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Abstract	Observations of planet Earth and especially all climate system components and forcings are increasingly needed for planning and informed decision making related to climate services in the broadest sense. Although significant progress has been made, much more remains to be done before a fully functional and dependable climate observing system exists. Observations are needed on spatial scales from local to global, and all time scales, especially to understand and document changes in extreme events. Climate change caused by human activities adds a new dimension and a vital imperative: to acquire climate observations of sufficient quality and coverage, and analyze them into products for multiple purposes to inform decisions for mitigation, adaptation, assessing vulnerability and impacts, possible geo-engineering, and predicting climate variability and change and their consequences. A major challenge is to adequately deal with the continually changing observing system, especially from satellites and other remote sensing platforms such as in the ocean, in order to provide a continuous climate record. Even with new computational tools, challenges remain to provide adequate analysis, processing, meta-data, archival, access, and management of the resulting data and the data products. As volumes of data continue to grow, so do the challenges of distilling information to allow us to understand what is happening and why, and what the implications are for the future. The case is compelling that prompt coordinated international actions are essential to provide for information-based actions and decisions related to climate variability and change.

Keywords (separated by "-")	Climate observing system - Satellite observations - Climate change - Data processing - Earth observations - Metadata - Climate data records

Challenges of a Sustained Climate Observing System

[AU1] **Kevin E. Trenberth, Richard A. Anthes, Alan Belward, Otis B. Brown, Ted Habermann, Thomas R. Karl, Steve Running, Barbara Ryan, Michael Tanner, and Bruce Wielicki**

Abstract Observations of planet Earth and especially all climate system components and forcings are increasingly needed for planning and informed decision making related to climate services in the broadest sense. Although significant progress has been made, much more remains to be done before a fully functional and dependable climate observing system exists. Observations are needed on spatial scales from local to global, and all time scales, especially to understand and document changes in extreme events. Climate change caused by human activities adds a new dimension and a vital imperative: to acquire climate observations of sufficient quality and coverage, and analyze them into products for multiple purposes to inform decisions for mitigation, adaptation, assessing vulnerability and impacts, possible geo-engineering, and predicting climate variability and change and their consequences. A major challenge

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is to adequately deal with the continually changing observing system, especially from satellites and other remote sensing platforms such as in the ocean, in order to provide a continuous climate record. Even with new computational tools, challenges remain to provide adequate analysis, processing, meta-data, archival, access, and management of the resulting data and the data products. As volumes of data continue to grow, so do the challenges of distilling information to allow us to understand what is happening and why, and what the implications are for the future. The case is compelling that prompt coordinated international actions are essential to provide for information-based actions and decisions related to climate variability and change.

Keywords Climate observing system • Satellite observations • Climate change • Data processing • Earth observations • Metadata • Climate data records

Acronyms

ALOS	Advanced Land Observing Satellite
ADEOS	Advanced Earth Observing Satellite
AIRS	Atmospheric Infrared Sounder
AR4	Fourth Assessment Report (IPCC)
ATMS	Advanced Technology Microwave Sounder
BSRN	Baseline Surface Radiation Network
CCSP	Climate Change System Program
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiant Energy System
CF	Climate and Forecast
CGMS	Coordination Group for Meteorological Satellites

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CLARREO	Climate Absolute Radiance and Refractivity Observatory
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CrIS	Crosstrack Infrared Sounder
DESDynl	Deformation, Ecosystem Structure, and Dynamics of Ice
DoD	Department of Defense
EarthCARE	Earth, Cloud, Aerosol, Radiation and Energy
ECMWF	European Centre for Medium-range Weather Forecasts
ECV	Essential Climate Variable
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
ERA	ECMWF Re-Analysis
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GAW	Global Atmospheric Watch
GCOM	Global Change Observation Mission (JAXA)
GCOS	Global Climate Observing System
GCMPs	GCOS Climate Monitoring Principles
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water ~~Cycle Experiment~~ (WCRP)
GFCS	Global Framework for Climate Services
GMES	Global Monitoring for Environment and Security
GNSS	Global Navigation Satellite System
GOES	Geosynchronous Operational Environmental Satellite
GOOS	Global Ocean Observing System
GOS	Global Observing System
GOSAT	Greenhouse Gases Observation Satellite (JAXA)
GPM	Global Precipitation Mission
GPS	Global Positioning System
GRUAN	GCOS Reference Upper-Air Network
GSICS	Global Space-based Intercalibration System
GTOS	Global Terrestrial Observing System
ICESAT	Ice, Cloud, and Land Elevation Satellite
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme
IGDDS	WMO Integrated Global Data Dissemination Service
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
JMA	Japanese Meteorological Agency
JPSS	Joint Polar Satellite System
LAI	Leaf Area Index

MERIS	Medium Resolution Imaging Spectrometer
MERRA	Modern Era Retrospective-Analysis for Research and Applications
MODIS	Moderate Resolution Imaging Spectro-radiometer (NASA)
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council (USA)
NWP	Numerical Weather Prediction
OCO	Orbiting Carbon Observatory
OMPS	Ozone Mapping and Profiler Suite
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
REDD	Reducing Emissions from Deforestation and Forest Degradation
SAPS	Synthesis and Assessment Products
SBSTA	Subsidiary Body for Scientific and Technological Advice
SCOPE-CM	Sustained Co-Ordinated Processing of Environmental satellite data for Climate Monitoring
SI	International System of units (Système International)
SMAP	Soil Moisture Active/Passive
SOC	State of Climate
TOA	Top of Atmosphere
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio-Studies
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	United States Global Change Research Program
VIIRS	Visible/Infrared Imager/Radiometer Suite
WCC-3	World Climate Conference-3
WCRP	World Climate Research Programme
WDAC	WCRP Data Advisory Council
WG	Working Group
WMO	World Meteorological Organization
WOAP	WCRP Observation and Assimilation Panel

1 Introduction

The first rule of management is often stated to be “you can’t manage what you can’t measure”. Indeed, Earth is observed more completely today than at any other time. Multiple observations are made from space in many different wavelengths via passive and active sensors that provide information on many geophysical and meteorological variables. However, a key question is the extent to which these observations are suitable for characterizing climate, and especially for climate monitoring and prediction.

As the climate system is continuously evolving, there is a need to measure changes globally and regionally, to understand the system, attribute the causes of the changes by linking the changes in state variables to various forcings, and to develop models that can simulate and predict the system's evolution (Trenberth et al. 2002, 2006). The observations must be processed and analyzed, often into globally gridded fields that can be used as an initial state for predictions using climate models. Accordingly, observations are used to document the state of the climate and how it varies and changes over time, along with documenting external influences on the system such as the sun, the Earth's radiation budget, the Earth's surface and changes in the climate system from human influences.

Moreover, because the climate is changing from natural and human influences (IPCC 2007) it is an imperative to document what is happening, understand those changes and their causes, sort out the human contribution, and make projections and predictions on various time horizons into the future (Trenberth 2008). Mitigation of the human influences, such as reducing greenhouse gas and aerosol emissions, is a major challenge yet to be adequately addressed and the effectiveness of any mitigation actions needs to be documented in order for them to continue. However, given the likelihood of large future human-induced changes, understanding and planning how to cope with the projected changes, and how well the predictions are verifying, become extremely important. Hence information related to adaptation to climate change is also vital. Process studies using special, perhaps short-term observations will help improve models and the information they can provide. Prospects of geo-engineering to offset climate change mandate diligent observations to ensure that the intended effects are in fact happening and to check for unforeseen side effects. Together, all of these activities and needs define the observation requirements for a climate information system that provides climate services to users of all kinds.

Many observations pertinent to this information system are made (Fig. 1), but most are not of sufficient quality to meet climate needs. In the atmosphere, most observations are made for weather forecasting which involves documenting the state of atmospheric weather systems such as low and high pressure systems, cold and warm fronts, tropical cyclones, rain bands, clear skies, and so forth as a first step to predicting their movement and evolution. Weather fluctuations are huge compared with climate change and so high measurement accuracy and precision have not been a priority, although this has changed as models have improved and the need to correct biases has grown. Climate change must discern relatively small changes over time, which calls for both stability and calibrated measurements of high accuracy. Knowing how the measurements of 20 or 50 years ago relate to those of today is very important.

The climate observing system challenge can be understood by considering that understanding and predicting this complex system requires many more variables than for weather prediction. The current estimate is 50 Essential Climate Variables (ECVs): 16 for atmosphere, 18 for ocean, and 16 for terrestrial (GCOS 2010).

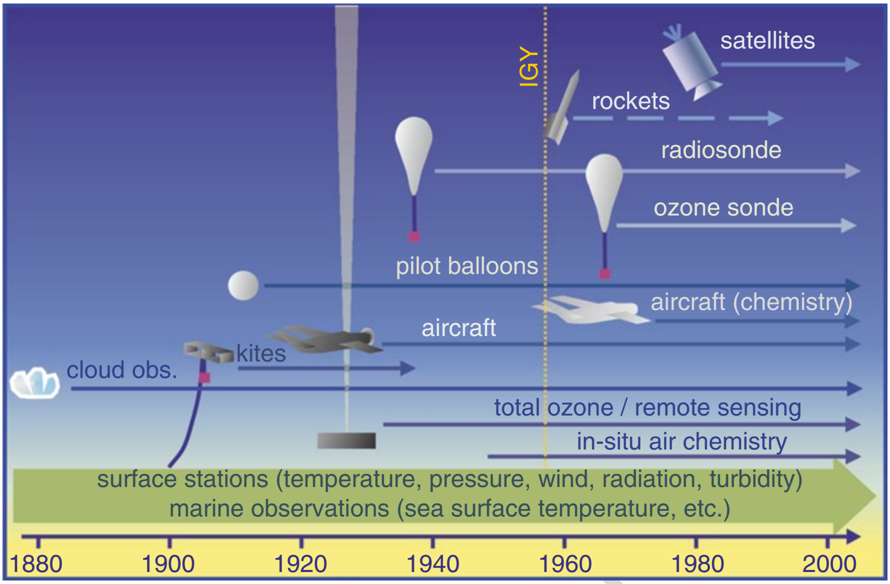

Fig. 1 Changes in the mix and increasing diversity of observations over time create challenges for a consistent climate record (Courtesy, S. Brönnimann, University of Bern. Adapted from Brönnimann et al. 2008)

The ECV accuracy requirement is also much more stringent than for weather observations (e.g., 0.1 K vs 1 K). Space and time scales are more extreme, ranging from aerosol and cloud physics occurring at seconds and micrometers, to global decadal change at 100 years and 40,000 km: a range greater than 10^9 in time, and 10^{13} in space.

At the surface, observing instruments can be calibrated, but sites often change and the representativeness of the observations is a concern. For instance, since the 1970s around 50,000 km^2 per year of natural vegetation across Africa has been converted to agricultural land or cleared (Brink and Eva 2009). Elsewhere the urban heat island effect associated with the concrete jungle of a city and its effects on runoff and heat retention plus space heating are important locally but make up less than 0.5 % of land (Schneider et al. 2009), and these changes are very small on a global basis. Radiosonde and other instrumental records suffer from biases that have changed over time.

Satellites have observed Earth for over 50 years now, and have provided a series of wonderful and enlightening imagery and measurements (NRC 2008). They help offset the otherwise uneven spatial coverage of *in situ* observations. Nonetheless, each satellite mission has a new instrument that is exposed to cosmic rays, outgassing contaminants, and a hostile environment, and the satellite orbit eventually decays and drifts in time. The instruments thus require on-board calibration and/or validation from in situ instruments. An exception is GNSS (Global Navigation Satellite System) radio occultation, which is self calibrating (Steiner et al. 2011). A mission typically lasts 5 years or so; thus determining how new measurements relate to old ones to ensure continuity of the record is a major issue (Fig. 1). Because of these issues, only a few satellite records (water vapor and microwave temperatures) were used to determine trends in the IPCC Fourth Assessment Report (AR4) (IPCC 2007).

In the following, the observing system and its suitability for climate purposes is outlined. Acronyms are given in an appendix. We describe recent improvements for cross calibrating space-based observations, for instance, and immediate prospects for the future. The needs are discussed along with the issues and challenges in meeting them. Indeed the needs are compelling and enormous, but also feasible with international cooperation and leveraging of resources.

2 The Current Climate Observing System

2.1 Status of Systematic Climate Observations

The Global Climate Observing System (GCOS) organization leads the international advisory oversight of systematic climate observations, and focuses on observations to support the United Nations Framework Convention on Climate Change (UNFCCC). Appendix A provides a brief summary of its organizational structure and charter. One of GCOS most critical roles is to produce regular assessments of the adequacy of climate observations, including suggestions for needed improvements. Recent GCOS reports provide an excellent reference point for discussing the status of climate observations.

A progress report (GCOS 2009) concluded that:

- the increasing profile of climate change had reinforced awareness of the importance of an effective global climate observing system;
- developed countries had improved many of their climate observation capabilities, but with little progress in ensuring long-term continuity for several important observing systems;
- developing countries had made only limited progress in filling gaps in their *in situ* observing networks, with some evidence of decline, and capacity building remained small in relation to needs;
- both operational and research networks and systems, established principally for other purposes, were increasingly responsive to climate needs including the need for timely data exchange;
- space agencies had improved mission continuity, observational capability, data reprocessing, product generation and access;
- GCOS had progressed significantly, but still fell short of meeting all the climate information needs of the UNFCCC and broader user communities.

The Third World Climate Conference (WCC-3) in 2009 underscored the importance of systematic observations (Manton et al. 2010; Karl et al. 2010). WCC3 recommended strengthening GCOS by:

- sustaining the established *in situ* and space-based components of GCOS;
- applying the GCOS Climate Monitoring Principles (GCMPs);
- improving the operation and planning of observing systems; identify deficiencies, achieving resilience, and assuring reliable and timely delivery of quality data, traceable to international standards;
- enhancing observing systems wherever feasible; filling gaps in spatial coverage and in the breadth of variables measured, improving measurement accuracy and frequency, increasing use of operational platforms for satellite sensors, monitoring urban and coastal conditions, and establishing reference networks;
- rescuing, exchanging, archiving and cataloging data, and recalibrating, reprocessing and reanalyzing long-term records, working towards full and unrestricted access to data and products;
- giving high priority to observational needs for adaptation planning, identifying country needs in National Adaptation Programs of Action;
- assisting developing countries to maintain and strengthen their observing networks through support for updating, refining and implementing the GCOS Regional Action Plans and other regional observational and service initiatives.

The 2010 update (GCOS 2010) also noted advances in observational science and technology, an increasing focus on adaptation, and the demand to optimize mitigation measures. It reaffirmed the importance of the GCMPs, emphasizing the need for and ways to achieve continuity and stability of measurements. Guidelines for operations including on-orbit calibration and validation, the need for global coverage, timeliness of data, and development of a maturity index for each ECV, were also included. It introduced a small number of new ECVs, and called for colocated measurement of ecosystem variables along with the ECVs that influence or are influenced by them. Table 1 provides details of the ECVs.

The 2010 GCOS update provided cost estimates for fully implementing and operating the climate observing system; around US$2.5 billion each year (in addition to the current annual global expenditure of some US$5–7 billion on global observing systems serving climate and related purposes). Around US$1.4 billion of this additional expenditure is needed for satellites or for *in situ* observation of the open ocean, in both cases for the benefit of all. In addition, around US$600 million per year are needed for *in situ* observations in developing countries (GCOS 2010). Consequently, the magnitude of the investment required is order $\frac{1}{3}$ to $\frac{1}{2}$ of the current expenditure (whose estimate depends on how costs are assigned when the observations serve multiple purposes).

A definition of a climate data record is, "…a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change" (NRC 2004). A challenge for climate observations is to have a consistent, well-understood framework for observations that is independent of a parameter's origin and observing approach, and, easily found and accessed.

Table 1 Essential climate variables (ECVs) that are both currently feasible for global implementation and have a high impact on UNFCCC requirements (GCOS 2010)

Domain	Essential climate variables
Atmospheric (over land, sea and ice)	**Surface:** air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget
	Upper-air: temperature, wind speed and direction, water vapor, cloud properties, earth radiation budget (including solar irradiance)
	Composition: carbon dioxide, methane, and other long-lived greenhouse gases; ozone and aerosol, supported by their precursors
Oceanic	**Surface:** Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean color, carbon dioxide partial pressure, ocean acidity, phytoplankton
	Sub-surface: temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial	River discharge, water use, ground water, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture

2.2 Building a System for Climate Observations

The push to develop a systems approach to climate observations has been detailed in Trenberth et al. (2002, 2006). Trenberth (2008) outlined a framework for how observations, data and analyses feed into assimilation and modeling that support prediction and attribution. Assessments build on the products to inform stakeholders, users and decision makers. Because of the long time scales associated with climate variations and change, basic research and operational applied research are inherent parts of the entire system that ultimately feed into climate services. All elements are essential for a useful and robust climate information system.

Not all observing systems and datasets are suitable for climate studies. The evolution of data systems to support climate observations has been a multi-step process. Many *in situ* observations originated in a single investigator or team developing an approach, building a network and eventually moving to a systematized network, *e.g.,* meteorological variables followed such a path and transitioned to primarily nationally operated and internationally coordinated observing enterprises by the mid-twentieth century. While *in situ* ocean, land, and ice observing activities have moved along similar trajectories, they have been less mature for the most part. In contrast, space-based remotely sensed observations required significant investments from the outset, most of which were national in origin. Thus, these activities were subject to a systems engineering rigor from very early in their evolution due to their platform dependencies and expense. Nevertheless, the same rigor did not apply to calibration, and recalibration and reprocessing of the data has become essential. It is important to appreciate that there are differing strategies and maturities associated with each ECV.

A "maturity matrix" (Privette et al. 2008) translated NASA concepts on technology readiness into similar attributes for satellite observation maturity. It defines six levels of maturity as a function of sensor use, algorithm stability, metadata completeness, documentation, validation, availability of data, and science and applications. Such an approach provides a framework for defining the attributes and readiness of space-based observations for use in climate applications. While this approach was applied initially to space-based observations, more recently it has been suggested that it be applied to *in situ* observations as well. CEOS, GCOS, GOOS, GTOS and GEOSS are stewarding an integrated approach for Earth observations along with WCRP through its WCRP Observations and Assimilation Panel (WOAP), which is transitioning into the WCRP Data Advisory Council.

The history of space-based observations and currently funded initiatives gives a basis for looking at the state of each ECV (Fig. 2). Combining this information with similar information from *in situ* systems provides the basis for doing assessments of integrated observing system health, gaps, and so forth.

2.3 Developing Operational Components

No single agency, organization, or country has the resources to develop a robust operational end-to-end system for monitoring Earth's climate over the required spatial and temporal scales. By operational we mean regular and with a sustained institutional commitment to the observing system, as opposed to single principle investigator-led or one-of-a-kind research missions. The developing international Global Framework for Climate Services (GFCS) led by WMO (WMO 2011) is a key driver of the need for a more operational approach to climate observations.

There are examples, however, that could serve as models or starting points for an operational climate system. One such example is the operational system that has been built over the last 40 years for weather observations, research, modeling and forecasting. Lives and property are saved everyday as a result of this operational weather system.

The challenges for climate monitoring are more complex, and are compounded by the lack of international agreements and architecture for developing a sustained, integrated climate monitoring capability. GCOS certainly provides an overarching framework and key components, yet much more is needed. Building blocks for an operational system would, at a minimum, include the following components: requirements identification and analysis, observations, intercalibration, contingency planning, analysis and product generation, archiving, distribution and dissemination, and user engagement and training.

Figure 3 shows key components required for an operational capability, which includes satellites sensors and data, climate data records (CDRs), satellite products,

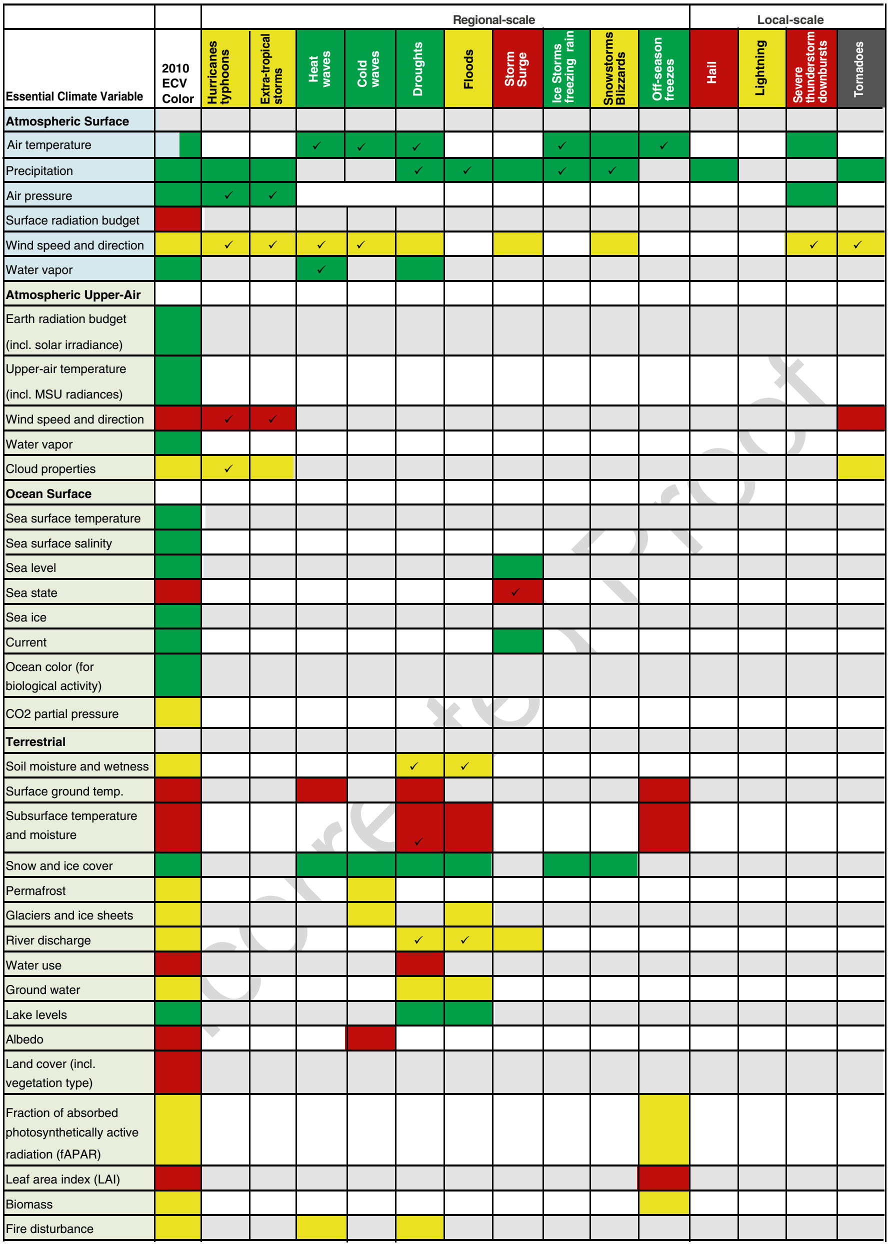

Fig. 2 Relationship of extreme phenomena to ECVs for monitoring. Both the phenomena and the ECVs are color coded to describe the adequacy of the current monitoring systems to capture trends on climate timescales set against alternating *grey* and *white* lines to enhance readability. *Green* indicates global coverage with a sufficient period of record, data quality, and metadata to make enable meaningful monitoring of temporal changes. *Yellow* indicates an insufficiency in one of those three factors. *Red* indicates insufficiency in more than one of the factors. The check mark in the colored ECV block indicates that the ECV is of primary importance to monitoring changes in the extreme event phenomenon

Fig. 3 Key components of an operational climate capability. Here *GSICS* is the global space-based intercalibration system, *IGDDS* WMO integrated global data dissemination service, *SCOPE-CM* sustained coordinated processing of environmental satellite data for climate monitoring, *VLab* virtual laboratory for training in satellite meteorology

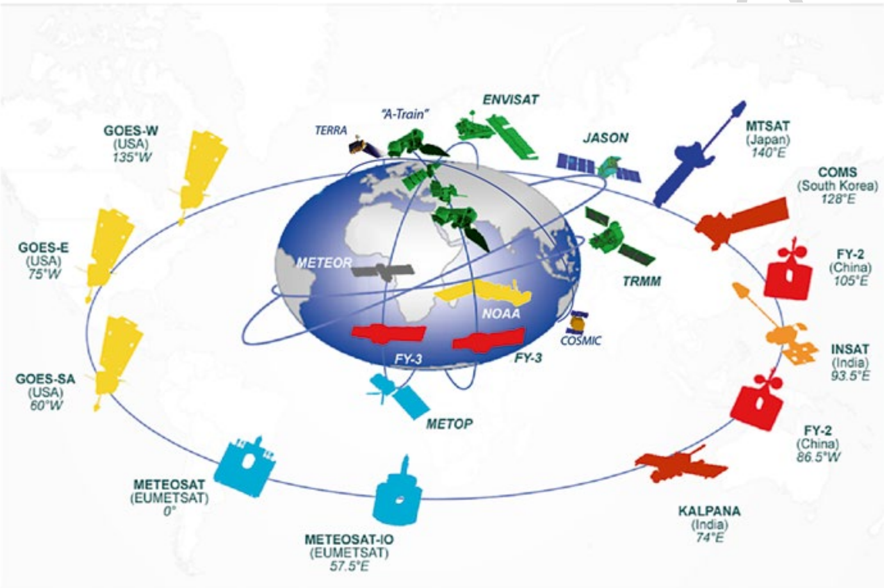

Fig. 4 Schematic of the space-based global observing system (*GOS*) as of about 2010

and ultimately users of those products. This value chain, although originally employed for weather purposes by WMO, is being extended for climate purposes by using the requirements that GCOS has identified and articulated for climate monitoring, e.g., the ECVs. Many agencies and organizations contribute to components of this value chain.

The WMO Global Observing System (GOS) (Fig. 4), was originally comprised of geostationary and polar-orbiting meteorological satellites (early 1960s to early 2000s) and has grown to include research and development satellites. This observing system, its underpinning architecture, and the results achieved illustrate the reliance on and importance of international collaboration. The GCOS reports suggest that the benefits countries receive from this global system far exceed the costs of their individual contributions. Additionally, the interplay between operational satellites and research and development satellites becomes more important to obtain the range of spatial and temporal scales and spectral resolutions needed for climate monitoring.

The Global Space-based Inter-Calibration System (GSICS) is an international program to improve the comparability of satellite measurements taken at different times and locations by different instruments operated by different satellite agencies (Goldberg et al. 2011). GSICS inter-calibrates selected instruments of the GOS including operational low-Earth-orbit and geostationary Earth-orbit environmental satellites and, where possible, ties these measurements to common reference standards. The agencies participating in GSICS have developed a comprehensive calibration strategy involving inter-calibrating satellite instruments, tying measurements to absolute references and standards, and recalibrating archived data. GSICS corrections, initially for infrared channels and thereafter for visible and microwave sensors, are being performed and delivered operationally. GSICS results are used for CDR processing activities, as illustrated in Fig. 3, by the Sustained Co-Ordinated Processing of Environmental Satellite Data for Climate Monitoring (SCOPE-CM) effort. At present, GSICS reference observations (e.g., AIRS, IASI, MODIS) are SI traceable, but not at the absolute accuracy required for climate change. Planned observing systems (e.g., CLARREO) are designed to enable climate change accuracy requirements to be met if deployed.

A number of SCOPE-CM projects are underway, led by one of three space agencies (EUMETSAT and its Climate Monitoring Satellite Application Facility, JMA or NOAA). Structures are being established for the sustained generation of Fundamental CDRs and Thematic CDRs. Extension of the network is also being sought, as the existing projects are primarily target ECVs from the atmospheric domain; increased coverage of the oceanic and terrestrial domain ECVs is needed.

3 Lost in Space: Climate Observations?

The existence of GEOSS, its climate observing component (GCOS), its satellite observing component (CEOS) and their implementation plans (GEO 2005; GCOS 2010) are a strong initial step toward a true international climate observing system. Necessarily, there are both strong *in situ* and global orbiting satellite components. However, a comprehensive system remains more vision than reality, although very promising developments through GCOS, GSICS and SCOPE-CM are taking place. In addition WMO, with CGMS and CEOS, are drafting a climate monitoring from space architecture plan. This section highlights some of the key remaining challenges in observations, especially from space.

3.1 Current and Programmed Satellite Observations

Many new satellite remote sensing programs are under way. The Japan Aerospace Exploration Agency (JAXA) is developing and implementing a suite of climate monitoring satellites including ALOS (mainly for land), GOSAT (for carbon balance estimation among other applications), GCOM-W (for tasks including water circulation), and the EarthCARE platforms (cloud and aerosol observations).

From Europe, satellites flying today plus commissioned systems have the potential to generate 29 of the ECVs. The European Space Agency's Climate Change Initiative, EUMETSAT Satellite Application Facility on Climate Monitoring and the ECMWF ERA reanalysis already support production of some 40 % of the ECVs over the next 5–10 years (Wilson et al. 2010). The European Earth Observation program, GMES (Global Monitoring for Environment and Security), includes five new missions (the Sentinels, which include radar imaging of land and ocean, multispectral 10 m resolution land monitoring and a mission to measure sea-surface topography, sea- and land-surface temperature, ocean color, and terrestrial variables such as FAPAR). The first Sentinels are planned for launch in 2013 and each has a 7-year design lifetime.

NASA is developing and implementing a broad range of Earth space-borne remote sensing missions including the Decadal Survey (NRC 2007) and Climate Continuity series of satellites. NOAA operates operational weather satellites including the polar orbiters [Joint Polar Satellite System (JPSS) (previously called National Polar-Orbiting Environmental Satellite System NPOESS)] and two geostationary satellites [Geostationary Operational Environmental Satellite (GOES)]. The backbone of current global terrestrial monitoring for the U.S. are the NASA Earth Observing System platforms Terra, launched in 1999, Aqua, launched in 2002 and Aura, launched in 2004. At higher spatial resolution, the Landsat satellite series has operated since 1972, with the next satellite in the series planned for January, 2013. The Earth Observing System (EOS) platforms are currently likely to operate through about 2015 and possibly longer.

The first U.S. National Research Council (NRC) decadal survey for Earth sciences (hereafter the Decadal Survey; NRC 2007) reviewed the expected ongoing observations and recommended new observations over the next decade (roughly until 2020). It also provided an overview of translating satellite observations into knowledge and information for the benefit of society. NASA Earth Science has been responsive to and acted upon these recommendations, but significant issues have resulted in a much slower schedule than called for in the Decadal Survey (NRC 2012). CLARREO (Climate Absolute Radiance and Refractivity Observatory), DESDynl (Deformation, Ecosystem Structure, and Dynamics of Ice), SMAP (Soil Moisture Active/Passive) and ICESAT-II (Ice, Cloud, and land Elevation Satellite-II) all had follow up workshop reports (see http://science.nasa.gov/earth-science/decadal-surveys/) and the NASA Earth Science Data Systems has been pursuing a "system of systems" architecture in response to the report recommendations.

The Decadal Survey also recommended that NOAA carry out a fully operational follow-on mission to COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate). COSMIC (2006-), and other radio occultation missions such as GPS/MET (1993–1995), CHAMP (2001–2010) SAC-C (2000-) and METOP-A (2006-) have demonstrated the value of radio occultation in producing precise, accurate, climate quality observations in all weather (Anthes 2011). A follow-on mission (COSMIC-2) has been proposed (http://space.skyrocket.de/doc_sdat/formosat-7-cosmic-2.htm) and significant funding secured from Taiwan. Implementation is beginning with key U.S. support (DoD: US Air Force) but NOAA support has not yet been solidified.

Continuity of the key ECVs initiated in the EOS era is intended to transfer to the JPSS series over the next decade, beginning with the NPOESS Preparatory Project (NPP). However, three expected "foundation" missions have had a troubled history. OCO (Orbiting Carbon Observatory) and GLORY (carrying aerosol polarimetry and solar irradiance) both failed on launch and ended up in the Pacific Ocean, and JPSS replaced the cancelled NPOESS program, which has had rapidly rising costs. Hence several foundation missions have failed or been delayed. The NPP, originally intended to be a risk-reduction mission for a subset of the NPOESS sensors, slipped in time but was successfully launched late October 2011. NPP, now called Suomi NPP, now has an operational mandate for weather and climate applications, since the JPSS missions are delayed until late in the decade, and will serve as a gap filler. The Suomi NPP platform carries the ATMS, CERES, CriS, OMPS (nadir and limb) and VIIRS sensors. The latter is the successor to the widely used MODIS sensor on the Terra and Aqua platforms. The other relevant land sensor will be the SMAP (Soil Moisture Active/Passive) mission planned for an early 2015 launch, which will continue to monitor surface wetness and freeze/thaw conditions of the land surface, building on results from ESA's Soil Moisture and Ocean Salinity (SMOS) mission that was launched in November, 2009. There is a replacement for OCO (OCO-2) that has been supported and should launch later in the decade as well.

The overall impact of the above issues remains to be seen, but it is becoming clear that there is a significant probability of a lack of overlap between the EOS platforms, Suomi NPP, and the next generation operational system (JPSS). Cross-calibration from old to new sensors while both are still in orbit is essential for retaining ECV continuity for multiple decades. Lack of overlap provides challenges to continuity. Recent NOAA budget cuts have jeopardized the timely launch of the first full JPSS platform, originally planned for 2015, now possibly delayed to 2017–2018. An estimate of the likelihood of obtaining at least 1 year of intercalibration overlap as a function of instrument and spacecraft design lifetimes (Loeb et al. 2009) can be applied to 3 key climate sensors on EOS (CERES, MODIS and AIRS) with the follow-on sensors on NPP and JPSS-1 (CERES, VIIRS, CrIS). With a JPSS launch by late 2017 the probability of successful 1-year overlap for all three instruments is only about 37 %. Further delays in launching JPSS will lower this probability. However, some progress concerning cross-calibration of U.S. and European sensors, and the validation of products derived from them is being made (Zibordi et al. 2010).

Consistent measurement of the energy received from the sun is a case in point. There are considerable calibration issues with such measurements from space, but meaningful time series exist since 1979 only because of overlap between measurements. However, with the loss of Glory and because of cost constraints in JPSS that impact inclusion of a solar irradiance instrument, there is a distinct possibility of a gap that would break a more than three decades long record. Exploring alternative means of measuring solar output should be a high priority.

A number of emerging remote sensing programs are under development by other organizations and nations, including China, India and the Republic of Korea. Each of these contribute to the GOS and thus to GEOSS and, as the systems become operational, they are sharing increasingly more data and participating in GSICS in order to increase the quality of their observations.

3.2 Adequacy of In-Situ Observations

Many *in situ* measurements need to be combined with satellite measurements: for calibration/validation and for broader spatial coverage, and sometimes for temporal resolution. Examples of these synergies include greenhouse gases (many cannot yet be reliably measured from space), ozone (suborbital measurements can provide detailed vertical information), snow depth, cover and snow water equivalent. Other observations are of vital importance to understanding the physical climate system, including observations of the Earth surface radiation budget (such as the BSRN), temperature, greenhouse gases, leaf area index, land cover, surface albedo, precipitation, winds, and sea level. Other priority observing networks pertain to elements of the climate system and the important feedbacks therein: ocean color, biomass, fire disturbance, and water use.

Current *in situ* climate observations capabilities are diverse and contribute to both national needs and global partnerships. These capabilities make use of a broad range of airborne, terrestrial, and oceanic observations, some of which were designed primarily for climate, but many of which also serve other purposes. Overall, capabilities are most mature in the atmospheric domain, bolstered by observations made for weather forecasting, while needs and priorities are still emerging in the terrestrial, cryosphere, and oceanic domains. Gleick et al. (2012) provide examples of how some terrestrial *in situ* observations are evolving.

Unfortunately, many *in situ* networks have been in decline, as discussed more fully in Sect. 5.1 and, as noted in Sect. 2.1, hundreds of millions of dollar investments are needed to improve the adequacy of the in situ network.

An *in situ* climate observing component is highly desirable and is beginning to occur through the Global Reference Upper Air Network (GRUAN) (GCOS 2007). While other operational upper air observations exist they were not designed for climate purposes. A reference observation requires:

- traceability to SI or another commonly accepted standard
- comprehensively estimated uncertainty
- documentation of instrumentation, procedures and algorithms
- validation of the data products.

GRUAN will provide reference observations of upper-air ECVs, through a combination of *in situ* measurements made from balloon-borne instruments and ground-based remote sensing observations. The primary goals of GRUAN are to:

- Provide vertical profiles of reference measurements suitable for reliably detecting changes in global and regional climate on decadal time scales.
- Provide a calibrated reference standard for global satellite-based measurements of atmospheric essential climate variables.
- Fully characterize the properties of the atmospheric column.
- Ensure that gaps in satellite programs do not invalidate the long-term climate record.

The envisaged capabilities of a fully-implemented GRUAN (GCOS 2007) include plans to expand to include 30 or 40 sites worldwide. Strict site selection criteria and operating principles have been established, coordinated through the GRUAN Lead Centre, currently hosted by the Lindenberg Meteorological Observatory, Germany. Although GRUAN is a vital component for an adequate climate observing system, adequate support has been slow in developing.

3.3 *The Scope of the Challenge of Satellite Observations: Adequacy and Issues*

As noted in Sect. 1, an extreme range of scales, accuracy, and processes occurs across oceans, atmosphere, biosphere, cryosphere, and biogeochemistry. How scientists deal with this range is illustrated in Fig. 5. In general, climate process data are taken at small time/space scales more similar to weather data. These are critical to understanding underlying climate physics (blue box/text), but the accuracy of climate predictions of decadal change is primarily determined by decadal change in natural and anthropogenic radiative forcings (black) and decadal observations of the climate system response to those forcings (red box and text). The decadal change forcing and response observations drive the need for very high accuracy at large time/space scales. Resolving variability at finer spatial resolutions, however, is also required for many purposes such as extremes. To achieve high accuracy mandates a rigorously maintained link from satellite observations to metrological international physical standards, with a focus on traceability to SI standards at climate change accuracy in both ground calibration as well as in-orbit (green box); see Sect. 3.4.

3.3.1 The Missing Satellite Observing System Principles

The GCMPs include ten that are specifically directed at satellite observations (GCOS 2010). Two important additional principles have been proposed (USGCRP 2003):

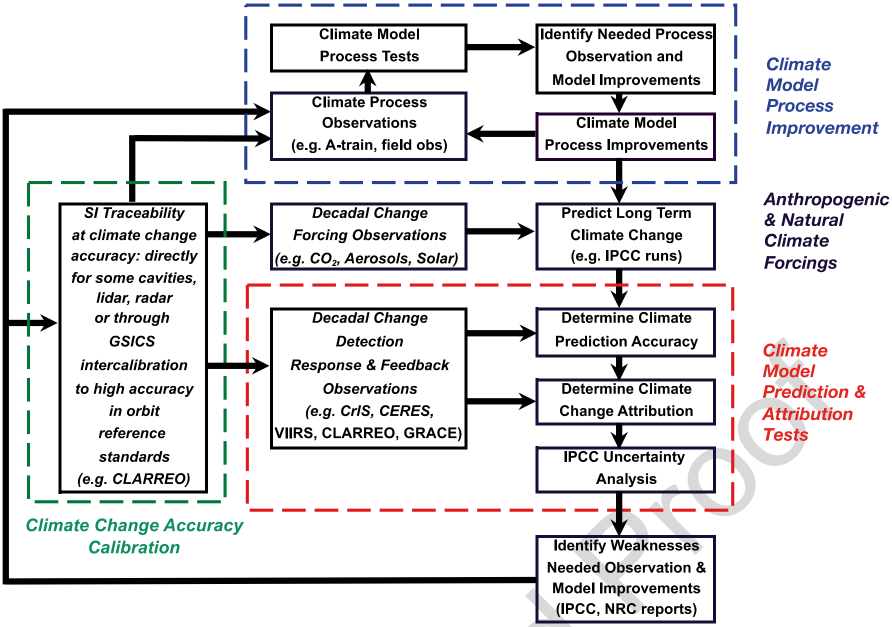

Fig. 5 The schematic shows the role of climate process and monitoring observations in climate change science: detection and attribution of climate change, climate model testing, and climate model improvements

- Provision for independent observations, especially to verify accuracy of other systems and to confirm and/or refute surprising climate change results.
- Provision for independent analysis of observations, especially satellite remote sensing data where analysis systems may involve ten thousand to a million lines of computer code.

The need for these two principles is well recognized in the metrological community. International standards are not accepted until they are independently verified, complete with an analysis of uncertainty in each step. A similar standard is required of fundamental tests of physical laws in research groups at particle accelerator laboratories around the world. Unfortunately, the need for independent scientific verification demands extensive resources especially for independent satellite observations. This may explain the absence of formal acceptance of these principles to date. But recent arguments over the accuracy of climate change observations reaffirm the need for the addition of these two key principles, as independent verification is the key to high confidence needed for societal decision making.

Independent analysis exists for some, but not most, current climate observations and processing. It also remains difficult to judge whether our current priorities will still be the same decades from now. However, a corollary advantage of the independence principles is to add reliability to the observing system when unexpected satellite failures occur such as the recent failures of Glory, OCO, and CryoSat missions, or premature loss in orbit of entire satellites, such as ADEOS and ADEOS 2.

3.3.2 Delays and Cost Increases

Technical development, schedule, and budget issues can also delay satellite observations as shown by the delays of JPSS, and the recent indefinite delay of the CLARREO and DESDynI missions, as well as a follow on copy of the Global Precipitation Mission radar. The delays of NPP and NPOESS/JPSS would already have had dire consequences had the Terra and Aqua missions not lasted a factor of 2 longer than design life. If those missions had only lasted the nominal 5 years planned, as did the recent ALOS satellite, the gap of a wide range of climate relevant observations would have begun in 2007 (Aqua 5 years old, Terra 7 years old), and continued until at least the end of 2011 with launch of the delayed NPP mission.

Delays and failures compromise the climate observing system's ability to deliver information concerning core UNFCCC needs and severely limit capacity to meet new demands. As emphasized in the introduction, we must have the ability to relate measurements of 20 or 50 years ago to those of today. This is equally the case for new demands for climate information, such as quantifying terrestrial source/sink dynamics of CO_2, and interchanges with the atmosphere, (a need that is implicit in new policy instruments considered in the REDD++ framework). A mitigation example is testing different approaches with forests: by planting to enhance carbon sinks or reducing emissions from avoided deforestation and degradation. Therefore observations inherent in measures of disturbance are required as well as of land-cover and land-use change, from deforestation, wildfire, or other human activities which also influence albedo and water balance (Running 2008; Justice et al. 2011). Metrics to describe degradation require monitoring at spatial resolution of 30 m resolution and finer. These new demands are in danger of remaining unmet because of delays, and monitoring remains a challenge.

Accessible archives of historical observations are also fundamental to give that vital 20 or 50 year perspective on such changes – Landsat has been making observations since 1972 and significant progress has been made in cross calibrating the radiometry of the different sensors flown (Chander et al. 2009), but more than two thirds of the 7 million+ scenes acquired are held in largely inaccessible archives, which results in very uneven spatial and temporal coverage. Furthermore, the operational status of the Landsat system is still not fully secure. The unbroken record, secured since 1972, might not continue to grow. Landsat 5, which provided an unprecedented (and totally unexpected) 27 years of service suspended imaging mid-November 2011, Landsat 7 still flies, but with compromised sensor performance, and the launch of the next satellite in this series has been delayed. Gaps in the archive might yet be avoided if Landsat 7 survives until the follow-on mission's expected January 2013 launch date.

3.4 *Decadal Change Accuracy: Unbroken Chain of Uncertainty to SI Standards*

3.4.1 Accuracy and SI Standards

Observations of climate change require stability over decades, and unless overlapping observations are sustained, including verification of stability, absolute accuracy is required. Confidence in these observations depends on how accurately we can relate satellite observations in one decade to those in another decade. However, few observations provide the rigorous on-board calibration and cross-calibration needed. Fortunately, progress is being made in cross calibration of U.S. and European sensors.

The schematic in Fig. 6 shows an example of the traceability required from SI standards as the anchor through instrument calibration, in-orbit intercalibration, retrieval of geophysical properties, orbit sampling, to final decadal change observations that could be used to test climate model predictions. The figure shows the goal of traceability to SI standards at the foundation that have absolute accuracy uncertainty much smaller than the signals expected from decadal change (NRC 2007; Ohring et al. 2007). In support of this, CEOS and GEO have led the development of [AU2] a new internationally endorsed Quality Assurance Framework for Earth Observation (QA4EO) (CEOS 2008; GEO 2010). The framework concludes that "*All data and derived products must have associated with them a Quality Indicator (QI) based on documented quantitative assessment of its traceability to community agreed (ideally tied to SI) reference standards*."

Some satellite observations can meet this goal: examples are GNSS radio occultation (e.g., Anthes 2011; Ho et al. 2010; Steiner et al. 2011), ocean altimeters and ice sheet or cloud elevation lidars which trace their accuracy in refractivity or height to SI standards in time measurement. Indeed, there have been marked improvements to atmospheric temperature and water vapor analyses through assimilation of COSMIC observations (see the bias reductions in Fig. 7 as an example and Poli et al. 2011). As another example, the diurnal heating of spacecraft platforms and instruments as they move into and out of the sun's shadow noticeably affects microwave and infrared soundings that can be corrected using radio occultation observations, as the latter are not so affected (Ho et al. 2009; Anthes 2011).

Most satellite instruments, including solar reflected and infrared emitted spectrometers and radiometers, as well as passive microwave instruments, do not currently achieve SI traceable in-orbit climate change accuracy. These instruments rely on less direct arguments of stability in orbit, and overlap of different instruments to remove calibration bias differences. This produces a fragile climate observing system with much weaker ties to SI standards than desired and severe vulnerability to any gaps in the overlap of instruments. While GSICS provides a very useful relative intercalibration of radiometers in orbit, we still lack a set of reference radiometers that could provide the absolute accuracy to serve as "metrology labs" in orbit and benchmarks for the GSICS activity (GSICS 2006; Goldberg et al. 2011).

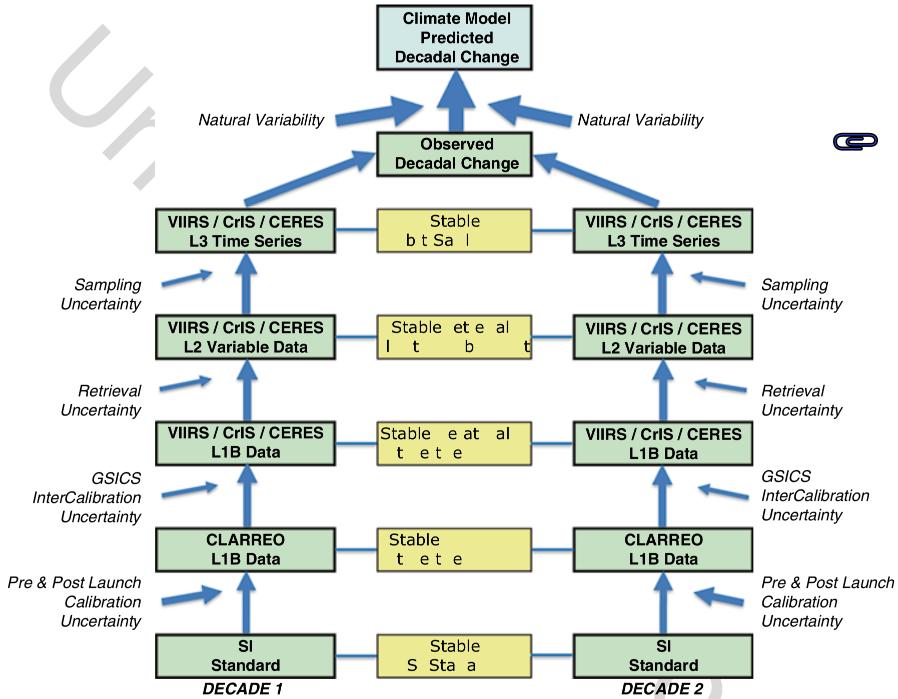

Fig. 6 Traceability of uncertainty in decadal change observations between two decades of data, followed by comparison of the observed decadal change with climate model predicted change. While the entire chain of uncertainty must be characterized, even perfect observations are limited by noise from natural variability of Earth's climate system itself (e.g., ENSO) when used to test climate models. The goal is to drive observation uncertainties to roughly a factor of 2 less than natural variability

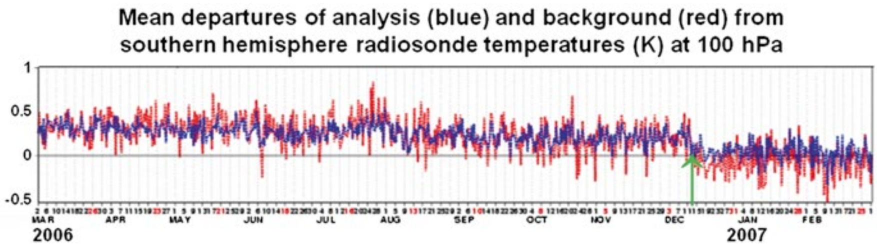

Fig. 7 Time series of the mean and standard deviations of the ECMWF background and analysis temperatures at 100 hPa showing a reduction in the bias errors on 12 December 2006 (*green arrow*) when COSMIC data began to be assimilated (After Luntama et al. 2008; courtesy Anthes 2011)

Examples of designs of such platforms include NASA's CLARREO NRC Decadal Survey mission, and the TRUTHS mission proposed in 2010 to ESA. CLARREO is intended to provide the first observations of the full spectrum of reflected solar radiation and infrared emitted radiation, as well as radio occultation observations. TRUTHS would provide full reflected solar spectra as well as spectral solar irradiance observations. Because of the full spectrum and mission design, these missions serve as SI traceable transfer radiometers in orbit that can be used to increase the accuracy of orbiting operational sensors by matching them in time, space, angle, and wavelength. This includes future sensors covering a broad range of climate variables including temperature, water vapor, clouds, radiation, surface albedo, vegetation, and ocean color. In this sense CLARREO and TRUTHS could become anchors of the global climate observing system, but neither of these missions has an approved launch date.

3.4.2 Stability of Observations and Algorithms

A second key issue is the stability over decades of satellite geophysical retrieval algorithms which all have bias errors larger than decadal climate change signals. Moreover, the algorithms and ancillary data they depend on evolve with time. Current climate studies assume that these biases remain sufficiently stable to cancel out in observing decadal change anomalies, an assumption that should be verified. Otherwise, it would be essential to develop retrieval algorithms that are optimized for decadal change as opposed to optimization for instantaneous retrievals such as those from weather satellites. Another possibility to limit sensitivity to retrieval biases is the use of reflected solar and infrared spectral fingerprinting studies of climate change (Huang et al. 2010; Feldman et al. 2011; Jin et al. 2011). These climate Observing System Simulation Experiment (OSSE) studies have shown that infrared and solar reflected spectral fingerprints are very linear at the large time/space scales relevant to decadal climate change, unlike their highly nonlinear behavior for instantaneous retrievals.

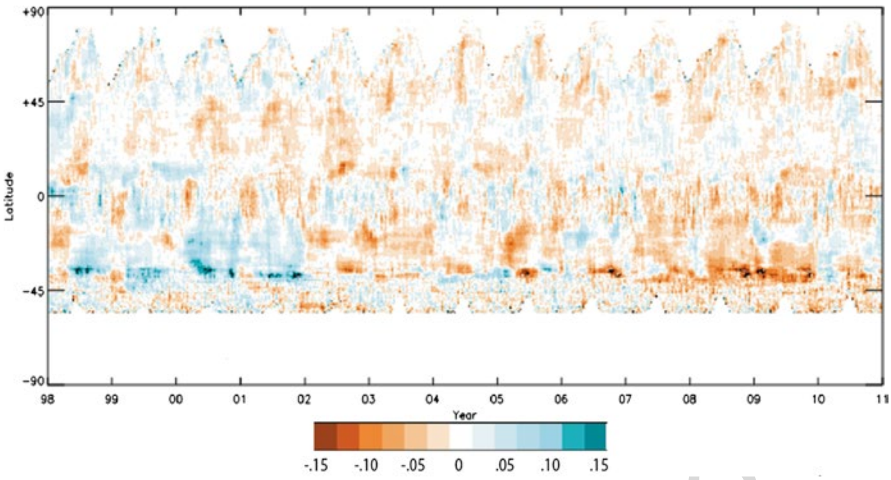

Fig. 8 Monthly zonal FAPAR anomalies relative to the period January 1998 to December 2010 estimated from decadal FAPAR products derived at a resolution of 0.5 × 0.5° from measurements acquired by the SeaWiFS (NASA) and MERIS (ESA) sensors. As rates of photosynthesis are affected by temperature and precipitation, FAPAR is an indicator of climate impacts on vegetation; favorable temperatures and soil moisture availability are accompanied by higher than average FAPAR values, drought and/or excessive temperature are accompanied by lower values (Gobron et al. 2010)

Increasing attention to calibration and to algorithm performance is increasing the overall robustness of the global climate observing system. For example, structural and radiometric measures of plant canopies quantifying vegetation dynamics (terrestrial net primary productivity, FAPAR, Leaf Area Index) are being monitored with improving reliability using satellite observations from a range of polar orbiting platforms (Knyazikhin et al. 1998; Gobron et al. 2006, 2008; Zhao and Running 2010), but this has only been possible as greater attention has been paid to cross calibration and product validation. An example of rigorous intercomparison with reference data (Gobron et al. 2006, 2008) is given in Fig. 8 which shows how plant dynamics vary in both space and time as derived from daily observations from SeaWiFS (1998–2006) and MERIS (2002–2010).

3.4.3 Accuracy

Finally, the question arises as to what level of absolute accuracy is required to eliminate issues with gaps in climate data records, and to eliminate the uncertainties of changing instrument biases in orbit over time? Leroy et al. (2008) use mid-tropospheric temperature interannual variability to suggest an accuracy for infrared radiometers of 0.03 K for a 1 sigma confidence bound. Similar analyses could be performed for a wide range of climate variables and time/space scales.

In summary, accuracy is not just about instrument calibration, but is the entire set of analysis steps required to move from SI standards at the foundation, to decadal change of a radiance or a geophysical variable at the other.

3.5 Improving Transitions Between Observing Systems

Arguably the biggest challenge to ensuring homogeneous time series is related to the timing of changes in observing systems and the critical need for continuity. Associated transitions in sampling (both in space and time), instrument accuracy (including biases), and processing methods are a major source of time-dependent biases in time series of Earth system observations. Nowhere is this more evident than in the satellite observing systems because of their relatively short lifetime of about 5 years, but *in situ* observing systems also have had a history of suboptimal transitions between old and new observing methods and systems. In some cases, information from other observations may help bridge gaps and constrain offsets.

Standard practice today either relies on launching a satellite on a planned date or launching in response to the loss of a satellite and/or specific instrument. In the former case, there may or may not be an adequate overlap, while the latter strategy does not comply with the GCMPs of planned overlaps. It inevitably leads to too short, or none-at-all observing overlaps between the old and new systems. Without absolute calibration and the use of exactly the same sampling strategy, undefined time-dependent observing system biases will likely be introduced into the time series. Poorly documented changes in processing systems can also introduce time-dependent biases. Similarly, for *in situ* observations, new observing methods and systems have been introduced with little consideration of the optimal overlap required with legacy systems.

Rule-of-thumb practices have resulted in seldom-adhered-to requirements of at least 1-year overlap between old and new observing systems to fully understand varying seasonal biases. It is unlikely that the overlap needed for a radiometer will be equivalent to that of a spectral irradiance sensor or an altimeter. Similarly, the overlap required for water vapor, precipitation measurements, and temperature are all likely to be different, especially when the sampling and accuracy changes.

Of course, to plan for an overlap, regardless of length, requires some prediction about the lifetime of the legacy observing system. For satellites, this includes the probability of failure of the satellite bus or the instruments. For some satellite research missions, Cramer (Remanifest of NASA's NPP and NOAA'S NPOESS instruments. Personal communication, 2008) and Loeb et al. (2009) have developed a few prototype probability density functions that help to understand the likelihood of failure of both instruments and the satellite bus.

For *in situ* observing systems, plans for a sufficient overlap must include an estimate of observing system degradation beyond which it cannot provide the sampling and accuracy needed to produce homogenous time series. Such analyses are needed for all climate-relevant observing systems. This would enable scientists to objectively communicate priorities for new observing systems. Optimization of observing system transitions could be based on climate risk assessments, which could then be evaluated in context with other requirements for multi-purpose observing systems.

3.6 How to Prioritize?

Observing system experiments (OSEs) have proven exceedingly useful in examining the impacts of a new set of observations (such as from a new satellite) by performing data assimilation with and without the new observations. This methodology also enables estimation of biases. The complexity of 50 ECVs, independent observations and analysis, and high accuracy traceability of all analysis steps to SI standards suggests that there is a need to also prioritize observation requirements within the climate observing system. This is fraught with difficulty because of the different and generally subjective underlying assumptions and the fact that observations are used for multiple purposes. The OSSE methodology (Sect. 3.4) can potentially be used to prioritize within the climate observing system but model errors currently limit their utility. However, as climate models become more accurate, OSSEs will become more effective and powerful, and needed to augment current dependence on scientific intuition "back of the envelope" estimates, and science committee voting approaches.

4 Analyses, Assessments and Reprocessing

Originally the task was getting a single time series of an ECV. Now there is a proliferation of multiple datasets purporting to be "the correct one". Many are created for specific purposes but all differ, often substantially, and the strengths and weaknesses or assumptions may not be well understood or well stated. Consequently, assessments are required to evaluate these aspects and to help improve the datasets. Moreover, continuous reprocessing is essential. Reprocessing can account for recalibration of satellite data from GSICS, take advantage of new knowledge and algorithms, and rectify problems and errors that have become evident. Repeat reprocessing and assessment should be hall-marks of a climate observing system.

Within the WCRP, the GEWEX Data and Assessments Panel is promoting the reprocessing of the GEWEX datasets so that they are globally consistent with regard to water and energy, complete with metadata and error estimates. The goal is to reduce errors, increase continuity, and improve homogeneity while comprehensively documenting uncertainties. The new processing will use calibrated and inter-calibrated satellite radiances for long time series of observations, and ensure that all products will "see" the same atmosphere especially in terms of temperature, water vapor, cloud and radiation. Surface radiative and turbulent fluxes are also included. ESA's Climate Change Initiative is also fostering reprocessing of individual variables to generate ECVs and take advantage of knowledge about problems and improved algorithms. At the same time, GEWEX is promoting the assessment of the variable products, not to rank the algorithms, because each often has a somewhat different application, but rather to adequately characterize each product as to its use in various ways. Some of these reprocessed data sets will provide the first long-term look at climate trends on a truly global basis for a number of climate variables. More generally, these reprocessing and assessment activities are promoted by WDAC and GCOS.

4.1 Reanalyses

Reanalysis is an activity to reprocess past observations in a fixed, state-of-the-art assimilation system. Most reanalysis activities have been for the atmosphere, but some exist for the ocean, sea ice and land variables. Reanalyses are based on data assimilation in numerical models, and are distinct from operational numerical weather prediction (NWP) as they can utilize data which were not received at the nominal analysis time as well as observations that have been more carefully processed than possible in real time. Freezing the analysis system removes the spurious variations that otherwise appear in the NWP analyses, and can potentially result in climate quality globally gridded products. However, the observing system changes as new sensors are developed and aging satellites expire (Fig. 1) thereby exposing different forecast model biases. As a result, some trends are not represented well in current reanalyses. Nevertheless, the model short-term predictions act as a powerful check on inconsistencies and errors in observations and model. The reanalysis process has become fairly mature and has developed variational techniques for bias correction of observations. The result can be an alternative source of an ECV record with an advantage that it is globally complete and associated variables are consistent with the ECV. A large user base is ensured by an open data policy and this enables scrutiny and evaluation of the results.

While reanalyses contain effects of both model and observation bias and error (see Fig. 9), there are some substantial strengths, such as their global scope. Simmons et al. (2010) show how the surface temperature record from reanalysis agrees with other analyses where overlapping data are available, but the reanalysis is able to extend the analysis into data sparse regions and provides a much better and more reliable record.

Uncertainty is important but difficult to quantify. A straightforward way to deal with it is to evaluate a multi-reanalysis collection of the variables of interest (e.g., Fig. 9). In addition, the imbalance of budgets (such as of mass of dry air or water, or energy) in reanalyses is representative of the forecast error (instantaneously) or the model and observation climate bias (long term). This needs to be better taken into account by users of reanalyses data. Lastly, reanalyses can provide the assimilated observations, as well as forecast error and analysis error for each observation.

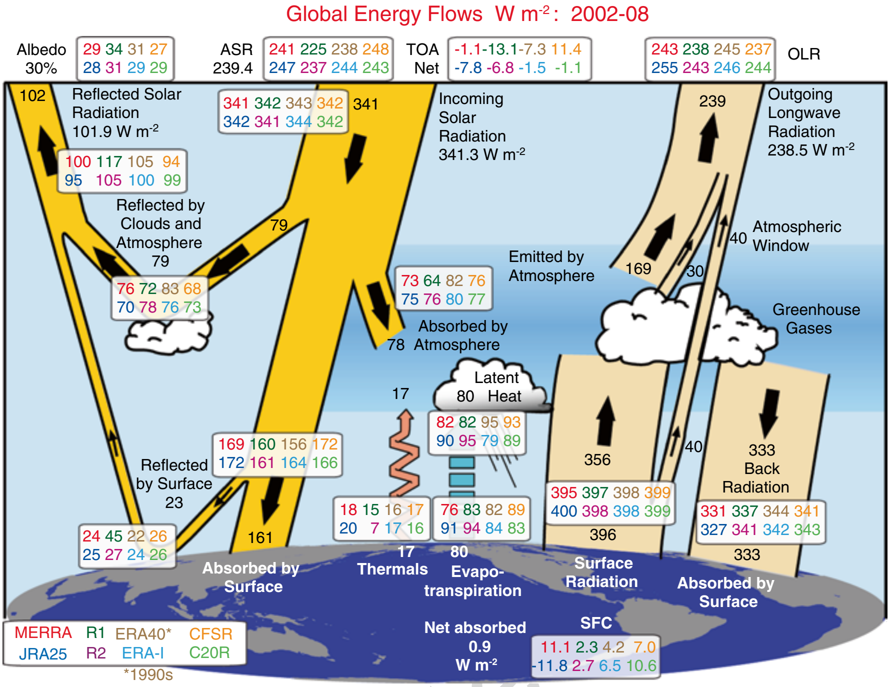

Fig. 9 The components of the global flow of energy through the climate system as given by Trenberth et al. (2009) as background values are compared with values from eight different reanalyses for 2002–2008 (except ERA-40 is for the 1990s), as given at lower left in the Figure, in W m^{-2}. From Trenberth et al. (2011). For example, the estimated imbalance at TOA and at the surface is 0.9 W m^{-2} for the 2002–2008 period, or 0.6 W m^{-2} for the 1990s, but values from reanalyses differ substantially at TOA and at the surface, and also differ between the two values implying a large source or sink in the atmosphere. Differences reveal assimilating model biases and the effects of analysis increments

4.2 Assessments

As well as assessments of datasets of individual variables, assessments of reanalyses are essential. The most comprehensive assessments with a focus on climate change are those of the IPCC that look at all aspects of the science. Nationally within the U.S. a series of Synthesis and Assessment Products (SAPs) has been carried out by the Climate Change Science Program (CCSP) and USGCRP, as well as Committee on the Environment and Natural Resources of the National Science and Technology Council.

The IPCC assessments are primarily based on peer-reviewed literature. But it is not just a review of the literature because conflicting claims and conclusions have to be reconciled to the extent possible. This means examining the methods, assumptions, and data used, and the logic behind the conclusions. The IPCC is convened by the United Nations jointly under UNEP and WMO. Its mandate is to provide policymakers with an objective assessment of the scientific and technical information available about climate change, its environmental and socio-economic impacts, and possible response options. It has provided policymakers assessment reports since 1990, and the Fourth Assessment Report (AR4) was released in 2007. The IPCC assessments are produced through a very open and inclusive process. The volunteer authorship of the AR4 in Working Group I included 152 lead authors and over 400 contributing authors from over 130 countries. In addition, there were more than 30,000 comments from over 600 reviewers, as well as formal coordinated reviews by dozens of world governments. All review comments are addressed, and review editors are in place for each chapter of the report to ensure that this is done in a satisfactory and appropriate manner.

The IPCC assessments provide a snapshot of the state of the science every 6 or 7 years, but increasingly there is a need for yearly, monthly and even shorter–term assessments. The "*State of the Climate*" reports published annually in the *Bulletin of the American Meteorological Society* are a step towards meeting needs between IPCC reports. NOAA's National Climate Data Center (NCDC) also reports monthly on the observed state and provides some commentary on what is happening and why. However, near-real time information and attribution is increasingly in demand, especially when major events occur, such as the 2010 Russian heat wave. How to include model prediction information and guarantee quality and peer review of near real time assessments to ensure that they have "authority" are key issues for climate services.

5 Further Needed Improvements

5.1 In Situ Observations

While the existing collection of *in situ* observations covers most of the high priority and currently feasible measurements, their spatial and temporal coverage is incomplete and many improvements can be envisioned. Such improvements would be based on technical innovations in the measurement techniques, the recognition of new needs for observations, and improved integration of variables for societally-relevant topics, including providing a sound scientific basis for mitigation and adaptation efforts.

There is a general need for improved integration and synthesis of satellite and *in situ* observations beyond that provided by reanalysis. Observations from multiple sources complement each other and provide calibration and validation. It should not be assumed, therefore, that observations from multiple sources are redundant and unnecessary. Some observation systems are currently at risk because they require substantial investments that cannot be done incrementally; or because budget constraints and ageing equipment have gradually reduced capabilities or data quality to unacceptable levels.

Several networks in need of physical repair and maintenance to ensure data quality include stream gauge networks, surface sensors for Earth radiation budget, ground-based snow cover (including snow depth), especially in mountainous areas; gaps exist in observations for ice caps, ice sheets, glaciers, and permafrost, and temperature profiles of permafrost in bore holes that are being degraded or lost by warming. Some important measurements could provide a cost-effective way to enhance the information obtained. These include enhancement of greenhouse gas networks including sensor automation, expansion of the network of ground-based soil moisture measurements, increased measurement frequency/time resolution, and airborne sensor deployments. Accurate and precise ground-based GPS measurements of total column water vapor also contribute to climate-quality data sets, calibration of other instruments, and verification of reanalysis data sets (Wang and Zhang 2009; Vey et al. 2010).

Measurements of variables describing terrestrial fresh water in its liquid and solid phase are currently limited, as are the fluxes (see Jung et al. 2010). Satellite altimetry is used to monitor river and lake levels, but only for a few river basins and large lakes. Fresh water is considered in more detail by Gleick et al. (2012). Snow-cover extent is mapped daily by satellites, but sensors change and continuing research and surface observations are needed to calibrate and verify satellite products for snow depth and snow water equivalent. Monitoring glaciers and ice caps is important for early detection of climate changes because their contraction indicates warming trends. Satellite observations of polar ice caps, continental mountain glaciers and ice shelves increasingly help provide a regular inventory. Satellite derived digital elevation maps of the ice surface for Greenland and Antarctica are available, though long term commitments to such monitoring are not in place.

One area where potential exists for cost savings, improved efficiency, and more comprehensive observations is through the consolidation and rationalization of the multitude of *in situ* networks that have grown up under different agencies and countries. For instance, the networks for radiosondes, ozonesondes, other atmospheric constituents (GAW), radiation (BSRN), flux towers (IGBP), and so on have been developed for specific purposes. By consolidating some of these measurements increased value accrues and the networks become more sustainable because they serve more purposes.

Numerous bilateral and multilateral international partnerships exist, providing highly productive avenues for coordination and cooperation. Partnership opportunities exist with communities other than the international framework: with defense agencies, the private sector, and non-governmental organizations, although sometimes with adverse consequences. Major strengths include the leveraging of individual national resources toward common goals, and the sharing of data and expertise. However, more effort is needed in overcoming differences in data and metadata standards, data sharing and data policy, and access to currently restricted data (this includes both *in situ* and satellite data).

In summary, WCRP should take a leadership role in an international coordination framework to perform a comprehensive assessment of the research priorities of an operational global *in situ* observation system. WCRP should also provide recommendations for transition from research to operational capability and identify where overlap is needed to prevent critical gaps in this extensive array of climate-relevant observations administered by many agencies from the international community. The challenge to WCRP is to recommend guidelines and identify specific ways that the international community can optimize this mix, across agencies and under consideration of international agreements and participation with other partners. Such a framework and set of guidelines could greatly serve the needs of the climate research community and yet exercise maximum fiscal responsibility for a global observation capability.

5.2 *Data Documentation and Adequacy of Metadata*

For several decades, metadata and data discovery have been inextricably intertwined because of the difficulty in keeping up with the explosion in observations and data products. Discovery alone, however, is not adequate for understanding observations and, more importantly, temporal variations in those observations. Excellent documentation of environmental observations and data, preferably in peer-reviewed literature, is more important today than ever before:

- Rapid evolution of the global climate adds requirements for understanding temporal variations in observed properties. Pertinent data must be documented so as to unambiguously recognize change and differentiate real change from observational, experimental or analytical error.
- The changing environment increases the importance of older observations that provide context but which may have been collected, processed or synthesized by scientists who are no longer available. Detailed documentation is essential to ensure that today's observations can contribute to answering tomorrow's questions.
- There are increased requirements for sharing data across broad communities with diverse expertise. Users include decision and policy makers, inter-disciplinary scientists, and the general public.
- The international environmental community is coming together in unprecedented collaborations.

A series of international metadata (International Organization for Standardization-ISO) standards have emerged recently, forming the foundation for effectively documenting observed and synthesized data. These standards include mechanisms for describing sensors, data quality assessments, provenance (sources and algorithms), and temporal variations in all these items. They also include mechanisms for creating metadata at many levels (sensor, platform, network, project…) and connecting to related documentation in standard or non-standard forms. The global scientific community needs to work together to:

- *Develop conventions for how standards will be used to describe important data types* to enable meaningful sharing of metadata. Like the Climate and Forecast Conventions for data, metadata conventions will include standard names and ontologies for shared concepts.

- *Extend high-quality documentation with increased emphasis on preservation and sharing of that documentation.* Adoption of the ISO standards supports both of these goals.
- *Participate in evolving the standards as documentation and sharing needs change.*

Considerable progress has been made towards supporting open data across a growing segment of the scientific community. Scientists around the world should share environmental observations along with their documentation, or risk undermining a basic scientific premise of independent verification of results that supports the credibility of the scientific process.

5.3 *Tracking Climate Observing Performance*

As we strive to be more effective in our climate observing and research activities, an important objective is the effective use of both operations and research for early identification of time-dependent biases. The International State of the Climate Report and the subsequent special NOAA report (SOC 2009) focused on a set of nine indicators in a warming world. In SOC (2009), numerous indicators and indices representing ECVs were compared and contrasted to ensure that observing systems (satellite and *in situ*) were providing a physically consistent set of information about climate and global change (Fig. 10). These analyses demonstrate the value of collectively analyzing a broad set of essential climate variables across various observing systems using independent time series developed by various science teams.

Figure 10 shows time series from independent observing systems (satellite and *in situ*) and various independent analyses. This kind of display enables checks of consistency among datasets of the same variable and also the physical consistency among variables.

Consistency among other variables is being explored within the GEWEX Data and Assessments Panel for temperature, water vapor, cloud, precipitation, surface fluxes of sensible and latent heat, and surface radiation. This kind of display therefore also reveals changes in the climate that are extremely useful for many purposes.

Nonetheless, understanding differences among datasets, their strengths and weaknesses is also very important in order to properly utilize the most appropriate data for certain purposes. At NCAR a new Climate Data Guide http://climatedataguide.ucar.edu/ is being developed to provide this information about the multitudes of datasets.

5.4 *Climate Observations at High Risk*

The GCOS is designed to meet evolving national and international requirements for climate observations. Certainly our current observing system and the one in the foreseeable future (taking all planned U.S., European and Asian satellite missions

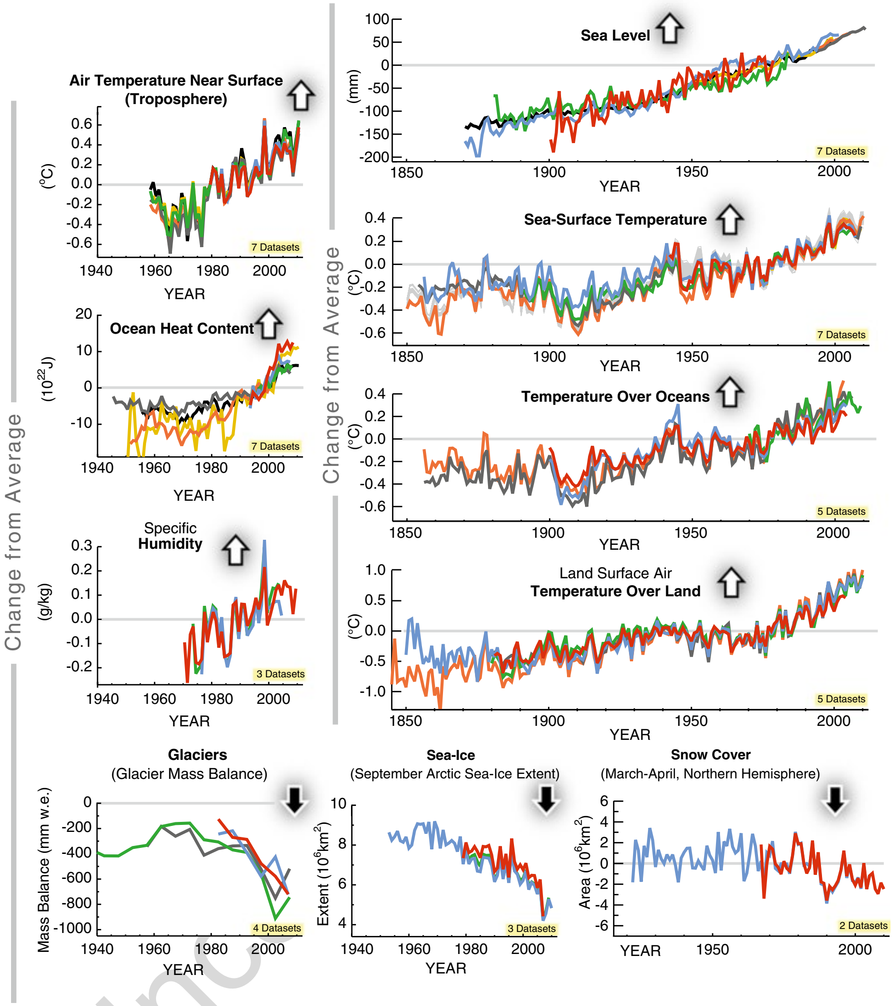

Fig. 10 Observations of the ten indicators over time (SOC 2009) (Adapted from figure courtesy NCDC, NOAA)

into account), will lead to a lot of new information about our planet and the climate system. Many observations can be used for climate purposes although more so for some ECVs than others. But unless there is major progress on climate observations, we shall not see as much or as clearly as needed for effective climate research and applications. Moreover, progress is much needed to reduce the probability of being tripped up by something unexpected that we cannot grasp with our deficient vision. While the need for climate information has greatly increased, the effort to meet this need has not.

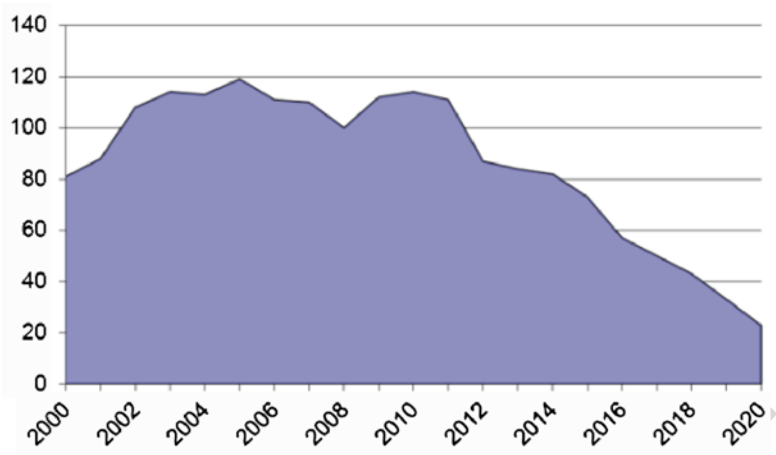

Fig. 11 Estimated number of NASA/NOAA Earth Observing instruments in space out to 2020 (NRC 2012)

A recent mid-course assessment of the Decadal Survey (NRC 2012) supports our assessment. It notes that despite some successes (e.g., successful launches of the Ocean Surface Topography Mission (OSTM), Aquarius, and the Suomi NPP), a number of significant issues have had damaging effects on the U.S. satellite observing system. These include significant budget shortfalls in NASA and NOAA, launch failures, delays, changes in scope, and cost growth of missions. NOAA has made significant reductions in scope to the future operational Earth satellites, omitting observational capabilities assumed by the Decadal Survey to be part of NOAA's future capability and failing to implement the three new missions recommended for NOAA by the Survey (the Operational GPS Radio Occultation Mission, the Extended Ocean Vector Winds Mission, and the NOAA portion of CLARREO).

Furthermore, the U.S. Earth observing capability from space is in jeopardy as older missions fail faster than they are replaced; thus the number of NASA and NOAA Earth observing instruments in space is likely to decline to as little as 25 % of the current number by 2020 (Fig. 11, NRC 2012).

While significant progress has been made in the last decade, we conclude that the climate observation architecture is still very much a work in progress, with a long way to go before we achieve a fully implemented climate observing system. Serious challenges remain in the areas of data accuracy, independence, continuity, and prioritization within the observing system. Comprehensive standard metadata is also missing for many observations. Much more complete spatial and temporal sampling is essential if we are to determine how extremes are changing; as an example the need for hourly data on precipitation has long been recognized because of its inherent intermittent nature. Changes in extremes are the main way climate change is perceived (Trenberth 2011) and of special interest are changes in hurricanes, storm surges, severe convection, tornadoes, hail, lightning, floods, droughts, heat waves and wild fires. All of these depend on detailed information about precipitation: its distribution, intensity, frequency, amount, type, and sequences in time. The evidence is increasing for changes in weather and climate extremes whereby, for example, 500-year events become 50-year events, but the information is not being made available and planning for those changes is wholly inadequate. The need to assess model capabilities from this standpoint is also clear.

Other needs are rearing up in the form of irreversible climate change and tipping points as thresholds are crossed, and whether it is possible to even recognize that we have passed such a point when we do, until decades or centuries later, when it is far too late to do anything about it (Solomon et al. 2009). A classic example is the increased melting of the Greenland and West Antarctic ice sheets. Are these reversible, or is it already too late?

Nations have continued to recognize the needs for a fully implemented climate observing system, for example through acceptance of the GCOS Implementation Plans and other reports by the Parties to the UNFCCC: most recently GCOS (2010); and in the resolutions of the WMO Congresses relating to GCOS. But in many cases, funding commitments have not yet been made by GCOS member nations to provide or improve key components of the climate observing system. As we have seen with losses of ADEOS, Cryosat, OCO, Glory, inability to fully implement COSMIC-2, delays of NPP and JPSS, CLARREO, DESDynI, the GPM follow-on, limb soundings, as well as the TAO buoy network preventive maintenance, the stream gauge network and an integrated carbon-tower network; the risk of major satellite and *in situ* observing system gaps is already present, and will grow in the future.

Climate observations today contain many very good pieces, but are not yet well coordinated, understood, developed, maintained and preserved as a true global observing system. Satellite and *in situ* observations must be synthesized and analyzed and reanalyzed into usable and well documented integrated climate quality products. We must solve these challenges if we are not to walk blindly into our planet's future.

6 Appendix A: The GCOS Organizational Framework

The Global Climate Observing System activities are collectively sponsored by the (WMO), Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), United Nations Environment Program (UNEP), and International Council of Science (ICSU) to meet national and international needs for climate-related observations of atmosphere, ocean and land. GCOS addresses the observations themselves, the transmission and management of data, the establishment of fundamental climate data records and the formation of products from these data records. In undertaking its review and advisory role, GCOS collaborates with other entities active in these fields, including the World Climate Research Program (WCRP).

GCOS functions through the contributions of nations to help implement:

- component comprehensive observing systems, principally the GOS and Global Atmosphere Watch (GAW), the IOC-led Global Ocean Observing System (GOOS) and the FAO-led Global Terrestrial Observing System (GTOS);
- baseline and reference networks designated or established for specific monitoring purposes;
- observing principles and guidelines for dataset production;
- operation of regional lead centers, network monitoring centers and lead centers for analysis/archiving and the reference upper-air measurement network;
- a cooperation mechanism and associated technical program for observing-system improvements in developing countries; and
- coordination of GCOS activities at national and regional levels across the atmospheric, oceanic and terrestrial domains.

GCOS is guided by a steering committee, and supported by co-sponsored panels, and by a secretariat working alongside those of WMO, GOOS and GTOS.

GCOS focuses on observations to support the United Nations Framework Convention on Climate Change (UNFCCC). Its activities include detailed assessments of the adequacy of the composite observing system, statements of required actions and reports on progress, and it interacts with the UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA) and open public reviews via responses and requests. Activities also cover many systematic observational needs for climate-change assessment, research and the provision of climate services, and serve many societal benefit areas of the GEOSS, including agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water and weather.

The Second Adequacy Report (GCOS 2003) identified a set of ECVs judged to be the minimum required to support the work of the Convention and to be technically and economically feasible for systematic observation. It was followed by a 5–10 year implementation plan in 2004, which identified 131 specific actions. The response to the space-based actions was coordinated by the CEOS, with the CGMS – the international forum for the exchange of technical information on geostationary and polar orbiting meteorological satellite systems.

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