefit from this work.

Action C-2: CEOS agencies will work with GEO to leverage progress and results from the implementation actions for climate to benefit all other relevant SBAs.

Ensuring sustained and effective actions

Recognizing that space agency plans and priorities change, CEOS recommends periodic evaluation of the adequacy of the global climate observing system. Planning future satellite missions for climate studies typically includes integration of substantial input from scientists representing a wide range of disciplines as well as from engineers and policy makers. Initial plans precede execution by several years and during that time, many changes can take place. As a result of new scientific discoveries, measurement priorities may shift and technological advances may enable measurements previously desired, but not planned or funded.

Action C-3: CEOS will work with GCOS to periodically evaluate climate needs and their realization.

4.2 Specific Cross-Cutting Needs Raised by GCOS

The GCOS-107 document further identifies nine cross-cutting needs that are common to many of the ECVs in the three domains. Recognising the need to ensure that future missions address the GCMPs in order to be fit for climate purposes, CEOS will engage the following actions:

1. Systematic and continuous attention given to the GCMPs for each of the designated FCDRs

CEOS recognises the importance of the GCMPs to climate needs and their value to other application areas and will ensure that consideration of these is implicit in agency processes.

Action C-4: CEOS agencies will adjust their internal procedures and mechanisms relative to satellite mission planning and operating processes in order to ensure adequate adherence to the GCMPs.

<u>Action C-5</u>: CEOS agencies will review their respective satellite data records with particular attention to adherence to the GCMPs and will consider undertaking necessary corrective actions within available resources.

Constellations

Space agency cooperative efforts are moving toward a more focused basis, with small groups of agencies working together to specialise in one or more types of measurement for a specific purpose, including the generation of FCDRs. Participation in one of the CEOS Constellations will require agencies to report the degree of compliance given to the GCMPs and any arrangements for access and stewardship by the relevant communities. GCOS is being invited to assist in the design of these Constellations to ensure that GCOS IP requirements will be satisfied. This systematic and specific approach will clarify, from the outset, which missions will, and will not, meet climate community needs. CEOS Constellations will also serve as an incentive for greater data utilisation.

<u>Action C-6</u>: CEOS will consider the GCMPs and relevant ECV requirements in defining criteria that will serve as the foundation for the CEOS Constellation studies being initiated in 2006 and beyond.

2. Comprehensive and routine calibration of satellite instruments

Careful calibration and validation is critical to climate needs and requires agencies to ensure common standards of calibration. Satellite-to-satellite intercomparison approaches may enable requirements to be met in missions that do not, in themselves, reach needed accuracy standards. To achieve this, current international coordination mechanisms need to be both strengthened and sustained to achieve consensus on issues such as validation, quality assurance, and mechanisms to evaluate progress in achieving the goals that GCOS and CEOS have determined to be important. Design of the climate observing system must ensure the establishment of global, long-term climate records that are of high accuracy, tested for system performance on-orbit, and tied to the irrefutable standards of the International System of Units (SI). Authoritative records can be obtained only if future operational satellite instruments have the necessary accuracy and stability specifications, and traceability to SI standards throughout the lifetimes of the sensors.

The concept of a Global Space-based Inter-Calibration System (GSICS) that improves the use of space-based global observations for weather, climate, and environmental applications through operational inter-calibration of the space component of Global Observing System has been endorsed by CGMS and WMO. GSICS notes the need for space-borne and ground-based high-quality reference measurements. CEOS will embrace GSICS principles and establish reference measurements in space, as well as on the ground and in the air, that will enable inter-calibration to quantitatively relate the radiances from different sensors to allow consistent measurements to be taken globally by all elements of the space-based observing systems. In addition, it would provide the ability to retrospectively re-calibrate archived satellite data in order to make satellite data archives worthy for climate studies.

Building on its long-standing experience in developing standards and protocols for space-based data calibration and validation, the CEOS WGCV will be asked to participate in GSICS development and to coordinate CEOS GSICS activities. Agreements on deliverables are to be formulated within the framework of CGMS and reported back to CEOS.

<u>Action C-7</u>: CEOS agencies will increase their cooperation in ensuring stability, accuracy, and inter-comparability of their respective satellite observations. These observations will be tied to irrefutable international standards in order to enhance the utility of space programmes for climate applications.

<u>Action C-8</u>: CEOS agencies will contribute to development of GSICS under development by CGMS and WMO to better integrate calibration efforts. Furthermore, CEOS agencies will continuously pursue establishment of reference measurements in space, complementing those

on the ground and in the air, which will enable absolute inter-calibration of radiance measurements.

***In situ* validation**

Integrating observations and products from different satellite systems requires validation. Ongoing validation efforts such as the EOS Validation Core Sites have been extremely valuable for achieving consistency and continuity in data products. Continuous, long-term, *in situ* systematic observations and periodic research field campaigns are essential components for successful validation. A review of existing validation protocols for ECV products should be undertaken and protocol development proposed where they do not currently exist. More comprehensive data integration techniques are needed to integrate data from multiple satellites as well as from *in situ* data. Research on data integration will lead to the refinement of data products from space observations and improve long-term records.

Action C-9: CEOS will charge its WGCV to promote existing *in situ* networks, identify new opportunities for product validation, and support both validation research and operational validation projects at an adequate level.

3. Archiving and dissemination

CEOS recognizes that space agency investments (particularly during the last decade), new instruments, and a dedicated scientific community have initiated a remarkably comprehensive climate data record that forms the basis for new understanding of the complexities of the Earth's atmospheric, oceanic, and terrestrial domains. However, this record is fragile. Hardware failures, operator errors, and information security incidents put the data record at risk. As the amount of data needing to be stored each year increases, so do associated costs, although technological advances in data storage may mitigate these costs somewhat. There is a need to coordinate future archiving and data dissemination efforts.

Action C-10: CEOS agencies will coordinate their efforts in designing future data archives and data dissemination systems, ensuring that past data holdings (including associated metadata) are preserved, assessing standards and protocols, and incorporating new information technology (IT) developments as much as possible. Practical actions in response to this cross-cutting need will be developed by CEOS' Working Group on Information Systems and Services (WGISS) in line with the technical solutions adopted by GEO.

4. Detailed specification of FCDRs and derived products

Action C-11: CEOS agencies will systematically consult with appropriate scientific and user advisory groups in establishing detailed specifications for each FCDR and derived products, including associated uncertainties.

5. Generation of FCDRs and derived products

In order to increase the accessibility of data records and ensure adequate stewardship of future data acquisitions, space agencies need to embrace and exploit cost reductions in hardware and new IT tools to lower data access costs to users, reduce delays in providing data products and high-quality metadata, and curtail risks to the data record. Developments such as grid computing, Internet services, and Extensible Markup Language (XML)-based protocols offer possibilities for increasing the efficiency of scientific data exploration and application. To this end, CEOS agencies will:

- engage and capture the experience of current large data centres for use in improving the design of future data archives;
- implement, in synergy with the on-going relevant GEO activities, the recommended standards and protocols that will reduce operational costs and encourage data and information sharing; and

- reduce the probability of innovation being lost when operational budget cycles do not mesh with academic innovation development.

<u>Action C-12</u>: CEOS agencies will consult on appropriate rules to ensure sustained, open accessibility to FCDRs in order to allow the periodic reprocessing and generation of homogeneous products.

<u>Action C-13</u>: CEOS agencies will generate, within available resources, independently processed data sets and products.

6. Reanalysis activities and real-time data analysis

Reanalysis activities

<u>Action C-14</u>: Recognising that space agencies are responsible for only a portion of the value chain involved in the generation of FCDRs, CEOS will explore ways to strengthen linkages to the communities involved in climate product generation and use, *e.g.*, through framework agreements with major reanalysis centres.

<u>Action C-15</u>: CEOS agencies will encourage funding of climate change research at an adequate level for multiple groups to analyze data records, reprocess climate variables, and perform reanalysis.

Real-time and near-real-time data analysis

Working to provide the highest quality data in real-time or near-real-time ensures several desirable outcomes in all domains:

- minimal data loss and improved artefact detection through involvement of both the science and applications communities in rapid turnaround data checking;
- improved data integrity and reduced reprocessing effort as a result of moving data quality checking and documentation closer to the time and location of the measurement;
- maintenance of the finest data quality by ensuring continued involvement of the scientific community in the observing system;
- sustainability of the climate record through collaboration of the science and applications communities; and
- maximized efficiency of the system with regard to the number of products and processing streams as well as the spatial and temporal resolution of the climate record.

Any improvements in provision of FCDRs from space must recognise the structural issues that dominate the sector. Research agencies do new things once; operational agencies commit to doing basically the same measurements over and over. If continuity is to be ensured, more climate variables need to be recognised as operational and responsibility assigned to an operational agency. Alternatively, a convergence of research and operational requirements needs to occur, with reassignment of responsibilities between existing agencies. Wherever possible, operational measurements should be specified so that they satisfy climate community needs.

<u>Action C-16</u>: CEOS agencies will consider, in the context of the CEOS Constellations, ways and means to support the transfer of demonstrated observations from research satellites into operational capabilities. In particular, CEOS will encourage "convergence" of climate-observing requirements (usually for high-quality data) with operational requirements (usually for rapid and ensured data availability), and support institutional arrangements that would help transfer ECVs from research to operations.

7. Emerging products

<u>Action C-17</u>: CEOS agencies will maintain R&D efforts aimed at confronting the knowledge challenge posed by climate and climate change, and strive to overcome the current scientific and technical limitations of climate-quality measurements.

Action C-18: CEOS agencies will ensure that data acquired through research satellites are fully used for the benefit of creating and/or improving the FCDRs of all ECVs.

8. Unique fundamental data sets

CEOS agencies are aware of the invaluable legacy from early space-based sensors—a legacy that provides unique multi-decadal data sets for a variety of climate-related products.

Action C-19: CEOS agencies will continue to devote particular efforts to the reprocessing and improvement of these fundamental data sets.

9. Improved community awareness of available and planned satellite missions and data records

CEOS agencies realize that although full global coverage is a unique characteristic of space observation, it is not matched by global participation in the use and application of such data. CEOS agencies recognize the need to ensure global access to key satellite products, and that projects such as the Preparation for Use of Meteosat Second Generation (MSG) in Africa (PUMA) that allow wider participation should be supported. CEOS agencies hope the products derived from space observations will be able to meet the needs of the UNFCCC for global participation. CEOS also notes that such aspirations are central to the mandate of GEO and participating United Nations (UN) system bodies.

Also, as noted earlier, many of the past missions that now provide a valuable climate record were developed for other purposes As a result, CEOS recognises that future usage of these valuable records now requires the transfer of old data records to modern media, assembly of the matching metadata, and the publication of arrangements to access these (often very large) data sets.

Action C-20: CEOS agencies will endeavour to ensure global, easy, and timely access to climate-related products, including by developing countries.

Action C-21: CEOS will establish a programme in 2007 to document the data archive and access arrangements in place for each of the FCDRs contributed by space agencies. WGISS will lead this effort in order to evaluate practical solutions to current obstacles and issues.

Lastly, some aspects of these cross-cutting needs clearly require actions from contributors other than space agencies, and coordination of efforts must be a high priority if the GCOS requirements are to be satisfied.

Action C-22: CEOS agencies will continue their efforts, both individually and through the CEOS Working Group on Education and Training (WGEdu), to build capacity.

5. THE WAY FORWARD

Steady progress has been made since CEOS' inception in 1984. Yet at the start of the 21st century and with the advent of GEOSS, the need for increased coordination of Earth observations from space is even more apparent. This report focuses on the gathering of atmospheric, oceanic, and terrestrial data relevant to the issue of monitoring climate and climate change. Coordination of satellite-based Earth observation is equally essential for the other SBAs being addressed by GEOSS, including disaster mitigation, human health, energy resource management, water resource management, weather forecasting, ecosystems conservation, and sustainable agriculture. The acquisition of data on climate is, however, a need that cuts across all SBAs and CEOS recognises the opportunities and challenges of ensuring maximum synergy in meeting the requirements expressed in the GCOS IP.

In taking actions forward, agreements among several—even multiple—CEOS agencies present opportunities to create and coordinate Constellations of satellites that can increase spatial, spectral, and temporal coverage of the Earth in specific sectors. It is not difficult to envision one country's satellite providing continuous and complete global coverage at a low- to middle-spatial resolution while another country's satellite complements that base coverage with more localized, higher temporal frequency, or greater and more diverse spectral observations. Integrating these observations across time and space and ultimately transforming them into products and information for policy makers has the potential to bring about an extraordinary revolution in global monitoring. Indeed, such a level of global monitoring is a necessity if climate change and the other SBAs are to be addressed in any serious and timely manner.

CEOS recognises that the UNFCCC requirements for satellite observations detailed in the GCOS IP, its supplement (GCOS-107), and the GCMPs are well-judged and technically feasible but challenging in terms of a sustained and coordinated response. The requirements represent a unique incentive for space agencies to improve the way in which multi-agency cooperation on climate-related observations is prioritised, agreed, funded, implemented, and monitored. In addition to better coordination of existing and future capabilities, improvements that will require additional resources and/or mandates beyond the present capacity of space agencies are needed. CEOS recognizes that it will take time and political will to better coordinate, design, operate, process, store, and distribute measurements to satisfy the GCMPs.

Any improvements in provision of FCDRs from space must recognise the structural issues that dominate the sector. Research agencies do new things once; operational agencies do more or less the same things over and over. If continuity is to be ensured, more climate variables must be classified and recognised as operational, and made the responsibility of an operational agency. Alternatively, a convergence of research and operational requirements must occur—with potential reassignment of responsibilities among existing agencies. Wherever possible, operational measurements should be specified so that they satisfy climate community stated needs.

As noted in the GCOS IP, additional Earth-observation resources will be required to meet the GCOS requirements. More importantly, at least initially, is the fact that countries must be willing to make more widely available the data gathered by their civilian Earth-observation satellites, so that the combined value of groups, *i.e*., Constellations, of satellites can be established. Wider use of data, as well as the combination of data from an extended range of missions, should greatly increase data utilisation. Additionally, agreed-upon international standards for calibration and validation, metadata, and data handling would ensure a higher return on investment for satellite missions, although it must be admitted that much remains to be done from an engineering and technical perspective.

In the nearly 15 years since the UNFCCC was adopted, government recognition and public awareness of global climate change has increased substantially. GCOS, in consultation with its partners, has developed a credible plan that, if implemented, will lead to a much-improved understanding of climate change and, through the substantial and inevitable synergy with observation needs of other SBAs, provide major overall improvement in Earth observation.

In summary, CEOS expresses its sincere appreciation to the UNFCCC and the Parties supporting space agencies for this opportunity to comment, and proposes the following way forward:

1. The Parties are invited to note the many wide-ranging and challenging actions identified in this report. CEOS agencies will work with their governing bodies to secure the additional resources that are required to meet the UNFCCC needs.

2. CEOS will work with GCOS to continue to strengthen the communication and cooperation that has led to the extremely productive dialogue of recent years.

3. CEOS notes the encouragement of past UNFCCC decisions and welcomes feedback from the Parties on the CEOS response to the GCOS IP. CEOS also understands the importance of reporting to the UNFCCC on systematic observations and progress, and, if requested by the Parties, would be willing to do so.

In conclusion, CEOS recognizes that satellite and *in situ* data are required to better monitor, characterize, and predict changes in the Earth system. While *in situ* measurements will remain essential and largely measure what cannot be measured from satellites, Earth-observation satellites are the only realistic means to obtain the necessary global coverage, and with well-calibrated measurements will become the single most important contribution to global observations for climate.

6. ACKNOWLEDGEMENTS

This report has been prepared under the direction of the incoming Chair of CEOS, Associate Director of the U.S. Geological Survey Barbara J. Ryan, edited by Rebecca L. Johnson, and with the substantial support of Tom Armstrong, Stephen Briggs, L. DeWayne Cecil, Ivan Csiszar, Jean-Louis Fellous (lead, oceanic domain), Roy Gibson, Chu Ishida, Eric Lindstrom, Paul Menzel (lead, atmospheric domain), Brad Reed, John Townshend (lead, terrestrial domain), and Stephen Ward. Paul Mason and his GCOS colleagues provided extensive insights and innumerable suggestions throughout the process. Appreciation is extended to the many other people who participated in the report's development. These individuals and their respective institutions are noted in Appendix 8. Thanks are also due to the many reviewers who took time to carefully consider the various drafts and provide useful comments. The direct financial support of the U.S. Geological Survey and the European Space Agency is also gratefully acknowledged, without which this report could not have been written.

Appendix 1: CEOS Actions in Response to the GCOS IP

Atmospheric Domain
Action A-1: In 2007 CEOS agencies will review the capability of passive microwave sensors to make scatterometer-quality measurements and will work to ensure A.M. and P.M. satellite coverage of surface wind speed and direction by 2015.
Action A-2: CEOS will strive to ensure continuity of GPS RO measurements with, at a minimum, the spatial and temporal coverage established by COSMIC by 2011. CEOS will continue efforts in 2007 to exploit the complementary aspects of radiometric and geometric upper-air determinations of temperature and moisture.
Action A-3: CEOS will support in 2007 investigations of cloud properties and cloud trends from combined satellite imager plus sounder measurements of clouds (with horizontal as well as vertical information) using Cloudsat/CALIPSO for validation.
Action A-4: CEOS agencies will ensure continued improvements to precipitation determinations demonstrated by TRMM and planned by GPM in 2010. The Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA) will lead a CEOS study team to establish, by 2007, the basis for a future Global Precipitation Constellation.
Action A-5: CEOS will plan by 2011 to make absolute, spectrally resolved measurements of radiance emitted and reflected by the Earth to space for information on variations in both climate forcings and responses.
Action A-6: CEOS agencies will participate in re-planning, by 2007, the Earth Radiation Budget Sensor (ERBS) removed from the planned payload of NPOESS.
Action A-7: CEOS agencies will participate in re-planning, by 2007, the Total Solar Irradiance Sensor (TSIS) removed from the planned payload of NPOESS.
Action A-8: CEOS agencies will participate in re-planning, by 2007, the OMPS limb instrument removed from the planned payload of NPOESS.
Action A-9: CEOS agencies will participate in re-planning, by 2007, the APS instrument removed from the planned payload of NPOESS.
Action A-10: CEOS agencies will participate in planning, by 2011, the operational follow-on to the chemistry missions planned for the next 5 to 7 years.
Action A-11: CEOS agencies will commit in 2007 to reprocessing the geostationary satellite data for use in reanalyses projects before the end of the decade.
Action A-12: CEOS will determine options by 2010 for continuing improvements to wind determinations demonstrated by MODIS and to be demonstrated by ADM Aeolus.

Oceanic Domain
Action O-1: CEOS agencies will examine their respective plans to maintain provision of microwave brightness temperatures and visible/infrared radiances for the sea ice ECV.
Action O-2: Relevant CEOS space agencies will consult with the science community on appropriate retrieval algorithms of passive microwave observation for reprocessing sea-ice products. Norway has expressed interest in committing to operational production of a global sea ice ECV (an initiative by the Norwegian Meteorological Institute, and coordinated by the Norwegian Space Center). The European Space Agency (ESA) is currently reprocessing the relevant ERS and Envisat archive to complement Canada's Radarsat in the context of WCRP's Climate and the Cryosphere (CLiC) core project.
Action O-3: New space-based measurements and products, including ice thickness and ice drift, will be considered by CEOS agencies as part of their future research missions.

Oceanic Domain, continued

Action O-4: The National Oceanic and Atmospheric Administration (NOAA) and EUMETSAT will lead a CEOS study team to establish, by 2007, the basis for a future Ocean Surface Topography Constellation that satisfies the threshold requirements for the sea level ECV (and those of the sea state ECV). This will include consideration of a future Jason-3 mission and requirements for new altimeter technologies to improve spatial resolution and extend observations in coastal regions (and over lakes and rivers for the lakes ECV).

Action O-5: The Centre National d'Etudes Spatiales (CNES) and the Indian Space Research Organization (ISRO) will cooperate on a new polar-orbiting altimeter aimed at filling a potential data gap beyond 2008. ESA and the European Union (EU) will lead planning for Sentinel-3 carrying an altimeter to complement spatial/temporal coverage of the sea level (and sea state) ECVs (and possibly sea ice extent and thickness, river, and lake level with the altimeter operating in Synthetic Aperture Radar (SAR) mode beyond 2012).

Action O-6: An ATSR-like instrument is planned on ESA's Sentinel 3, presently scheduled for launch in 2012. JAXA will lead planning for Global Change Observation Mission-Water (GCOM-W) and GCOM-C (Climate) to maintain continuity of the sea surface temperature ECV.

Action O-7: CEOS agencies will examine their respective plans to maintain provision of microwave brightness temperatures for the sea surface temperature ECV.

Action O-8: Relevant CEOS agencies will examine their respective plans to maintain continuity of a 10-km-resolution sea surface temperature data sets global product.

Action O-9: CEOS agencies will cooperate to support the combination of all existing sea surface temperature data sets into a global FCDR.

Action O-10: ISRO will lead planning of Oceansat-2, ESA and the EU of Sentinel-3, and JAXA of GCOM-C, which are all new missions planned to carry an ocean colour sensor.

Action O-11: Relevant CEOS agencies will examine their respective plans to maintain continuity of the 25-km-resolution ocean colour global product.

Action O-12: CEOS agencies will cooperate to support the combination of all existing ocean colour data sets into a global FCDR.

Action O-13: In consultation with GCOS and the relevant user communities, CEOS agencies will explore the means to secure, by 2011, continuity of the 1-km-resolution global ocean colour product needed to fulfil the target GCOS requirements.

Action O-14: CEOS agencies will cooperate with the user community to support efforts aimed at building on the decade-long satellite sea state records and making a comprehensive use of future altimeter- and SAR-bearing missions.

Action O-15: ESA will fly SMOS in 2007 to demonstrate measurement of the sea surface salinity (and soil moisture) ECV; NASA/CONAE will fly Aquarius/SAC-D in 2009 to demonstrate measurement of the sea surface salinity ECV.

Action O-16: CEOS agencies will cooperate in developing future plans for an Ocean Salinity Constellation.

Action O-17: CEOS agencies will undertake planning for reprocessing past data to improve FCDRs and legacy databases (e.g., AVHRR Pathfinder, ATSR, Sea Level Pathfinder, and the sea ice ECV) in close coordination and partnership with existing advisory groups and reanalysis centres. All Level 2 data products for use in reanalysis should be properly accompanied by estimates of their uncertainty.

Action O-18: CEOS, through its Working Group on Calibration and Validation (WGCV) and in the context of developing standards for on-going missions and for the Constellations, will recommend best practices for pre-launch and onboard calibration of ocean sensors and for validation of space-based ocean observations with in situ sensors, including the establishment and maintenance of calibration and validation sites and networks. This will facilitate the combination of data from different sources and enable the establishment of global data sets and long-term series.

Action O-19: CEOS agencies, in cooperation with other partners, will support planning for a follow-on to GODAE by 2007.

Terrestrial Domain

Action T-1: CEOS agencies will determine which alternative approach best fills the current Landsat-class data gap and will explore the potential of integrating high-resolution data from multiple platforms (e.g., China-Brazil Earth Resources Satellite (CBERS), Indian Remote Sensing (IRS) satellite, Landsat, Satellite Pour l'Observation de la Terre (SPOT), and others) based on the results of a CEOS study team led by the United States Geological Survey (USGS) that will establish, by 2007, the basis for a future Land-Surface Imaging Constellation.

Action T-2: CEOS agencies will assess the feasibility of generating global historic and continuing ECVs at fine resolutions for land cover and glacier change.

Action T-3: CEOS (led by USGS and NOAA), in cooperation with relevant stakeholders, will explore the feasibility, by 2007, of retrieving and reprocessing the 1-km AVHRR data record from various centralized archives (NOAA and High Resolution Picture Transmission (HRPT) stations).

Action T-4: CEOS will work to enhance the quality of the FCDRs and the ECVs generated from the AVHRR record to meet threshold requirements.

Action T-5: CEOS agencies will undertake research to support satellite technology development, such as lidar or P-band sensors, that are capable of retrieving biomass and LAI globally that meet GCOS requirements. CEOS agencies will also support research to improve algorithms that do not currently meet GCOS threshold requirements. New satellite technology and algorithms should be available by 2015.

Action T-6: CEOS will assess the feasibility of collecting operational multi-angle observations. Research will be carried out by CEOS agencies to improve radiation transfer schemes for albedo and fAPAR, especially under cloudy conditions.

Cross-Cutting Actions

Action C-1: CEOS will review the prevailing institutional arrangements in place for the planning and implementation of cooperative efforts by space agencies in the domain of climate (among others) by 2007. In particular CEOS agencies will review the ways to improve coordination of future remote sensing tasks that address the upcoming space-based measurement challenges, so as to avoid duplication of efforts while taking cooperation between the international partners to a higher level.

Action C-2: CEOS agencies will work with GEO to leverage progress and results from the implementation actions for climate to benefit all other relevant SBAs.

Action C-3: CEOS will work with GCOS to periodically evaluate climate needs and their realization.

Action C-4: CEOS agencies will adjust their internal procedures and mechanisms relative to satellite mission planning and operating processes in order to ensure adequate adherence to the GCMPs.

Action C-5: CEOS agencies will review their respective satellite data records with particular attention to adherence to the GCMPs and will consider undertaking necessary corrective actions within available resources.

Action C-6: CEOS will consider the GCMPs and relevant ECV requirements in defining criteria that will serve as the foundation for the CEOS Constellation studies being initiated in 2006 and beyond.

Action C-7: CEOS agencies will increase their cooperation in ensuring stability, accuracy, and inter-comparability of their respective satellite observations. These observations will be tied to irrefutable international standards in order to enhance the utility of space programmes for climate applications.

Action C-8: CEOS agencies will contribute to development of GSICS under development by CGMS and WMO to better integrate calibration efforts. Furthermore, CEOS agencies will continuously pursue establishment of reference measurements in space, complementing those on the ground and in the air, which will enable absolute inter-calibration of radiance measurements.

Action C-9: CEOS will charge its WGCV to promote existing in situ networks, identify new opportunities for product validation, and support both validation research and operational validation projects at an adequate level.

Cross Cutting Actions, continued

Action C-10: CEOS agencies will coordinate their efforts in designing future data archives and data dissemination systems, ensuring that past data holdings (including associated metadata) are preserved, assessing standards and protocols, and incorporating new information technology (IT) developments as much as possible. Practical actions in response to this cross-cutting need will be developed by CEOS' Working Group on Information Systems and Services (WGISS) in line with the technical solutions adopted by GEO.

Action C-11: CEOS agencies will systematically consult with appropriate scientific and user advisory groups in establishing detailed specifications for each FCDR and derived products, including associated uncertainties.

Action C-12: CEOS agencies will consult on appropriate rules to ensure sustained, open accessibility to FCDRs in order to allow the periodic reprocessing and generation of homogeneous products.

Action C-13: CEOS agencies will generate, within available resources, independently processed data sets and products.

Action C-14: Recognising that space agencies are responsible for only a portion of the value chain involved in the generation of FCDRs, CEOS will explore ways to strengthen linkages to the communities involved in climate product generation and use, e.g., through framework agreements with major reanalysis centres.

Action C-15: CEOS agencies will encourage funding of climate change research at an adequate level for multiple groups to analyze data records, reprocess climate variables, and perform reanalysis.

Action C-16: CEOS agencies will consider, in the context of the Constellations, ways and means to support the transfer of demonstrated observations from research satellites into operational capabilities. In particular, CEOS will encourage "convergence" of climate-observing requirements (usually for high-quality data) with operational requirements (usually for rapid and ensured data availability), and support institutional arrangements that would help transfer ECVs from research to operations.

Action C-17: CEOS agencies will maintain R&D efforts aimed at confronting the knowledge challenge posed by climate and climate change, and strive to overcome the current scientific and technical limitations of climate-quality measurements.

Action C-18: CEOS agencies will ensure that data acquired through research satellites are fully used for the benefit of creating and/or improving the FCDRs of all ECVs.

Action C-19: CEOS agencies will continue to devote particular efforts to the reprocessing and improvement of these fundamental data sets.

Action C-20: CEOS agencies will endeavour to ensure global, easy, and timely access to climate-related products, including by developing countries.

Action C-21: CEOS will establish a programme in 2007 to document the data archive and access arrangements in place for each of the FCDRs contributed by space agencies. WGISS will lead this effort in order to evaluate practical solutions to current obstacles and issues.

Action C-22: CEOS agencies will continue their efforts, both individually and through the CEOS Working Group on Education and Training (WGEdu), to build capacity.

Appendix 2: Atmospheric Domain—ECV Analysis

For each ECV in the atmospheric domain, the adequacy of past, present, and future provisions of FCDRs has been assessed in great detail by the contributors to this report. Results of this analysis, together with clarifying remarks, are summarized below.

Surface Wind Speed and Direction (A.1)[10]

Past provisions

- Passive microwave radiances of Special Sensor Microwave Imager (SSM/I) (1987~), AMSR-E(2002~) and SMMR (1979-1984) as supplement
- Scatterometry of ERS (1993~), QuikSCAT (1991~)

Present/future provisions

- Passive microwave radiometric measurements of SSM/I (1987~), Special Sensor Microwave Imager Sounder (SSM/IS) (2003~), and AMSR-E (2002~); planned missions include GCOM-W/AMSR F/O (2010~)
- Scatterometry of QuikSCAT (1991~) and ASCAT (2006~)

Adequacy of provisions

- Only one scatterometer and the fact that passive systems are poor in low winds, particularly in the tropics, indicate further investigation of the capability of passive microwave sensors to make scatterometer-quality measurements of surface winds is needed. For example, passive microwave radiometers in space with a full polarimetric capability provide both wind speed and wind direction simultaneously with less ambiguity from 2-3 frequencies. The direction retrieval, however, becomes less accurate under light wind conditions, as compared to scatterometers.

Upper Air Temperature (A.2)

Past provisions

- Passive microwave sounding of MSU (1979~), AMSU (1999)
- GPS RO of GPS/meteorology (1994 -1996) and Coral Health and Monitoring Program (CHAMP) (2001~)
- IR-based sounding from HIRS (1979~) and Atmospheric Infrared Sounder (AIRS) (2002~)

Present/future provisions

- Passive microwave sounding of MSU (1979~) and AMSU (1999~)
- GPS RO of CHAMP (2001~), COSMIC, and Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS) (2006~)
- IR-based sounding of HIRS (1979~), AIRS (2002~), IASI (2006~), and Cross-track Infrared Sounder (CrIS) (2009)

Adequacy of provisions

- Continuity of the record of RO measurements established by CHAMP, COSMIC, and GRAS must be planned.
- Further efforts to exploit the complementary aspects of radiometric and geometric upper-air determinations of temperature and moisture are needed.
- New sustained global positioning systems (*e.g.* Galileo) for RO measurements need to be explored and leveraged.

Water Vapour (A.3)

Past provisions

- Passive microwave measurements of SSM/I (1987~), SSM/IS (2003~), and AMSR-E (2002~)
- UV/VIS imagery of MERIS (2002~)
- IR imagery and soundings in 6.7 µm band of HIRS (1979~) and AIRS (2002~), and microwave soundings in the 183 GHz of SSM/I (1987~), SMMR (1979-1984), and Special Sensor Microwave/Temperature Profiler (SSM/T-2) + Advanced Microwave Sounding Unit B (AMSU-B) + Microwave Humidity Sounder (MHS) (1993~)
- Ground-based measurements of GPS-delay

Present/future provisions

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[10] Nomenclature following the ECV title refers to its designation in GCOS-107.

- Passive microwave imagery of SSM/I (1987~), SSM/IS (2003~), and AMSR-E (2002~). Planned missions include GCOM-W/AMSR F/O (2011~).
- UV/VIS imagery of MERIS (2002~)
- IR imagery and soundings in 6.7 μm band of HIRS (1979~), AIRS (2002~), IASI (2006~), and CrIS (2009~) and microwave soundings in the 183 GHz of SSM/T-2 + AMSU-B + MHS (1993~)
- Ground-based measurements of GPS-delay

Adequacy of provisions

- The new capabilities of AIRS, IASI, and CrIS plus AMSU-B/MHS to determine tropospheric/stratospheric water vapour profiles should be leveraged.
- Adequate moisture reference measurements in the upper troposphere, noting in particular that measurements with high vertical resolution are needed to study the tropical tropopause layer, should be established.

Cloud Properties (A.4)

Past provisions

- VIS/IR imagery and IR and microwave soundings of AVHRR/HIRS (1978~), MODIS/AIRS (2000~), and Spinning Enhanced Visible and Infrared Imager (SEVIRI) (2003~)

Present/future provisions

- VIS/IR imagery and IR/microwave soundings of AVHRR/HIRS (1978~), MODIS/AIRS (2000~), AVHRR/IASI (2006~), VIIRS/CrIS (2009~) and Geostationary Operational Environmental Satellite (GOES) (1994~), SEVIRI (2001~), and Multi-functional Transport Satellite MTSAT (2004~)
- Active radar and lidar of Cloudsat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (2006) gives cloud microphysics, and EarthCARE (2012~)

Adequacy of provisions

- EOS measurements from MODIS/AIRS should be used to simulate past AVHRR/HIRS measurements as well as future AVHRR/IASI and VIIRS/CrIS measurements and thus act as a bridge from past to future cloud property estimation.
- Discerning cloud properties and cloud trends from combined imager plus sounder measurements of clouds (with horizontal as well as vertical information) in favour of imager-only or sounder-only measurements of clouds is important. Support should be arranged to do so.
- Additional information from geometrical measurements from instruments such as the Multi-angle Imaging Spectroradiometer (MISR) should be appended whenever possible.
- Cloudsat/CALIPSO should be used for validation and should be continued.
- Microwave studies of precipitating clouds should be fostered.

Precipitation (A.5)

Past provisions

- Passive microwave imagery of SSM/I (1987~), TRMM Microwave Imager (TMI) (1997~), and AMSR-E (2002~)
- Active radar for calibration of TRMM (1997~)

Present/future provisions

- Passive microwave imagery of SSM/I (1987~), TMI (1997~), and AMSR-E (2002~). Planned missions include GCOM-W/AMSR F/O (2011~).
- Active radar calibration of TRMM (1997~). Planned missions include GPM (2013~).

Adequacy of provisions

- TRMM F/O mission should be arranged as soon as possible to mitigate the likely data gap in these unique measurements.
- The need for enhanced detection of light rain and solid precipitation, especially at high latitudes indicates expansion to a global snow and rainfall detection mission should be considered.
- Geostationary microwave measurements should be demonstrated and studied for discerning the diurnal signal of precipitation.
- Current requirements should call for 50-km resolution so that they are consistent with water vapour requirements.
- Research space agencies are asked to support their space-based developments with campaigns in order to further understand the relationship between observed passive μ-wave radiances and precipitation.

Earth Radiation Budget (A.6)

Past provisions

- Appropriate radiances of Earth Radiation Budget Experiment (ERBE) (1984~) and CERES (1997~)

Present/future provisions

- Appropriate radiances of CERES (1997~)

Adequacy of provisions

- A CERES gap is likely to occur after Terra and before NPOESS C-1 in 2014.
- Incoming and outgoing solar as well as outgoing thermal spectral irradiance must be measured.
- The likely absence of TSIS indicates that re-planning must be done so that a substitute can be found.
- Spectral irradiance at the Earth surface must also be measured.

Ozone (A.7)

Past provisions

- Appropriate UV/VIS and IR/microwave radiances of TOMS (1979~), SBUV (1979~), and HIRS (1979~)

Present/future provisions

- Appropriate UV/VIS and IR/microwave radiances of TOMS (1979~), SBUV (1979~), HIRS (1979~), Global Ozone Monitoring Experiment (GOME) (2006~), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (2003~), Ozone Monitoring Instrument (OMI) (2003~), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) (2003~), and Tropospheric Emission Spectrometer (TES) (2005~)

Adequacy of provisions

- Reprocessing of data sets with improved algorithms is planned to overcome instrument biases.
- The ozone limb profiler component of the NPOESS OMPS has been demanifested, indicating that some re-planning must occur if it is not remanifested.
- The discontinuation of solar occultation measurements will profoundly impact one of the FCDR pillars of ozone assessments.
- Solar occultation (UV and Visible) limb soundings should be added to the GCOS requirements.
- A major effort underway to implement the International Global Atmospheric Chemistry Observations (IGACO-O3) strategy (see http://www.igaco-o3.fi/) should be supported. The Senior Advisory Panel requested input from the community and generated a series of actions related to ground-based networks, data centres, and data access.

Aerosols (A.8)

Past provisions

- Selected wavelength in VIS/NIR of SAGE (1979~), TOMS (1979~), AVHRR (1979~), MISR (2000~), and MODIS (2000~)

Present/future provisions

- Selected wavelength in VIS/NIR of SAGE (1979~), TOMS (1979~), AVHRR (1979~), MODIS (2000~), MISR (2000~), Polarization and Directionality of Earth Reflectances (POLDER) (2002~), Along Track Scanning Radiometer 2 (ATSR-2) (1995), Parasol (2006~), and SCIAMACHY (2003~). Planned missions including VIIRS (2009~) and GCOM-C/Second Generation Global Imager (SGLI) (2012~)
- CALIPSO/Cloudsat in 2006
- lidar of GLAS, ADM/Aeolus (2007~), and Atmospheric Lidar (ATLID)

Adequacy of provisions

- No operational aerosol instruments measuring particle composition and size/shape have been flown to date. Efforts should be made to rectify this.
- Efforts should be made to establish a measurement baseline with MODIS/MISR.
- Aerosol measurements from APS are no longer likely, indicating that some re-planning must occur.
- Maintain continuity of retrievals from geostationary platforms with advanced instruments (GOES-R).
- Operational active sensing (lidar, *e.g.*, CALIPSO) from satellites should be considered.

Carbon Dioxide, Methane, and Other Greenhouse Gases (A.9)

Past provisions

- Appropriate NIR/IR radiances of AIRS (2002~), Envisat (2002), SCIAMACHY (2003~), MIPAS (2003~), High-Resolution Dynamics Limb Sounder (HIRDLS) (2005~), and Microwave Limb Sounder (MLS) (2005~)

Present/future provisions

- Appropriate NIR/IR radiances of AIRS (2002~), Envisat (2002), SCIAMACHY (2003~), MIPAS (2003~), HIRDLS (2005~), MLS (2005~), IASI (2006~), OCO and Greenhouse Gases Observing Satellite (GOSAT) (2008~)
- GOSAT in 2008 but no F/O

Adequacy of provisions

- Atmospheric chemistry missions planned for the next five to seven years will be demonstrating potential future operational measurements, but there are no plans for operational implementation or R&D F/O.
- Efforts to integrate high spectral resolution infrared CO_2 measurements with the CO_2 measurements from missions such as OCO should be supported.

Upper Atmospheric Winds (A.10)

Past provisions

- Appropriate imagery of AVHRR (1979~) and MODIS (2000~)
- Geostationary imagers, GOES (1975~), Meteosat (1978~), and Geostationary Meteorological Satellite (GMS) (1980s~)

Present/future provisions

- Appropriate measurements of AVHRR (1979~) and MODIS (2000~)
- Geostationary imagers, GOES (1975~), Meteosat (1978~), GMS (1980s~), Feng Yun (FY) (2000s~), and Indian National Satellite (INSAT) (2000s~)
- Doppler wind lidar instrument of ADM/Aeolus (2007~)

Adequacy of provisions

- Repeated reprocessing of these wind data is necessary in order to reduce wind-speed biases and spurious trends in the operational products.
- An operational F/O mission to Aeolus must be planned.
- Efforts to establish adequate height assignments for atmospheric motion vectors (to date, they remain inadequate for climate records) should be renewed.
- No F/O mission for polar water vapour winds has been secured indicating that a gap is likely. Plans for a replacement of the MODIS capability should be initiated as soon as possible.

Atmosphere Reanalysis (A.11)

Past provisions

- Weather and Climate Centres reanalyzing *in situ* and satellite data records have produced 40- and 50-year reanalysis (*e.g.,* European Centre for Medium Range Weather Forecast Re-Analysis, 40)

Present/future provisions

- Weather and Climate Centres continuing efforts at reanalyzing *in situ* and satellite data records

Adequacy of provisions

- Reanalysis systems that enable assimilation of many different data sets to create integrated climate products are essential. The importance of multiple groups analyzing data records, reprocessing climate variables, and performing reanalysis needs to be recognized and supported.
- Numerical Weather Prediction (NWP) centres should be encouraged to provide reanalysis products based on updated model physics and data assimilation techniques.
- Dedicated efforts by data centres should be supported to assess (and improve) the quality of the Level 1 radiances and associated metadata. Ultimately FCDRs should be used as input to the reanalysis.

Appendix 3: Oceanic Domain—ECV Analysis

For each ECV in the oceanic domain, the adequacy of past, present, and future provisions of FCDRs has been assessed in great detail by the contributors to this report. Results of this analysis, together with clarifying remarks, are presented below.

Sea Ice (O.1)[11]

Past provisions

- Microwave brightness temperatures and retrieved sea ice concentration/extent from SMMR (1978-), SSM/I (1987-) , and AMSR-E (2002-)
- VIS/IR radiances of AVHRR (1981-) and MODIS (1998-)
- Normalized radar cross-section (σ_0) and sea-ice cover from ERS-1/2-Envisat (1991-) and QuikSCAT (1998-)

Present/future provisions

- Microwave brightness temperatures are being continuously provided by SSM/I, SSM/IS, and AMSR-E. Planned missions include NPOESS/CMIS (2012-) and GCOM-W/AMSR F/O (2011-2024). There is a potential gap between AMSR-E and AMSR F/O or CMIS in terms of high-resolution ice observation.
- VIS/IR data records with moderate resolution will be provided by MODIS on Aqua and Terra, NPOESS/VIIRS, GCOM-C/SGLI (2012-2025), and so forth.
- QuikSCAT is the only mission (and the nominal lifetime is already over) that is currently providing continuous σ_0 data record. MetOp/ASCAT (2006-) will improve this situation and increase diurnal coverage that is important for detecting drift and melt/refreeze process of ice surface.
- Supporting measurements, including ice thickness and ice drift: there is a need to investigate future missions.

Adequacy of provisions

- Currently, long-term sea ice products are generated and distributed by many countries and institutions including the United States and Europe. Some of the GCMPs (*e.g.*, overlap, continuity, and maintaining baseline instrument) are satisfied, although measurements may not have been intended for climate purposes. There are some calibration-related problems in older data holdings of microwave brightness temperature. Sea-ice extent and concentration is the only sea ice product that can be derived uniformly over the existing 25 year record, but it is not accompanied by sufficient information on uncertainties. Future products need to take this into account.

Sea Level (O.2)

Past provisions

- High-precision altimetric time series have been supplied by the TOPEX/Poseidon and Jason-1 missions since August 1992. A F/O mission is planned (Jason-2) for launch in mid-2008.
- Complementary altimetric data have been supplied by the ERS-1, ERS-2 and Envisat radar altimeters and by the Geosat F/O missions, which can be used in conjunction with high-accuracy altimetric data to extend geographical coverage.

Present/future provisions

- Following Jason-2 launch in mid-2008, there is not yet any approved F/O mission to maintain the precision altimetric time series. NOAA and EUMETSAT are currently planning a Jason-3.

Adequacy of provisions

- Satellite altimetry, supplemented by tide gauges, has proven adequate to revolutionize the view of global sea level variability. Current efforts should be maintained and strengthened.
- Jason-1 is a good example of adherence to GCMPs. The mission was planned in accordance with GCMPs and a seamless time series of sea level is obtained by the overlap of the TOPEX/Poseidon and Jason-1 missions.
- The production of sea level from space-borne radar altimeters requires *in situ* calibration sites, a global array of tide gauges, geodetic reference frame maintenance and precision orbit determination infrastructure.
- The international Ocean Surface Topography Science Team (largely supported by NASA and CNES) is the expert group with oversight of calibration, validation, analysis, and reprocessing of the altimetry time series.

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[11] Nomenclature following the ECV title refers to its designation in GCOS-107.

Sea Surface Temperature (O.3)

Past provisions

- SST time series have been supplied with the NOAA AVHRR instruments for almost 30 years (AVHRR/1 on NOAA-6 was launched on 27 June 1979). This has been completed by ESA's (Advanced) Along Track Scanning Radiometer (A)ATSR series since 17 July 1991.

Present/future provisions

- The AVHRR/3 series will be maintained in the morning orbit with the expected launch of the first MetOp in 2006 and is planned until 2019. The afternoon orbit will not be covered after the end of the current NOAA missions and until VIIRS is launched on NPOESS.
- A likely gap of two years is to be expected between the end of (A)ATSR on Envisat and the launch of Sentinel-3 with an ATSR-like instrument.

Adequacy of provisions

- The entire AVHRR time series using consistent SST algorithms, improved satellite and inter-satellite calibration, quality control, and cloud detection have been reprocessed and are available from 1985 to the present. The same activity is on-going for the (A)ATSR time series and shall be completed by mid-2007. This is probably one of the best examples of adherence to GCMPs. This effort shall be maintained for future missions and applications.
- The production of SST requires a permanent set of *in situ* measurements for product verification, calibration, and validation. Arrays of buoys measuring surface bulk temperature shall be completed by radiometers to access skin temperatures. There is a need from non-space agencies to sustain the 1250 surface drifters that provide the current basis for *in situ* calibration. Studies on the effect of the atmosphere on the final product shall be continued.
- The international GODAE High Resolution Sea Surface Temperature (GHRSST) Project federates a large community dedicated to SST. It covers all aspects from calibration and validation activities to applications.

Ocean Colour (O.4)

Past provisions

- Ocean Colour FCDR started with the start of MODIS operations on Terra on 24 February 2000. This first mission was followed closely by MERIS on Envisat, MODIS on Aqua, Parasol, and AVNIR. All these missions currently are running in parallel. Other missions are planned in future but not totally secure until the approved launch of ESA's Sentinel-3. Degradation is to be expected within a year or so with only one secured mission left. There could be no mission at all in operation if Sentinel-3 is delayed. GCOM-C/SGLI is planned to be launched in 2012.

Present/future provisions

- A potential gap in operational ocean colour data is expected in the future. The MERIS instrument is in perfect condition and there is no indication of potential failure. However, it is unlikely that the Envisat spacecraft will last until the Sentinel 3 launch. The continuity of and, if possible, increase in the number of ocean colour instruments would be beneficial to the quality of the data thanks to instrument inter-calibration.

Adequacy of provisions

- The generation of MERIS Level 3 products started recently for the complete mission. The projection grid and the algorithm follow the International Ocean Colour Coordinating Group (IOCCG) recommendations for ocean colour data binning.
- Ideally, all the data sets (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), MODIS and MERIS) shall be reprocessed up to Level 3 in a common format and time averaging (monthly, weekly or daily).

Sea State (O.5)

Past provisions

- There is no past provision of space-based FCDR for this ECV, though sea state is used as a fundamental correction in deriving climate-quality sea surface topography for the sea level ECV.

Present/future provisions

- Future missions: see Sea Level (O.2).

Adequacy of provisions

- Current sea-state records exist from ERS-1, TOPEX/Poseidon, ERS-2, Jason-1, Envisat, and Geosat F/O. Reprocessing of past data records needs commonly agreed scheme and definitions among the climate community, then among space agencies.

- New SAR altimeter (such as on ESA's Sentinel-3) and wide-swath altimeter (as on NASA's Wide Swath Ocean Altimeter (WSOA) instrument) will help improve sea state retrievals in coastal areas.

Ocean Salinity (O.6)

Past provisions

- There is no past provision of space-based FCDR for this ECV.

Present/future provisions

- New satellite missions, namely ESA's SMOS (in cooperation with CNES and Spain) and NASA/CONAE's Aquarius/SAC-D, are planned for flight in the 2007-2010 timeframe, and will provide the first demonstration of sea surface salinity measurements from space.

Adequacy of provisions

- Production of sea surface salinity estimates requires simultaneous measurements or estimates of sea surface temperature and surface roughness.
- Once level of accuracy in sea surface salinity retrieval is demonstrated it should be possible to develop plans to ensure adequate, sustained provision of ECV ocean salinity using an optimal combination of satellite and *in situ* instruments through data assimilation systems.

Ocean Reanalysis (O.7)

Past provisions

- Requirements for this product are for FCDRs of appropriate altimetry and ocean surface measurements as described above under O.1 through O.6. The main issue lies in the provision to reanalysis centres of homogeneous data sets **with associated uncertainty estimates.** See individual ECVs (above) for details.

Present/future provisions

- See individual ECVs (above) for details.

Adequacy of provisions

- See individual ECVs (above) for details.

Appendix 4: Terrestrial Domain—ECV Analysis

For each ECV in the terrestrial domain, the adequacy of past, present, and future provisions of FCDRs has been assessed in great detail by the contributors to this report. Results of this analysis, together with clarifying remarks, are presented below.

Lake Level (T.1.1 and T.1.2)[12]

Past provisions

- TOPEX/Poseidon (1992-2006) and Jason-1 (2001-) altimetry missions are now available for nearly 1000 continental lakes, with a typical height precision of 20 cm and temporal sampling delay of 10 days.

Present/future provisions

- With the denser ground-track coverage of ERS-2 (1995-) and Envisat (2002-) altimetry missions, there are several thousands of surface water bodies that can be continuously monitored; but in these cases, the revisit time is longer (35 days).
- Following the Jason-2 launch in mid-2008, there is not yet any approved F/O mission to maintain the precision altimetric time series. NOAA and EUMETSAT are currently planning Jason-3.

Adequacy of provisions

- Although current results are very interesting and promising, they don't meet the GCOS requirements (*e.g.*, 10-cm vertical resolution). But this subject is still a field of active research and there are good ideas for improving the processing of the data and the performances of future instrumentation. In particular, a dedicated and optimised mission such as Water Elevation Recovery (WatER), if decided and implemented, would improve quite significantly the performances of the space-based system.
- Several databases have been developed recently that provide direct access through the Internet to altimetry-derived surface-water-level time series (*e.g.*, the U.S. Department of Agriculture's database, the Hydroweb database from Laboratoire d'Etudes en Géodésie et Océanographie Spatiales (LEGOS) in France, and the "River and Lake" database from De Montfort University in the United Kingdom and ESA).

Lake Surface Temperature (T.1.3)

Past provisions

- Time series have been supplied with the NOAA AVHRR instruments for almost 30 years (AVHRR/1 on NOAA-6 was launched on 27 June 1979). This has been completed by ESA's (A)ATSR) series since 17 July 1991. (A)ATSR data are currently being reprocessed to version 2. This will be ready in late 2007 and will be a continuous data record from July 1991 to present. (A)ATSR lakes as part of land surface temperature (LST) have been validated over Lake Tahoe as part of an ongoing validation program. MODIS data are also available since launch of EOS-Terra.

Present/future provisions

- For the AVHRR series, a F/O mission is planned on the EUMETSAT's MetOp launched in July 2006; this will cover the morning orbit. The afternoon orbit will not be covered after the end of the current NOAA missions and until VIIRS is launched on NPOESS. The AVHRR/3 series will be maintained until 2019. An ATSR-like instrument is planned on ESA's Sentinel 3. A likely gap of two years is to be expected between the end of (A)ATSR on Envisat and the launch of Sentinel-3 with an ATSR-like instrument. GCOM-C/SGLI is planned to be flown between 2011 and 2024.

Adequacy of provisions

- Accuracy of 0.2 °C is only achievable under exceptional circumstances, treating each lake on an individual basis. Daily coverage is not possible owing to cloud cover and limited swath/repeat coverage of current instruments. As lakes must be treated on an individual basis, a prioritised list of ECV Lakes is needed, *e.g.*, the 20 most important lakes for climate monitoring.

Glaciers, Ice Caps, and Ice Sheets (T.2.1-T.2.2)

Past provisions

- Area/Outline Mapping: For long-term VIS/NIR FCDR data, only Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+) have been applicable in practice due to high spatial resolution (30-m in multispectral), low-cost availability, and the long period of coverage (from 1983). SPOT and other high and very-high spatial resolution sensors have successfully been applied in case studies, but data costs are

[12] Nomenclature following the ECV title refers to its designation in GCOS-107.

too high for global systematic monitoring. In the shorter term, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is currently the key visible and near infrared (VNIR) data source with its data of 15-m spatial resolution (in operation from 2000). Landsat TM, ETM+, and ASTER data time series, with its rather long and continuous temporal coverage, represents an extremely valuable data set. Reprocessing is not necessary, but availability needs to be improved, in particular by making all existing (relevant) images available through one Internet service.

- Ice Sheet Elevation Change: There is an 11-year record of dh/dt (1992-2002) from ERS-1 and -2 over high-elevation parts of Greenland and ~ 70% of Antarctica, but critically not sampling the most dynamic marginal parts of the ice sheets. High accuracy measurements are available from Ice Cloud and Land Elevation Satellite (ICESat) but with poor spatial and temporal sampling due to instrument failures. Interferometric Synthetic Aperture Radar (InSAR) measurements of surface velocity have been used to determine mass balance of ~60% of Antarctica and ~90% of Greenland but with unacceptable errors for mass input (accumulation). Gravity Recovery and Climate Experiment (GRACE) data have been used to determine mass trends for both ice sheets for a 3-year period (2002-05), but with large uncertainties on post-glacial rebound signal, leakage terms, and water storage for Greenland.
- The Radarsat SAR Antarctic Mapping Mission provided a complete snapshot of Antarctica, but future repeat coverage is needed to analyse change. Some radar altimeter data has been reprocessed and made available by NASA/Goddard Space Flight Center (GSFC) (http://icesat4.gsfc.nasa.gov/index.html), but this does not include Envisat and all ERS-2 data. ICESat data are being documented and distributed by the National Snow and Ice Data Center (NSIDC).

Present/future provisions

- Area/Outline Mapping: None of the relevant sensors for visible and infrared mapping, SAR, and interferometry analyses was designed for the purpose of operational climate monitoring, so the FCDRs do not fully adhere to the GCOS GCMPs. There are currently no operational sensors for development of FCDRs relevant for climate monitoring of glaciers. CEOS notes that, after failure of Landsat 7 ETM+, global glacier mapping from space relies solely on data from the ASTER sensor, which will pass its expected lifetime in 2006. Data from other multispectral sensors are not practically available for global scientific applications due to their commercial distribution. For the future, a 10-m multispectral sensor on an operational satellite delivering low-cost data is needed for large-scale accurate monitoring of glacier area outline. Depending on cost policy, the Advanced Land Observation Satellite (ALOS) may provide a useful data stream.
- Ice Sheet Elevation Change: Three FCDRs contribute to determining ice sheet mass balance. Elevation change measurements by satellite altimetry, complemented by observations of flux divergence from repeated SAR surveys and gravity measurements of ice mass change from satellites such as GRACE, are desired. The proposed data streams do not meet the quoted spatial resolution requirement (10 m), which is necessary for margin studies, but 1 km would be adequate for the main ice sheet. For the future, there are continuing and planned SAR missions and CryoSat-2 is planned for 2009. ICESat 2 status remains uncertain. Terrestrial glaciers and the Greenland and Antarctic ice sheets have the potential to raise global sea level by many meters. There is observational evidence of accelerating flow from outlet glaciers both in southern Greenland and in critical locations in Antarctica. Both inland snow accumulation and marginal ice melting have increased over the Greenland ice sheet, but there is no evidence for any significant accumulation trend over the Antarctic ice sheet. InSAR data, with requisite processing and archiving, are required for assessment of changes in velocity and mass balance from outlet glaciers around Greenland and Antarctica. High-resolution (10- to 100-m) data are required to resolve narrow outlet glaciers. A combination of FCDRs will provide improved estimates of ECV for ice sheets. The current main limitation for flux divergence estimates is uncertainty in surface mass balance (accumulation and ablation).
- None of the relevant sensors was designed for the purpose of operational climate monitoring, and the corresponding FCDRs do therefore not fully adhere to the GCOS GCMPs.

Adequacy of provisions

- For glacier extent, assets exist that will allow ECV thresholds to be reached. The key issue is whether an acquisition strategy will be implemented by space agencies to ensure that the observations are collected.
- Planned missions will allow improved estimates of ice sheet elevation change though the needed spatial resolution requirement at the margins will only be achieved by development of an acquisition strategy for fine-resolution missions.
- Continued, long-term measurements from GRACE, ICESat, SAR, and F/O missions are crucial to reduce uncertainty and to model future changes. The needed spatial resolution requirement at ice sheet margins will only be achieved by development of an appropriate acquisition strategy for fine-resolution missions.

Snow Areal Extent (T.3)

Past provisions

- Snow Area: Snow area extent monitoring using satellite imagery has been performed by NOAA since 1968 using Television Infrared Observation Satellites (TIROS)/AVHRR series sensors and is ongoing using AVHRR, SSM-I, and GOES. However, this data set does not meet the 1-km, daily historical threshold requirement. Reprocessing of 1-km AVHRR data can provide this requirement to ~1985. Circa 2000 snow cover maps are being produced globally by NASA MODIS at 500-m resolution, daily in absence of clouds, with accuracy close to target requirements.
- Snow Water Equivalent (SWE): Snow water equivalent monitoring has been made possible with the advent of passive microwave sensors. SMMR (1978–1985) and SSM/I (1987 to present) provide a long time series of observations. AMSR-E (2002 to present) is attractive for present and future observations due to increased spatial resolution. The SMMR-SSM/I data series needs sensor recalibration in order to reduce the effects of various noise sources and sensor cross-calibration is needed to make the full-time series usable. Cross-calibration between this time series and AMSR-E is also recommended to prolong the FCDR with AMSR-E data into the future. This data set meets the requirement of gridded daily SWE products for regional and global assessments at 25-km and higher resolution. SAR data have been tested for SWE determination in deep snow regions and complex terrain, but are only used on a regional basis. Products are not produced on a global or climatological basis.
- Snow Depth: The most extensive global record comes from daily climate station measurements of depth. No satellite-only derived record of snow depth is currently produced. SSM/I and AMSR-E can be used to produce snow depth products at 25 km.

Present/future provisions

- Snow Area: Ongoing production of 500-m resolution, daily snow cover should continue from MODIS and be supplemented by (potentially 250- to 300-m resolution) snow cover maps based on VIIRS/Sentinel-3. Integration of FCDRs from Geostationary Imagers as well as passive microwave sensors with polar orbiting imagers is likely required to achieve continuous daily global coverage.
- Snow Water Equivalent (SWE): Ongoing production of gridded daily SWE products at 25-km or higher resolution is required. The higher resolution AMSR-E data provide improved resolution, but the future of higher resolution passive microwave data are at risk as the NPOESS program is rationalized. SSM/I–type sensors proposed as F/O or operated by other nations can contribute to production of SWE products. Cross-calibration of sensors is required, and validation of resulting products is an ongoing need.
- Snow Depth: This product links to SWE products with similar concerns and needs.

Adequacy of provisions

- Historical snow areas extent ECVs are within accuracy thresholds but do not meet 1 km daily resolution requirements. AVHRR and geostationary imagery can offer sufficient resolution back to the mid-1980’s with adequate reprocessing. Post-2000 products are adequate with the exception of some temporal gaps due to cloud cover. Consistent approaches for validating global snow cover maps should be developed.

Albedo (T.4)

Past provisions

- Prior to 2000, there are no FCDRs of sufficient quality to derive surface albedo with the requested 5% accuracy; however, there are a series of geostationary satellites that can produce albedo at less than threshold accuracy:
    - (0º longitude) Meteosat 1, 2, 3 (1981-1989); Meteosat 4, 5, 6, 7 (1989-present);
    - (63º E longitude) Meteosat 5 (1998-present);
    - (150º E longitude) GMS 3, 4, 5 (1987-2003);
    - (135º W longitude) GOES 4, 6 (1981-1989); GOES 9, 12 (1996-present);
    - (5º W longitude) GOES 5, 7 (1981-1997); and
    - (5º W longitude) GOES 8, 10 (1997-present).
- The current estimated accuracy of surface albedo derived from geostationary orbits is between 10-20% (relative error) according to the radiometer and processed period. There is still room to decrease these uncertainties.

Present/future provisions

- Current sensors that are capable of providing albedo products include MODIS (available since 2000), MISR (available since 200), POLDER (available since 1996), and MERIS (available since 2002).

Adequacy of provisions

- The FCDRs are not yet in an acceptable form for the generation of consistent albedo products for climate data records. Efforts already undertaken have, however, demonstrated the possibility to decrease the uncertainty of these data.
- Meteosat VIS band has been systematically calibrated in a consistent way applying the same vicarious calibration method. However, data acquired prior to the early 1990s are still suffering from erroneous or inaccurate ancillary information. GOES and GMS archived VIS data still need to be consistently re-calibrated and historical AVHRR data need to be collected and reprocessed.

Moderate-resolution maps of land cover type (T.5.1)

Past provisions

- There are adequate FCDRs both from the U.S. and from Europe suitable for generation of these products. For periods earlier than 2000, the AVHRR record is of value especially if it is available at 1-km resolution. However, it has not yet been established that this record is sufficient to retrospectively generate global land cover products for the 1990s when 1-km data are available. Before 1990, only 8-km data are currently available globally. Current products generated from moderate-resolution instruments are adequate and do not require reprocessing. Use of AVHRR and SPOT-VEGETATION (VGT) data for pre-2000 land cover classification has not yet been established as being adequate. There is a need for the reprocessing of the AVHRR data record and for the establishment of the AVHRR-ATSR/(A)ATSR-MODIS-VIIRS consistent record.

Present/future provisions

- Global land cover products at 250- to 500-m resolution are currently being generated in the U.S. with MODIS Land (MODLAND) and in Europe with Global Land Cover service (GLOBCOVER). There are several moderate-resolution (250-m to1-km) multispectral instruments with adequate FCDRs. Sensors include AVHRR, ATSR, (A)ATSR, MODIS, VIIRS, and sensor on Sentinel-3.

Adequacy of provisions

- Significant processing of these observations will be needed to turn them into adequate FCDRs for this purpose. There must be some revisiting of the 5-year reporting of change, particularly in tropical areas, as within 5 years significant areas can be cleared but will then regrow so that they may be difficult to distinguish from intact forest.

High-resolution maps of land cover type, for the detection of land cover change (T.5.2)

Past provisions

- For the period from 2000-03 the long-term acquisition plan of Landsat 7 ensured adequate holdings for much of the world. Some areas with very high cloud amounts were not monitored adequately. Since 2003, problems with the ETM+ of Landsat 7 have significantly reduced its capabilities.
- The TM and ETM+ of Landsat 5 and 7 provide adequate FCDRs. These sensors have been very well characterized, as have those of the SPOT-High Resolution Visible (HRV). For sensors with similar spatial resolutions, much less thorough characterization has been carried out. Near-global orthorectified Landsat coverage is available for the mid-1970s, 1990, and 2000.

Present/future provisions

- Land cover change products have been created regionally and on a country basis, but no comprehensive global land cover change products have been generated. Scaling up the country and regional efforts is feasible, with the principal limitation being resources for the ECV creation.
- The current collection of satellite imagery is not sufficient to meet the requirements for this action. Scattered regional maps at 30-m resolution exist—*e.g.,* Coordinated Information on the European Environment (CORINE) for Europe, Africover for eastern Africa, Brazil's Programa de Cálculo de Desflorestamento de Amazônia (PRODES), and Canada's Earth Observation for Sustainable Development of Forests (EOSD)—but institutional arrangements to ensure operational generation of global land cover maps at these resolutions are not yet in place.

Adequacy of provisions

- There are current U.S. plans to create a global, mid-decadal data set based largely on Landsat 5 data supplemented with composited Landsat 7 data. Securing this data set is a very high priority for the carbon community. There is likely to be a continuing gap of high-resolution records until early in the next decade and international cooperation should be initiated to use existing assets to fill this continuing major deficit.
- 30-m spatial resolution represents the threshold, but for areas with more spatial heterogeneity 10-m data should be the target. For many parts of the world a 5-year frequency would reduce many uncertainties. But higher-frequency imaging and product generation is needed regionally.

- There is probably an over-reliance on optical sensing for land cover monitoring. Some areas are persistently cloudy; these areas must be delimited and the resulting information used to determine an acquisition strategy for radars. This is in addition to the role of InSAR measurements in estimating biomass. A long-term commitment for this type of sensing is needed but currently absent.

Supporting Product to T.5.1, T.5.2: Land surface temperature, in conjunction with land cover type (T5.3)

Past provisions

- Sensors that may be used for land surface temperature include AVHRR (global data sets based on AVHRR Ch4 and Ch5 radiometric data have been available since 1982) and (A)ATSR. With the launch of ATSR onboard ERS-1 in July 1991, the first sensor operating in biangular-mode was available. ATSR measures at nadir and at forward view, less than 55º.
- ATSR-2, onboard ERS, and (A)ATSR, onboard Envisat, are currently the only observing systems able to provide quasi-simultaneous multispectral (from visible to thermal infrared) measurements at two view angles (approximately 0‡ and 53‡ at surface).

Present/future provisions

- Global LST maps with an accuracy of ±1 ºC and emissivity maps with an accuracy of ±0.005 are available from (A)ATSR, MODIS, and ASTER data for many surface types.
- ATSR is currently being reprocessed to version 2. This will be ready near the end of 2007 and will be a continuous data record from July 1991 to present.
- MODIS (since 2000) uses coefficients in the split window algorithm that are given by interpolation on a set of multi-dimensional look-up tables.

Adequacy of provisions

- The ECV threshold may be reached for LST. The key issue is whether an acquisition strategy will be implemented by space agencies to ensure that historical AVHRR observations are collected.
- Continued, long-term measurements from VIIRS and other F/O missions are crucial to reduce uncertainty and to model future changes.

fAPAR (T.6)

Past provisions

- Global, 10-day, 1-km fAPAR estimates are available based on atmospherically corrected visible and infrared radiance measurements, often using a blue band for atmospheric correction, interpreted with land surface radiative transfer models.
- Global fAPAR products from NASA, ESA, and the European Commission (EC) Joint Research Centre (JRC) have been generated with temporal coverage beginning in 1997. Limited intercomparisons of these products and validation with *in situ* measurements suggest differences are larger than the acceptable accuracy.
- Polar-orbiting (AVHRR, SeaWiFS), and geostationary (GOES, Meteosat) visible and infrared radiance measurements have been acquired that can provide global coverage since ~1985 with the use of appropriate algorithms. Extract form archives, calibration, and reprocessing will be required to produce 1-km fAPAR.

Present/future provisions

- Ongoing production of 250-m to 1-km resolution fAPAR is possible with current and planned geostationary (GOES and MSG at ~1 km) and polar orbiting sensors (SPOT-VGT, MERIS, MODIS,VIIRS, Sentinel-3, GCOM/SGLI at ~250 m, and AVHRR/MetOp at ~1 km).
- Coordinated international intercomparison, benchmarking, and accuracy assessment is required to track improvements in fAPAR accuracy.
- Radiometric calibration and accurate pointing and geo-referencing of measurements are essential for long-term stability. Multi-angle measurements may substantially improve retrieval accuracy.

Adequacy of provisions

- There is no adequate global fAPAR ECV for historical and current periods that uniformly meets threshold requirements. Regional fAPAR (U.S., Canada, Europe) ECVs are available for some areas that meet threshold requirements although temporal coverage varies. CEOS assets (SPOT-VGT, MODIS, MERIS, ATSR/(A)ATSR) are available that can meet threshold requirements, except in areas of signal saturation, from 1998-present. CEOS assets providing long-term, 1-km resolution observations prior to 1998 are limited to AVHRR, SeaWiFS, and ATSR-1/ATSR-2 polar orbiters. AVHRR data will require geometric and radiometric reprocessing at 1-km resolution if global long-term coverage is to be achieved historically. *In situ* data sets were not consistently collected in terms of measurement approaches and temporal and spatial sampling protocols. CEOS WGCV has developed consistent approaches that could be adopted to improve this situation. Long-term *in situ* monitoring networks suitable for cal/val of a fAPAR ECV are not available. The EOS cal/val sites as well as other regional sites could serve as a starting point for ongoing monitoring.

<u>Leaf Area Index (LAI) (T.7)</u>

Past provisions

- LAI fields were typically derived by interpreting land surface reflectances in visible and infrared bands using land cover or biome-specific radiative transfer algorithms.
- Global LAI fields have been produced with coverage from 1991 (early AVHRR and SeaWiFS products from NASA) through ~2000 (MODIS products from NASA, SPOT-VGT-based LAI from EC JRC, and recently, MERIS products from ESA). Recent intercomparison and validation studies suggest that none of these products are consistently performing within threshold requirements globally but meet regional threshold requirements.
- Improved LAI retrievals (meeting or approaching threshold requirements) have been demonstrated from multi-angle spectral measurements from POLDER and MISR. Neither sensor was designed for ongoing ECV monitoring and the spatial resolution of POLDER (~7 km) and narrow swath of MISR prevent meeting threshold requirements.
- Regional LAI products at sub-continental scale are available from ~2000 that meet threshold requirements. The regional products often use short-wave infrared reflectance to avoid issues related to signal saturation, noise due to atmospheric correction uncertainties, and biases due to mixed land cover.

Present/future provisions

- Ongoing MODIS and SPOT-VGT observations, coupled with VIIRS and Sentinel-3, will offer suitable global measurements for LAI retrieval at or near threshold requirements assuming data continuity. Shortwave infrared (SWIR) bands on these sensors will allow for LAI retrieval up to ~6 but uncertainties related to Bidirectional Reflectance Distribution Function (BRDF) effects will remain.
- Multi-spectral, moderate-resolution, visible and infrared radiance measurements will likely be needed to meet threshold requirements consistently. GCOM-C/SGLI (JAXA) has the capability to observe at multi-angle, 250-m resolution; planned launch is in 2012.
- Active sensors such as lidar or P-band radars may be required to retrieve LAI past the saturation level of passive optical sensors.
- Regional tuning of algorithms and selection of spectral bands may be desired to reduce saturation and land-cover-specific biases if target provisions are to be met.
- Consistent, long-term intercomparison and validation is required for all LAI products. This could follow the CEOS Belmanip sampling scheme and CEOS WGCV validation protocols.

Adequacy of provisions

- There are no adequate global LAI ECVs for historical and current periods that uniformly meet threshold requirements. Regional LAI (U.S., Canada, Mexico, Siberia, parts of Fenno-Scandinavia) ECVs are available for some areas that meet threshold requirements but temporal coverage varies.
- CEOS assets (SPOT-VGT, MODIS, MERIS, ATSR/(A)ATSR) are available for production of LAI ECVs that can meet threshold requirements, except in areas of signal saturation, from 1998-present.
- CEOS assets providing long–term, 1-km resolution observations prior to 1998 are limited to AVHRR, SeaWiFS and ATSR-1/ATSR-2 polar orbiters. AVHRR data will require geometric and radiometric reprocessing at 1-km resolution if global long-term coverage is to be achieved historically.
- *In situ* data sets were not consistently collected in terms of measurement approaches and temporal and spatial sampling protocols. CEOS WGCV has developed consistent approaches that could be adopted to improve this situation.
- Long-term *in situ* monitoring networks suitable for cal/val of LAI ECVs are not available. The EOS cal/val sites as well as other regional sites could serve as a starting point for ongoing monitoring.
- LAI ECVs meeting threshold requirements are available at regional extents from 1998–present based on MODIS and SPOT-VGT sensors. These products rely on *in situ* data sets for calibration that are not currently available globally.
- A global set of long-term *in situ* cal/val sites does not currently exist. CEOS WGCV has proposed a sampling plan and methodology for both long term *in situ* cal/val and intercomparison of LAI products.

Biomass (T.8)

Past provisions

- Production of a biomass product from satellite measurements was not possible in the past. Currently, research data production is being planned. Actions need to be taken by space agencies to develop a concept for above-ground biomass product estimation, for example, one based on low frequency (L- and P-band) SAR for both direct and indirect approaches.

Present/future provisions

- Direct Approach: The ALOS L-band SAR (launched in January 2006) should provide the first systematic global observations for generating biomass maps. Longer wavelengths (P-band) should also be considered for future missions. Although historical Japanese Earth Resources Satellite (JERS) data are available through JAXA and ESA, calibration issues and lack of systematic coverage prevent their use for global biomass mapping.
- Indirect Approach: Two techniques are able to retrieve forest heights from space: Polarimetric SAR Interferometry (Pol-InSAR) and lidar. For continuous wide-area coverage, the Pol-InSAR technology seems able to provide the requested accuracy and the ALOS system will be used to test the viability of this approach. Experimental airborne data are available (Indonesian Airborne Radar Experiment (INDREX II) for tropical forests and TreeSAR for temperate forests). JAXA is promoting systematic global observation of the ALOS Phased Array L-band Synthetic Aperture Radar (PALSAR) through the provision of 1) systematic global observations and consistent data archives, and 2) derived and verified thematic products. To map or model above-ground biomass, it would be most useful if stratified by vegetation, as defined by existing satellite land cover maps. Using other vegetation and physiographic information may be a useful way to frame the biomass information.

Adequacy of provisions

- Past holdings do not exist and future products will be experimental for the foreseeable future.

Fire Disturbance: Maps of Burned Area (T.9)

Past provisions

- The 1-km AVHRR archive goes back to 1982, but there are substantial gaps in the coverage, particularly in the 1980s.

Present/future provisions

- ATSR/(A)ATSR data record starts in 1991 and continues to the present. AVHRR is currently flown and will be also flown on MetOp. SPOT-VGT has been flown on the SPOT series since 1998. MODIS is available since 2000. MERIS has been flown on Envisat since 2002. VIIRS will provide measurements useful for burned area mapping. GCOM-C/SGLI is planned to be flown between 2012 and 2025.

Adequacy of provisions

- The AVHRR archive held by NOAA (and NASA) should be reprocessed to correct for known deficiencies in sensor calibration, and also for known directional/atmospheric problems. There is also a need for reprocessing of the products derived from recent sensors. There is no consensus algorithm and large inconsistencies exist between the various products. Product validation protocol has been adapted by CEOS WGCV and needs to be promoted. Systematic processing needs to be maintained and undertaken by the operational agencies. Current and planned systems are only marginally adequate to meet the target requirement of daily 250-m resolution maps.

Supplemental Product to T.9: Active Fire Maps

Past provisions

- Mid-infrared (MIR) and thermal infrared (TIR) detectors have been included on some polar-orbiting and geostationary satellites. Active fire products from MODIS and ATSR-2 have been systematically produced with the best validation possible, but ATSR-2 detections are not available during daytime. Reprocessing of AVHRR may provide a longer time series provided the geo-location of hotspots improves.
- MODIS has been used to produce a global active (hotspot) product. Although some geostationary meteorological satellites (GOES, MSG) have been adequate for monitoring active fires between approximately 50 N and 50 S, they are not adequate beyond these latitudes or for detecting small fires. A global network of fire monitoring from geostationary satellites is needed to complement products from polar orbiters.

Present/future provisions

- There is a requirement for 250-m MIR and TIR sensors operating on a small constellation of satellites. ESA's Sentinel satellites under Global Monitoring for Environment and Security (GMES) will provide a 1-

km resolution TIR imager. There is also an opportunity to include a 250-m TIR imager on Sentinel 2. This will provide information on hotspot locations.

- In the absence of a constellation of 250-m satellites, there is a requirement for MODIS continuity to maintain global monitoring of hotspots. VIIRS on the NPOESS Preparatory Project (NPP) and NPOESS platforms is expected to provide compatible fire detection capabilities.
- All geostationary meteorological satellites should include SEVIRI-class instruments.

Adequacy of provisions

- The active fire data record is marginally adequate before MODIS (late 2000), due primarily to low sensor saturation temperatures (AVHRR and ATSR), geolocation errors (AVHRR), and incomplete spatial and temporal coverage of the current holdings. Reprocessing of the data record will need to account for sensor differences and satellite orbital drift effects. Current and projected systems (MODIS, Sentinel, VIIRS) are adequate for active fire detection, but the 250-m threshold requirement is not met.

Supplemental Product to T.9: Fire Radiated Power (FRP)

Past provisions

- The sensors on polar orbiters used for active fire detection before MODIS (AVHRR, ATSR) did not provide measurements useful for FRP retrieval due to their low saturation level. Experimental FRP products have been derived from GOES Imager.

Present/future provisions

- MODIS has been used to produce a global FRP product. VIIRS on NPP and NPOESS platforms is expected to provide FRP retrieval capabilities for a more limited range of conditions.
- GOES Imager and MSG SEVIRI also provide the potential for FRP retrieval at coarser resolutions. All geostationary meteorological satellites should include the SEVIRI-class instruments that enable FRP retrievals at high temporal frequency.
- There is a requirement for 250-m MIR and TIR sensors operating on a small constellation of satellites. ESA's Sentinel satellites under GMES will provide a 1-km resolution TIR imager. There is also an opportunity to include a 250-m TIR imager on Sentinel 2. This will provide the capability to retrieve FRP.

Adequacy of provisions

- The FRP data record is inadequate before MODIS due to low sensor saturation temperatures. Bands with the proper dynamic range of sensors such as MODIS, SEVIRI, Sentinel, and VIIRS provide the capability for generating an FRP data record. However, due to missing or inadequate calibration across the entire dynamic range the data record is only marginally adequate. The 1-km target requirement for spatial resolution will be met.

Soil Moisture (T.10)

Past provisions

- ERS (from 1991) Scatterometer data have been used for global soil moisture estimation on a scale of 50 km, but are no longer available.

Present/future provisions

- AMSR-E (from 2002) provides improved soil moisture products for global soil moisture estimation with spatial resolution of 60 km at 6.9 GHz. ALOS L-band PALSAR provides soil moisture products from 2006. ESA plans to launch SMOS mission for global soil moisture in 2007 (TBC).

Adequacy of provisions

- These observations are not sufficient for the GCOS requirements (25-km horizontal resolution, 7-day observation cycle, 1-year delay, accuracy 5%) except for horizontal resolution provided by ALOS L-band SAR and observation cycle and accuracy by SMOS.
- Space-based measurements provide estimates of water in the upper 5-10 cm of soil. While these meet the needs for some applications, many applications require moisture measurements through the soil profile.

Appendix 5: Importance of Consistent Calibration and Validation

CEOS stresses the importance of calibration and validation activities for all ECVs to ensure the sustainability of climate records. Calibration is the process of quantitatively defining system responses to known, controlled signal inputs. Thus, a calibrated product is the output from the complete calibrated data generation chain. Vicarious calibration is indirect calibration achieved by simulating the signal at the satellite sensor input based on independently measured geophysical parameters, and comparing it to the actual signal measured by the sensor. The outcome of the comparison can be used to calibrate the sensor output. Validation is the process of assessing, by independent means, the quality of the data products derived from system outputs.[13] Validation ensures that the quality of the products is properly assessed, via quantification of the uncertainties in Level 1b and Level 2 products. Thus, a validated product is the output from the complete validated data generation chain. Geophysical validation is the process of assessing, by independent means, the quality of geophysical data products derived from the system.

Applications for climatology are by nature based on data sets, with their calculated uncertainties, collected with evolving technologies and systems (including ground-based and space measurements), and operated by a variety of entities. Fusion of these heterogeneous data sets is required to guarantee access to comprehensive and coherent climate records with adequate temporal resolution covering the Earth.

To integrate observations and products from different satellite systems, measurements must be inter-calibrated. Without inter-calibration of instruments—and inter-validation of data sets—the full benefit of observations cannot be realized. For instance, in climate applications, “jumps” (systematic biases) can occur in time series constructed from data gathered by different sensors. A proper scientific approach to account for such instrument-to-instrument biases is to directly compare observations from different instruments under well-controlled conditions

In order for this strategy to guarantee proper relative calibration of various observing systems, however, it must be based on a well-defined and standardized absolute calibration of each individual mission. This is a prerequisite for attaining the full benefit of observing systems. Furthermore, calibration activities need to be maintained throughout each individual mission to guarantee proper understanding of the evolution of the observing instruments and immediate intervention. Additionally, constant monitoring of instruments enhances understanding of instrument characteristics, which in turn enhances adequacy of data processing, ultimately leading to improved final products and feedback on the next generation of instruments.

Data assimilation can be a powerful tool for adequate, relative validation of data sets, but it needs to be supported by absolute calibration and validation processes largely supported by comparison with *in situ* measurements. Continuous, long-term, *in situ* stations systematically sensed by various instruments and regularly repeated measurement campaigns are fundamental elements of any operational observing system. Use of these facilities is also the only way to link different spaceborne data sets separated in time for use in long-term data records.

[13] CEOS Standard Terminology for Microwave Radiometry, 10 September 2003, p. 4

Appendix 6: The Committee on Earth Observation Satellites[14]

Since its establishment in 1984 under the aegis of the Economic Summit of Industrialised Nations Working Group on Growth, Technology and Employment, the Committee on Earth Observation Satellites (CEOS)—with nearly 30 space agency members worldwide—has evolved to provide a broad framework for international coordination of space-borne Earth-observation missions. Despite not having intergovernmental status, CEOS as an ad-hoc coordination mechanism has had considerable impact over its more than twenty years of existence. The CEOS framework is voluntary and progresses on a best-efforts basis that is dictated by the priorities and available resources of the participating space agencies. The activities of CEOS and its subsidiary groups are diverse, reflecting its primary objectives:

- to optimise benefits of space-borne Earth observations through cooperation of its participants in mission planning and in development of compatible data products, formats, services, applications, and policies;
- to serve as a focal point for international coordination of space-related Earth-observation activities; and
- to exchange policy and technical information to encourage complementarity and compatibility of observation and data exchange systems.

Participating CEOS agencies meet in Plenary annually, with activities and coordination occurring throughout the year. The Plenary reviews progress on the various projects and activities being undertaken within CEOS. CEOS has established a Strategic Implementation Team (SIT) with the responsibility to address the composition and function of the space component of IGOS. The SIT provides a forum where the heads of space agencies can meet to develop agreements on programme commitments in order to address gaps or overlaps in mission planning.

CEOS also has three Working Groups:

- the Working Group on Calibration and Validation (WGCV) is tasked with enhancing coordination and complementarity, promoting international cooperation, and focusing activities in the calibration and validation of Earth observations for the benefit of CEOS agencies and the international user community. WGCV addresses sensor specific calibration/validation and geophysical parameter/derived products validation.
- the Working Group on Information Systems and Services (WGISS) works to facilitate data and information management and services for users and data providers in dealing with global, regional, and local issues. In particular, it addresses the capture, description, processing, access, retrieval, utilisation, maintenance, and exchange of spaceborne Earth-observation data and supporting ancillary and auxiliary data and information, enabling improved interoperability and interconnectivity of information systems and services.
- the Working Group on Education and Training (WGEdu) works to establish an effective coordination and partnership mechanism among CEOS agencies and institutions offering education and training around the world by facilitating activities that substantially enhance international education and training in Earth system science and the observation techniques, data analysis, and interpretation required for its use and application to societal needs.

The more than 20 years invested by space agencies toward CEOS and its activities and objectives has resulted in recognition of CEOS as the primary forum worldwide for coordination of space-based Earth observations. CEOS is the logical respondent to the call from UNFCCC to Parties that support space agencies to respond to the GCOS IP.

[14] Adapted from the *CEOS Earth Observation Handbook*, 2002, http://www.eohandbook.com/

Appendix 7: Glossary of Abbreviations and Acronyms

(A)ATSR	(Advanced) Along Track Scanning Radiometer
ADM	Advanced Dynamics Mission (ESA)
AIRS	Atmospheric Infrared Sounder
ALOS	Advanced Land Observation Satellite
A.M.	Ante Meridiem
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	Advanced Microwave Scanning Radiometer – EOS
AMSU	Advanced Microwave Sounding Unit
AMSU-B	Advanced Microwave Sounding Unit B
APS	Aerosol Polarimeter Sensor
Aquarius/SAC-D	Aquarius/Satélite de Aplicaciones Científicas-D
ASCAT	Advanced Scatterometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLID	Atmospheric Lidar
ATMS	Advanced Technology Microwave Sounder
ATSR	Along Track Scanning Radiometer
ATSR-2	Along Track Scanning Radiometer 2
AVHRR	Advanced Very High Resolution Radiometer
AVNIR	Advanced Visible and Near Infrared Radiometer
BRDF	Bidirectional Reflectance Distribution Function
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CBERS	China-Brazil Earth Resources Satellite
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiant Energy System
CGMS	Coordination Group for Meteorological Satellites
CH_4	Methane
CHAMP	Coral Health and Monitoring Program
CLiC	Climate and the Cryosphere
CMIS	Conical Scanning Microwave Imager/Sounder
CNES	Centre National d'Etudes Spatiales
CO_2	Carbon Dioxide
CONAE	Comisión Nacional de Actividades Espaciales
COP	Conference of the Parties
CORINE	Coordinated Information on the European Environment
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
CrIS	Cross track Infrared Sounder
EC	European Commission
ECV	Essential Climate Variable
ENSO	El Niño Southern Oscillation
Envisat	Environmental Satellite
EOS	Earth Observing System
EOSD	Earth Observation for Sustainable Development of Forests
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Sensor
ERS	European Remote Sensing satellite
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper+
EUMETSAT	European Organization for the Exploitation for Meteorological Satellites
FCDR	Fundamental Climate Data Record
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation
F/O	Follow-On
FY	Feng Yun satellite
GCMP	GCOS Climate Monitoring Principle
GCOS	Global Climate Observing System

GCOM	Global Change Observation Mission
GCOM (-W, -C)	Global Change Observation Mission (-Water, -Climate)
GCOM-C/SGLI	Global Change Observation Mission-C/Second-generation Global Imager
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GFO	Geosat Follow On
GHRSST	GODAE High Resolution Sea Surface Temperature
GHz	Giga-Hertz
GLOBCOVER	Global Land Cover service
GMES	Global Monitoring for Environment and Security
GMS	Geostationary Meteorological Satellite
GODAE	Global Ocean Data Assimilation Experiment
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GOS	Global Observing System
GOSAT	Greenhouse Gases Observing Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRAS	Global Navigation Satellite System Receiver for Atmospheric Sounding
GSFC	Goddard Space Flight Center
GSICS	Global Space-based Inter-Calibration System
HIRDLS	High-Resolution Dynamics Limb Sounder
HIRS	High Resolution Infrared Radiation Sounder
HRPT	High Resolution Picture Transmission
HRV	High Resolution Visible
IASI	Infrared Atmospheric Sounding Interferometer
ICESat	Ice Cloud and Land Elevation Satellite
IGOS	Integrated Global Observing Strategy
INDREX	Indonesian Airborne Radar Experiment
InSAR	Interferometric Synthetic Aperture Radar
INSAT	Indian National Satellite
IOCCG	International Ocean Colour Coordinating Group
IP	Implementation Plan
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRS	Indian Remote Sensing
ISCCP	International Satellite Cloud Climatology Product
ISRO	Indian Space Research Organization
IT	Information Technology
JAXA	Japan Aerospace Exploration Agency
JERS	Japanese Earth Resources Satellite
JRC	Joint Research Centre
LAI	Leaf Area Index
LEGOS	Laboratoire d'Etudes en Géodésie et Océanographie Spatiales
Lidar	Light Detection and Ranging
LST	Land Surface Temperature
MERIS	Medium Resolution Imaging Spectrometer
Meteosat	Meteorological Satellite
MetOp	Meteorological Operational satellite
MHS	Microwave Humidity Sounder
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MIR	Mid-Infrared
MISR	Multi-angle Imaging Spectroradiometer
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MODLAND	MODIS Land
MSG	Meteosat Second Generation
MSMR	Multi-frequency Scanning Microwave Radiometer

MSU	Microwave Sounding Unit
MTSAT	Multi-functional Transport Satellite
NASA	National Aeronautics and Space Administration
NIR	Near-infrared
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NSIDC	National Snow and Ice Data Center
NWP	Numerical Weather Prediction
OCO	Orbiting Carbon Observatory
OLS	Operational Linescan System
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OOPC	Ocean Observation Panel for Climate
PALSAR	Phased Array L-band Synthetic Aperture Radar
P.M.	Post Meridiem
POLDER	Polarization and Directionality of Earth Reflectances
Pol-InSAR	Polarimetric SAR Interferometry
PRODES	Programa de Cálculo de Desflorestamento de Amazônia
PUMA	Preparation for Use of MSG in Africa
QuikSCAT	Quick Scatterometer mission
R&D	Research and Development
Radarsat	Radar Satellite
RO	Radio Occultation
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SBA	Societal Benefit Area
SBSTA	Subsidiary Body on Scientific and Technical Advice
SBUV	Solar Backscatter Ultraviolet
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SGLI	Second Generation Global Imager
SI	International System of Units (Système International d'Unités)
SMMR	Scanning Multi-channel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SPOT	Satellite Pour l'Observation de la Terre
SSM/I	Special Sensor Microwave/Imager
SSM/IS	Special Sensor Microwave/Imager Sounder
SSM/T	Special Sensor Microwave/Temperature
SSM/T-2	Special Sensor Microwave/Temperature Profiler
SST	Sea Surface Temperature
SWE	Snow Water Equivalent
SWIR	Shortwave Infrared
TES	Tropospheric Emission Spectrometer
TIR	Thermal Infrared
TIROS	Television Infrared Observation Satellite
TM	Thematic Mapper
TMI	TRMM Microwave Imager
TOMS	Total Ozone Mapping Spectrometer
TOPEX/Poseidon	Ocean Topography Experiment/Poseidon
TRMM	Tropical Rainfall Measuring Mission
TSIS	Total Solar Irradiance Sensor
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USGS	United States Geological Survey
UV	Ultraviolet
VGT	Vegetation

VIIRS	Visible Infrared Imager/Radiometer Suite
VIRS	Visible Infrared Scanner
VIS	Visible
VNIR	Visible and Near Infrared
WatER	Water Elevation Recovery
WCRP	World Climate Research Programme
WGCV	Working Group on Calibration and Validation
WGEdu	Working Group on Education and Training
WGISS	Working Group on Information Systems and Services
WMO	World Meteorological Organization
WSOA	Wide Swath Ocean Altimeter
WWW	World Weather Watch
XML	Extensible Markup Language

Appendix 8: Contributors to this Report

This report has been prepared under the direction of the incoming Chair of CEOS, Associate Director of the U.S. Geological Survey Barbara J. Ryan, edited by Rebecca L. Johnson, and with the substantial support of Tom Armstrong, Stephen Briggs, L. DeWayne Cecil, Ivan Csiszar, Jean-Louis Fellous, Roy Gibson, Chu Ishida, Eric Lindstrom, Paul Menzel, Brad Reed, John Townshend, and Stephen Ward. Paul Mason and his GCOS colleagues provided extensive insights and innumerable suggestions throughout the process. Appreciation also is extended to the following people who participated in the report's development:

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