TECHNICAL REFERENCE DOCUMENT

UNDERSTAND, ASSESS, PREDICT, MITIGATE, AND ADAPT TO CLIMATE VARIABILITY AND CHANGE

1. Introduction

The Earth environment is a dynamic system undergoing continuous change on seasonal, annual, decadal and longer timescales. Many scientific observations indicate that the Earth may now be undergoing a period of more rapid change on these time scales, when compared to the historical record. Scientific evidence suggests that a complex interplay of natural and human-related forces may explain this observed recent climate variability.

2. User Requirements

To understand, assess, predict, mitigate, and adapt to such changes, a climate observing system must:

- Improve knowledge of Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and changes;

- Improve quantification of forces bringing about changes in Earth's climate and related systems;

- Observe climate system variables that specify the state, forcings and feedbacks

- Reduce uncertainty in projections of how Earth's climate system may change in future;

- Incorporate/integrate observations from research/experimental observing systems in order to improve the representation and parameterization of climate processes in coupled climate prediction/projection models;

- Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes;

- Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

The climate observing system must be linked to an integrated data system that provides full and open access, which in turn links to tools that support the generation and access to climate information needed to inform decisions relating to adaptation and mitigation of climate change. The climate observing system, data system, associated tools, and the community of users of the information together will constitute the climate component of an Earth Information System (EIS), end goal of the integration of the Earth observing system of systems. Users of climate data and information include government agencies (federal, state, local), private industries (energy industries such as oil & gas, tourism, shipping, agriculture, fishing, insurance/re-insurance, etc.), universities, public institutions (education, recreational) and individuals, and non-governmental (non-profit) organizations. End-to-end support to make use of climate information is needed. Usage is diverse, and includes research and operational applications, policy making and coordinated planning for climate change adaptation and mitigation, as well as decision-making by businesses, organizations, and individuals, applied in local, regional, national, and international contexts. Coordination of federal acquisition of climate information, and support for its application, is a required ongoing activity of federal agencies that participate in the Climate Change Science Program (CCSP) and the Climate Change Technology Program (CCTP), under the Committee on Environmental Research (CENR) of the National Science and Technology Council, acting for the President's Office of Science and Technology Policy.

Earth Observations are urgently needed by Earth Systems Models, which are society's primary EIS tools for (a) integration of observations into a comprehensive analysis of the climate system; (b) forecasting the climate system on multiple time/space scales; and (c) simulating the impact of a particular gap or enhancement of the comprehensive Global Earth Observing System of Systems (GEOSS). Existing codes (e.g. from GFDL, NSIPP, GMAO, NCAR, NCEP, and others) are now transitioning to an improved architecture, the Earth System Modeling Framework, that will enable improved incorporation of new observations, comparison of multiple models, and testing and validation of new approaches to climate modeling, [e.g., see ESMF reference].

The following sections focus on capabilities and challenges related to observing, understanding and predicting climate change, based primarily on the CCSP Strategic Plan finalized in July 2003. The CCTP Strategic Plan, as well as ongoing work of the Intergovernmental Panel on Climate Change (IPCC) Working Group 2, will provide a sound basis for IWGEO to address important issues of adaptation and mitigation of climate change impacts, which are expected to come to the fore as IWGEO, and the GEO process, evolve.

3. Existing Capabilities and Commonalities

Development of space-based, airborne and surface global observing capabilities has been a primary focus of U.S. efforts, particularly in recent years. Several new Earth-observing satellites, suborbital systems, surface networks, reference sites, and process studies are now producing unprecedented high-quality data that have led to major new insights about the Earth-climate system. The United States is now contributing to the development and operation of several global observing systems which collectively attempt to combine the data streams from both research and operational observing platforms to provide for a comprehensive measure of climate system variability and climate change processes. These systems provide a baseline Earth observing system and include: NASA, NOAA and USGS Earth-observing satellites; the global component of the Integrated Ocean Observing System; the Global Climate Observing System (GCOS) sponsored by the World Meteorological Organization (WMO); the Global Ocean Observing System (GOOS) sponsored by Intergovernmental Oceanographic Commission (IOC); and the Global Terrestrial Observing System (GTOS) sponsored by the Food and Agriculture Organization (FAO). Table 1 is the GCOS list of essential climate variables, based on the GCOS Second Adequacy Report, April 2003. [See http://www.wmo.ch/web/gcos/gcoshome.html] This set of required observables provides an excellent baseline, but will clearly need to be augmented. For example, incoming solar irradiance is listed, but also needed are *in situ* measurements of profiles of radiative fluxes in the atmosphere. Additional extensions are needed for atmosphere, ocean and terrestrial variables.

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

	Biomass, Fire disturbance.

Table 1 GCOS List of Essential Climate Variables,

A process for updating these variables needs to be established as we learn more about the climate system. Appendix 12.1, from Chapter 12 of the CCSP Strategic Plan [see http://www.climatescience.gov/Library/stratplan2003/final/ccspstratplan2003-chap12.htm] subdivides required climate variables into those specifying the "State" and those specifying the "Forcing/Feedback" of the climate system, and further identifies measurements made by surface, airborne and space-based instruments, respectively, for which operational or systematic (research) observing systems/networks and international programs exist. A current inventory of U.S. systems contributing to global climate observing, and related to the atmospheric, oceanic, and terrestrial climate subsystems, can be found in the U.S. Detailed National Report on Systematic Observations for Climate [August 2001, see http://www.eis.noaa.gov/gcos/soc_long.pdf].

Required observed variables include benchmark large-scale climate observations such as the total radiative energy output from the Sun that drives Earth's climate system, the Earth's global average surface temperature, the atmospheric concentration of CO2 and other atmospheric constituents, as well as climate variables such as precipitation, land use, and land cover, that undergo regional and local changes that have significant environmental and human impacts. In order to meet climate requirements, monitoring systems for climate must adhere to the 10 GCOS climate monitoring principles listed in CCSP Appendix 12.4. These were adopted in paraphrased form by the Conference of the Parties to the UN Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November 1999. For satellite systems, CCSP Appendix 12.4 specifies a further 10 principles to ensure that observations meet the required stringent standards of calibration and sampling necessary for useful climate applications.

4. Major Gaps and Challenge

The CCSP Strategic Plan dedicated separate chapters to each of seven climate research elements that parallel subcommittees of the CENR. Each element has an associated working group within CCSP, which has identified challenges and priorities, documented in detailed published plans. By chapter number, the research elements are [3] atmospheric composition; [4] climate variability and change; [5] water cycle; [6] land use/land cover change; [7] carbon cycle; [8] ecosystems; and [9] human contributions and responses to environmental change. Themes associated with each research element that have unique observational challenges include: [3] aerosol, temperature, [4] polar climate/feedback, radiation budget, and paleoclimate. Collectively, all elements raise challenges associated with human dimensions themes, especially [6], [8] and [9].

A critical challenge is to maintain current observing capabilities that already exist in each of these areas. For example, maintenance of the observational record (column and profile) of stratospheric ozone is essential so that the effects of climate change on the nature and timing of expected ozone recovery can be discerned. Other key variables requiring maintenance include atmospheric carbon dioxide and global surface temperature. Potential gaps in continuity needing particular attention are described below in 5.2. Since the value of existing climate datasets greatly increases as the record is extended in time, it is imperative that existing observing capabilities are maintained and improved. At the same time new requirements must be incorporated.

We focus below on existing and new capabilities that most urgently need attention, while keeping in mind the need to continue doing what is already being done well. Table 2 identifies in column 1 each of the above themes by a brief title, with the relevant chapter of the CCSP Strategic Plan [in brackets], and in column 2 observables, or variables, whose measurement represent significant challenges that must be met by future climate observing systems. In columns 3, 4 and 5 are satellite, suborbital, and sur face observing systems, respectively, that have the potential to meet these challenges.

It should be noted that the observations that need to be made under any one theme frequently overlap with those that need to be made under one or more of the other themes of the CCSP. Thus observations of vegetation are required for the water cycle (evapotranspiration moisture fluxes) as well as the carbon cycle (carbon budget) and ecosystems (biodiversity) etc. Similarly, radiation budget parameters are required by nearly all themes and for quantification of forcing and feedbacks within and between components of the climate system. Precipitation, though identified under the water cycle is also needed by the land, ecosystems, human dimensions, carbon, and polar themes.

Table 2 provides both research, transitional, and operational satellite observing systems; the latter which provide for long term satellite observations, and this is a direct tie to the transition of instruments developed in a research mode and trans itioned to sustained operations. Such initial technologies are typically developed by NASA and then put into sustained operations by NOAA. The archival of the vast amount of this data is an immense undertaking with large cost and management issues which CCSP agencies are address in coordinated activities.

Themes / Needs	Variables	Satellite Observing Systems	Suborbital Observing Systems	Surface Observing Systems
Land/ Ecosystems/ Human [6, 8, 9]	Land Use and Cover, Sea Level	Landsat Continuity with Long-term Acquisition Plan	UAV hyperspectral/Lidar/ SAR/thermal mapping system	LTER, Tide Gauge and Experimental Watershed Networks
Polar Climate and Feedback [4]	Land ansd Sea Ice Thickness, Ice mass balance	GLAS/IceSat CMIS	Low, slow geostationary polar mapping system	Surface Polar Observatories

Aerosol [3]	Natural and Anthropogenic, Cloud processes and structure	Polarimeter, APS	High spacetime resolution, sfc to stratosphere, all weather profiling system	Aeronet, Ozonesonde, Third World Capacity Building
Carbon Cycle [7]	Ocean Carbon Fluxes, Heat Content	Orbiting Carbon Observatory	Low, slow UAV and AUV system	Ocean Reference Stations
Water Cycle [5]	Cloud processes and structure, Precipitation, Soil Moisture, Water Vapor, River Discharge, Groundwater	CloudSat, Calipso, AIRS, AMSR-E, GPM, VIIRS, CMIS, CrIS, ATMS, HYDROS, COSMIC (GPS radio occultation)	High spacetime resolution, sfc to stratosphere, all weather profiling system	GUAN, GPS Integrated Water Vapor, CRN, USGS Streamflow Data Network, USGS Groundwater Climate Response Network, USDA/USGS Experimental Watershed Networks ARM Sites
Radiation Budget [4]	Solar and Earth Radiative Fluxes at Top-of-Atmosphere and Surface	SORCE + CERES follow-on missions, total and spectral measurements, TIM, SIM	High resolution profiles of long and shortwave radiative fluxes [surface to stratosphere]	UV Calibration Facility, SURFRAD, BSRN, SURFX, ARM Sites
Temperature [3]	Stratosphere, Troposphere and Surface Temperature	AMSR-E follow-on, CMIS, COSMIC and other radio occultation missions	High resolution global temperature profiling system	High Altitude Surface Observing Network, Climate Reference Network
Paleoclimate [4]	Ocean Corals, Temperature and Composition Indicators		AUV ocean floor sampler, UAV hyperspectral monitoring of ocean coral reefs	Coral & Ocean Cores, High sedimentation rate deep sea cores, Integrated Q/C Data System

Table 2: Meeting Climate Challenges

The above table is ordered from the top down, beginning with themes in which the human dimension is most evident, to those having the most evident benefit to scientific understanding. Prioritizing contributions to these themes is a multi-dimensional problem that cannot be solved by linear approaches, and that must maintain a balance between science and applications as discussed in Chapter 1 of the CCSP Strategic Plan. Near term research priorities given focus by CCSP are (1) aerosols; (2) polar climate and feedbacks; and (3) carbon sources and sinks. These are most directly related to the first four areas listed in Table 2, but are also connected to each of the other areas. Observational elements that have a high degree of readiness, including heritage systems, have been identified to meet each of the above challenges, as indicated in the three rightmost columns, for satellite, suborbital and surface observing systems. Moreover, it is underscored that the baseline or reference station networks identified in column 4 are required to maintain a "reference" monitoring system for a few key climate system parameters. They are not in themselves sufficient to observe or monitor the entirety of the climate system. Thus, an integrated approach is required to the subject of observing systems, namely one that combines the long-term data and information that captures trends and change in climate together with more detailed observations and models of all other aspects of the climate system. For the latter, a combination of research-based satellite and *in situ* suborbital and surface-based observing systems, together with operational systems, need to be used in conjunction with the "reference" network.

Each of the above observing system elements consists of a spaceborne element that provides adequate global coverage and space-time resolution required to meet user needs, coupled with a related surface element providing process studies, va lidation, and appropriate local sampling. In addition, linking the local long duration space-time sampling of surface networks with the global sampling of the spaceborne systems requires a variety of innovative atmospheric and oceanic piloted and unpiloted platforms, including remotely piloted aircraft, long-duration balloons, kites, and other innovative surface platforms, as well as traditional aircraft, balloons, ships, buoys, and tide gauges.

Continuity of the Landsat data stream is crucial. The Landsat program has provided an uninterrupted 30-year record of the global land area in the form of high resolution, multispectral digital images acquired from a series of satellites. Two Landsat satellites remain in operation today, Landsats 5 and 7. Landsat 5 was launched in 1984 and is operating 17 years beyond its three-year design life. Its fuel will be depleted by 2008. Landsat 7 was launched in April 1999 and reached the end of its five-year design life in 2004. The Landsat 7 sensor, the Enhanced Thematic Mapper-Plus (ETM+), suffered a malfunction in May 2003, which produces intermittent gaps in the acquired images. At a time when the growing population is altering the land surface at a scale unprecedented in history, the launch of a follow-on Landsat satellite at the earliest possible date is a high priority.

Both the GCOS Second Adequacy Report and the CCSP Strategic Plan call for complete global coverage of the oceans with moored, drifting, and ship based networks. Without urgent action to address the global ocean, the nations of the world will lack the information necessary to effectively plan for and manage their response to climate change. The highest priority for the global component of the Integrated Ocean Observing System is sustained global coverage.

Climate information derivable from the above observational enhancements includes:

- Geographic extent of human impacts on the environment
- Elevation maps depicting areas vulnerable to sea level rise
- Global fluxes of CO2, between air and sea, air and land, within oceans, from land to ocean Changes in soil moisture and runoff, and tools to predict and adapt to drought
- Changes in aerosol, cloud cover, precipitation, global energy budget, and their relationships
- Variability and change in ice thickness and sea level, the ocean's storage and global transport of heat, and the ocean-atmosphere exchange of heat and fresh water
- Integrated paleoclimatic database for evaluation of climate models.

This subset of essential climate variables, identified above as observational challenges, also contributes to other themes. This is indicated in the following "crosswalk" table, where the first column lists the above selected variables, the rows refer to the chapter themes, and each "X" indicates a contribution of a selected climate variable to one of the chapter themes. Note that almost every row shows contributions in a majority of the chapter themes. See Appendix I for a more complete crosswalk that includes the above identified essential climate variables, of which the challenge areas are a subset.

IWGEO CHAPTER 4.0 THEMES	Weather	Disaster	Ocean	Climate	Agric	Health	Ecosys	Water	Energy
Land Cover and Use	X			X	X		X		X
Coastal Processes (e.g., Sea Level)	X	X	X	X			X	X	X
Glaciers and Ice Caps	X	X	X	X			X	X	
Sea Ice	X	X	X	X			X	X	
Aerosol	X	X	X	X	X	X	X		
Carbon/CO_2/pCO_2	X		X	X	X	X	X		X
Water Vapor (Surface and Upper Air)	X			X	X		X	X	X
Cloud Properties	X			X	X		X	X	
Precipitation	X	X	X	X	X	X	X	X	X
Solar, Earth, TOA & Surface Radiation	X	X	X	X	X	X	X	X	X

Air Temperature Profiles	X	X	X	X	X	X	X	X	X
Ocean Temperature and Salinity	X	X	X	X			X		X
Paleoclimate				X	X	X	X	X	

Table 3 –Subset of Essential Climate Variables

There are many observing systems measuring important weather and climate related observations (e.g., Earth observing system satellites, climate reference network, ASOS, and COOP). Climate requires highly precise calibrated long term data that grow in value as data ages, while weather needs near real time data that rapidly lose value with time. Climate is also sensitive to slowly changing variables not of primary importance to weather. The future climate observing system of systems must meet unique climate observing requirements.

Ensuring the longevity and continuity of satellite observations is a priority. One example identified above is the need to continue the long record of global seasonally refreshed Landsat data, meeting or exceeding current calibration and validation. This datastream meets a wide variety of needs for those studying the human dimensions of climate change, and its continuity is a priority. Another example is the continuity of the satellite altimetry record started with TOPEX and continuing with JASON-1, for monitoring ocean circulation, and for the record being obtained on regional and global mean sea level. Although the altimetry record is only a little over a decade in length, the technology offers promise in developing estimates of global sea level trends in conjunction with continued operation of key tide station locations.

A third example is continuation of the radiation budget record, one of the longest and most useful of our global climate records. The record began in 1978 with the Nimbus 7 spacecraft and has been maintained with instrument overlap through the present NASA Terra and Aqua missions. The radiation budget record is critical for separating external solar forcing from internal forcings, and for verification of climate model predictions of cloud/radiation feedbacks. Cloud feedbacks are the largest uncertainty in estimates of climate sensitivity and therefore in predicting future climate change (IPCC, 2001, NRC, 2003, CCSP, 2003). Cloud/radiation feedbacks currently are uncertain to at least a factor of 3. A recent U.S. multi-agency analysis of satellite calibration and stability requirements for the climate data records (Ohring et al., 2003) showed that overlapping observations of the radiation budget record are critical to achieving the decadal instrument stability necessary to directly observe cloud/climate feedback. The international Global Climate Observing System (GCOS) Second Adequacy Report (2002) reached a similar conclusion.

Similar related needs exist for the surface networks. Important examples being used and planned as essential climate networks are USDA-NRCS SNOwTelemetry (SNOTEL) and Soil Climate Analysis Network (SCAN), as well as other important mesonets (RAWS, High Plains, etc.) There is a pressing need to evaluate the nature and extent of (land-surface) hydrologic change and its particular effect on climate. Most (>75% by one accounting) major rivers in the Northern Hemisphere have been substantially modified by society, changing their discharge amounts and seasonality, which modifies distributions of inundation, evaporation, and transpiration on regional scales. The modernized COOP will be a network that can serve the nation as the backbone of an

Integrated Surface Observing System (ISOS). It will be the sustaining factor around which all surface environmental monitoring networks are integrated. The network will provide high-quality real-time weather, water, and climate information, and possibly air quality and biochemical hazard data. The Climate Reference Network (CRN) will provide the highest possible benchmark quality climate data for calibration of the ISOS. Three activities taking place today are related to the development of a system-of-systems approach to surface weather and climate monitoring. First, as the COOP modernization moves forward, the experience of CRN in the selection of instruments is being fully utilized. Second, a Memorandum of Agreement (MOA) is being developed related to the operation of the NOAA/NESDIS/National Climatic Data Center (NCDC) CRN and NOAA/NWS COOP network. And third, a national network of ground-based GPS receivers is emerging and is producing accurate and temporally continuous measurements of total water vapor in the atmospheric column. This information will be useful in weather prediction as well as in monitoring climate variability and trends.

Subsequent to this MOA it is expected, once the 100 CRN stations are fully deployed across the contiguous U.S. (FY07), that the NWS will work with NESDIS and OAR to develop a maintenance agreement for the CRN and modernized COOP. Whether maintenance for the CRN can be provided by the private sector, State Climatologists, Regional Climate Centers, NOAA personnel, or a combination of these, will be addressed over the next two Fiscal Years. This will require substantial community discussion including our Science Advisory Board Working Groups on Climate. NOAA is committed to developing a single integrated data ingest and quality control system for all the surface weather and climate data NOAA uses. At the present time the NCDC operates a comprehensive data quality control system and has protoyped an integrated surface, *in situ*, model, and space-based observations in our quality control, which will be useful in the ISOS framework. NWS and NESDIS are working to ensure a seamless end-to-end surface observing suite.

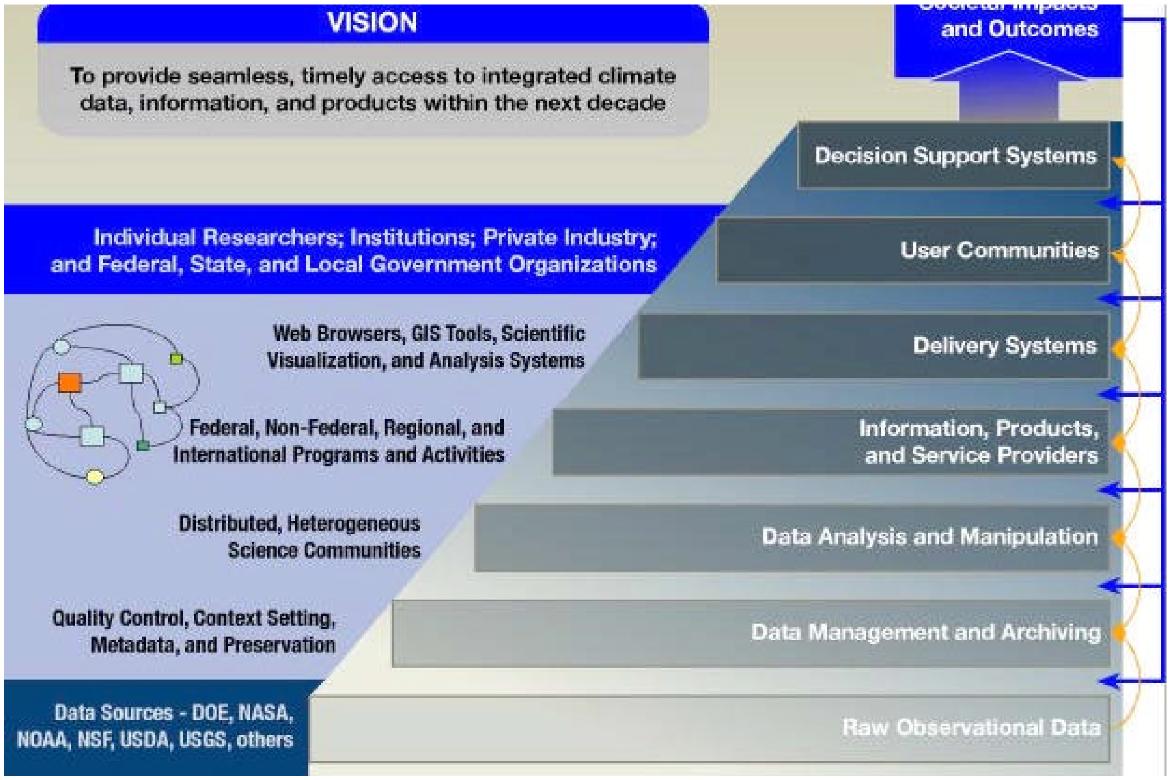

Figure 1

The above sections have briefly summarized the diverse array of observational systems, as well as the wide variety of user groups and applications. An integrated system must provide for a seamless link between the providers and users of climate information systems. Figure 1 summarizes the issues in terms of transforma tions of raw observational data from many sources, from the long term record of weather observations, observations collected as part of research investigations, highly precise continuous observations of variables collected expressly to document long term climate change, to paleoclimate observations. Such data requires a comprehensive and reliable data management archive, coupled to tools to derive information products, a system for distribution, support for user interactions with the information products, and decision support tools that provide for user feedback to maintain and improve the end-to-end system. Climate observation systems must provide for integration of the data in the full end-to-end system, that meets the required stringent standards of calibration, sampling and accuracy necessary for useful climate applications (as discussed in section 2), stability needed to maintain ongoing data archival, and processes for improvement that take into account user feedback.

5. Future Earth Observation Systems that May Fill Gaps

Since 1998, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have noted the decline in the global climate observing capability, and have urged Parties to (a) undertake programs of systematic climate observations and (b) strengthen their capabilities in the collection, exchange, and utilization of environmental data and information. A wide range of global observations are needed to understand and monitor Earth processes that contribute to climate, and an assessment of the effects of human and natural activities cannot be made by a single program, organization, or country.

Future Earth observing systems will learn from, leverage, and extend the current observing capacity, summarized in CCSP Appendix 12. The CCSP Strategic Plan is a framework to address some of the most complex questions and problems that the United States and the world now face. The issue of climate variability and change, the level and affects of potential human contributions to these issues and how we adapt and manage these impending forces is a capstone issue for our generation and those to follow. This plan addresses these challenges by leveraging existing knowledge to learn new things, building bridges across communities and scientific disciplines to gain greater insight, reaching out to decision-makers, and maintaining an open and transparent process to ensure that our partners are heard and we are hearing them.

Satellite observations provide a unique vantage point from which to study the Earth system. Moreover, they enable observation of rapid and/or remote changes, and provide a global perspective on regional and coastal changes. The Earth science community has come to rely on a suite of research satellites, such as NASA's Earth Observing System (EOS) missions, and operational missions, such as NOAA's Polar-orbiting Operational Environmental Satellites (POES). The National Polar-orbiting Operational Environmental Satellite System (NPOESS), with its more capable satellite instruments and stable Earth orbits, represents a significant opportunity to increase the usage of satellite data in climate research. NPOESS, and its pathfinder mission the NPOESS Preparatory Project (NPP), are primarily deployed in support of weather observations, but some climate requirements have been incorporated. NPP and NPOESS straddle the line between weather and climate observing and while they will not answer all climate questions, the deployment of these systems is essential in the transition from research to operations for a number of instruments deployed on earlier research missions (e.g., EOS series). GPS radio occultation (RO) soundings from the CHAllenging Minisatellite Payload (CHAMP), SAC-C, and COSMIC satellites, along with other RO missions will complement the Infrared (IR) and Microwave Sounding Unit (MSU) soundings, greatly improving the quality of the climate and weather analyses. Review processes will be needed to assure that the GCOS climate monitoring standards are met.

A globally coordinated network of demonstration ecological observing systems is needed to document long-term trends in ecosystem status and to serve as test beds for research and technology development to improve ecosystem observations in the future. Data from existing satellites must be fully exploited to observe ecosystem status, and ecosystem observation requirements must be considered in design of future satellites.

- Establish science planning teams to define core ecological observing system requirements for terrestrial, marine, and aquatic application (build on NSF-NEON and NOAA Ecosystems Observations plans among others)

- Identify existing sites nationally and internationally that could serve as the basis for the network of ecological observing systems

- Identify and monitor climate-sensitive 'sentinel species' in terrestrial, marine, and aquatic ecosystems that integrate climate signals over time and space; and that may serve as 'early warning indicators' of climate change

- Initiate accelerated research to build the scientific foundation and enhanced technological capability for detecting and forecasting responses of ecosystems to multiple environmental changes

- Collect and cross-calibrate all ecosystem-relevant remote sensing data to create and regularly update a global atlas of ecosystem status at the highest possible resolution

Information on aerosols represents one of the largest gaps in our understanding of potential climate change. Aerosols (airborne fine particles) arise from both natural (dust) and human-influenced (chemical emissions) sources. Aerosols influence the climate system in two major ways: (1) scattering (climate cooling) and absorption (climate warming) of radiation and (2) altering the brightness and amount of clouds (changing the natural radiation pathways), as well as precipitation characteristics. Climate models must adequately represent both if there are to meaningful projections of future of climate change by natural or human-caused agents. The 2001 IPCC assessment of the Intergovernmental Panel on Climate Change (IPCC) places the aerosols–climate interaction as the single largest uncertainty in the radiative forcing of climate change. Further, the science community and the U.S. Climate Change Science Program (CCSP) deem a better understanding of aerosols and climate to be one of the top three current research needs, with the largest uncertainty being the aerosol-cloud-climate interactions. The information needs are threefold: (i) global observations of aerosol properties and distributions, (ii) an understanding of the processes that link emissions of aerosols and precursors to global aerosols distributions and processes, and (iii) improved and evaluated models that link aerosol characteristics to the climate system.

The delivery of climate data and services has a significant research component. The science community is continuing to investigate the complexities of the climate system, expanding the types of data that are needed, refining the requirements for the measurements in terms of spatial and temporal resolution and other aspects of data quality. Climate research is not as mature as weather forecasting, where data product requirements are well defined. Data products that are useful for operational needs, such as short-term forecasting, generally do not meet the needs of the Earth science community, especially for the study of climate-related processes. Long-term archiving, careful calibration, and regular reprocessing with state-of-the-art algorithms are critical for climate research applications. Operational needs are characterized by rapid, predictable and extremely reliable delivery schedules of standardized data products. To serve the needs of climate research, the future observing system must provide the necessary climate research services and functions, and the climate data management system must be designed with long-term operational needs in mind.

6. Interagency and International Partnerships

The United States and International partners coordinate the implementation of the Climate Variability and Change strategic vision. Our Changing Planet FY 2003 illustrates the broad inter-agency involvement of a cross-section of relevant U.S. federal agencies, coordinated at U.S. cabinet level. U.S. CLIVAR has in place a nucleus of scientific and programmatic elements, and strong linkages with the weather prediction community will advance capabilities to address issues of high societal relevance. The cadre of regional climate centers and state climatologists help ensure that regional and user expertise is represented in the development of effective frameworks for making climate information available. International research programs such as the World Climate Research Programme (WCRP) and its projects Climate Variability and Predictability (CLIVAR), Stratospheric Processes and their Role in Climate (SPARC), Climate and Cryosphere (CliC), the Global Energy and Water Cycle Experiment (GEWEX), as well as the International Geosphere-Biosphere Programme (IGBP) are critical for developing global infrastructure. GCOS has fostered the integration of key elements The IGOS Partnership (IGOS-P) focuses specifically on the observations in providing information for decision-making. The implementation panels of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology are particularly well positioned to deploy and sustain the *in situ* ocean networks

Partnerships between governmental and non-governmental, including commercial, non-profit, and universities, will continue to be essential in all areas of this plan. Transfer of capabilities should be encouraged in both directions, as “spin-offs” from government to the private sector, and as infusion of new technology into government activities. Enhanced collaboration between federal data centers and external (university, commercial, and non-profit) data service providers is needed. This collaboration will build on the strong foundation provided by existing dis tributed systems, encompassing the data centers established by federal science agencies, including NASA, NOAA, DOE, U.S. Department of Agriculture, the Environmental Protection Agency, USGS data centers, and NSF. CCSP’s data management plan also calls for expanding partnerships with foreign governments, intergovernmental agencies, and international scientific bodies and data networks to provide data that are needed to address the international character of research and decision making. These collaborations should improve access to regional, state, and local data.

7. U.S. Capacity Building Needs

A primary objective of the CCSP is to develop information and scientific capacity needed to sharpen qualitative and quantitative understanding through interconnected observations, data assimilation, and modeling activities. The program will address the potential for future changes in extreme events and uncertainty regarding potential rapid climate change. The CCSP will build on existing U.S. strengths in climate research and modeling, and enhance capacity for development of

high-end coupled climate and Earth system models. Enhancements in the observational system will focus on the related distributions of aerosols, clouds, and rainfall; on closing the budgets of carbon and nitrogen; and on determining crucial climate feedbacks, especially in the sensitive Arctic and Antarctic climatic regions. A rigorous approach to quality control that will assess the precision and accuracy in accordance with climate modeling principles is essential.
Land Use and Land Cover Change (LULCC) research requires global multi-resolution Earth observations that are coupled with *in situ* measurements. These observations need to document baseline global land use and land cover types and patterns across multiple spatial and temporal scales.

To achieve the goals of LULCC, we require the following data for developing the tools, methods, and knowledge that better characterize historic and current land use and land cover attributes and dynamics:

- Multi-spectral imagery with different spatial (regional, national and global) and temporal resolutions (daily to annual). Especially critical are:

- High resolution (10-30m resolution) multi-spectral imagery that ensures continuity and comparability with the 32 year Landsat record.

- Daily calibrated global moderate resolution (100-1000m) resolution multi-spectral imagery that is compatible with the historical AVHRR and MODIS.

- Very high resolution (<10m resolution) multi-spectral imagery with improved sensor calibration is needed for local characterization and validation of global datasets.

- Hyperspectral, radar, and related advanced technology imagery for detailed characterization of landscape condition and processes.

- Field data that are useful for understanding current and projected changes in socioeconomic and ecological processes. Specifically, we require:

- Expanded ground-based environmental inventory and ecological process data collection programs (e.g., forest inventory, land management practices, land use change, water quality, etc.) that contribute to the explanation of the rates, causes, and consequences of landscape change.

- Socioeconomic data and land use histories to develop an understanding of primary drivers of landscape change and to support the development of projections of future land use and land cover

Data on disturbances such as fire and flooding that alter land cover and land use are needed, as well as compilation of local datasets, and development of a standardized database linking local data to national and global land cover data products.

The global-mean temperature at the Earth's surface is estimated to have risen by 0.25 to 0.4 ° Celsius (C) during the past 20 years. However, satellite measurements of radiances indicate that the temperature of the lower mid-troposphere (the atmospheric layer extending from the Earth's surface up to about 8 km) has exhibited a smaller rise of approximately 0.0 to 0.2° C during this period. Estimates of the temperature trends of the same atmospheric layer based on balloon-borne observations (i.e., radiosondes) tend to agree with those inferred from the satellite observations. These apparently conflicting trends between surface and lower troposphere have caused some to question the magnitude of the surface warming and has led to continuing studies of temperature trends, analysis techniques of surface, airborne and satellite remote sensing, and radiosonde data sets, and a need for sustained and improved observations.

A new active atmospheric sounding technique, radio occultation, which uses the Global Positioning System (GPS), has been shown to provide accurate and high-vertical resolution all-weather soundings of refractivity, which is a function of temperature, water vapor and pressure. The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), a joint U.S.-Taiwan mission, will consist of six small satellites in low Earth orbit, and will provide approximately 2500 soundings per day globally over a five-year period beginning in late 2005. These soundings will complement microwave and IR sounders such as MSU, AMSR-E and AIRS, and these independent systems when assimilated together in models will produce global atmospheric temperature and water vapor fields of unprecedented accuracy and resolution, greatly reducing the uncertainty in atmospheric temperature and water vapor variability and trends.

In addition to improvements in accuracy of observations, it is essential that the measurements from the numerous disparate observing subsystems be consistently and effectively combined to produce a state-of-the-art climate analysis. Such a climate analysis is achieved through the assimilation of the observations into numerical models of the climate system. In order to achieve the full benefits of the many different observing systems, it is essential that data assimilation capabilities be applied to construct ongoing climate analyses and that, as these techniques are refined, periodic reanalyses be conducted to improve our descriptions and understanding of past climate variability, for example, over the past 50 to 150 years. The first-generation of climate analyses and climate reanalyses have already demonstrated their tremendous value to climate scientists and end users by synthesizing and integrating the basic observations together in a model to provide a consistent picture of the climate system. Continued development and improvement in climate analyses and periodic reanalyses must be considered as just as fundamental to a complete climate observing system as improvements in the observational sub-systems themselves.

Modeling research is also required to improve simulations of seasonal-to-interannual variability in global climate models, and to improve seasonal-to-interannual climate predictions. Access to model products, predictions, and tailored value-added information must be provided to the decision-making community to foster progress in utilizing prediction capabilities. Efforts should be focused on key regions/phenomena that are especially vulnerable to abrupt climate change, such as the tropics, the Arctic and Antarctic regions, and the ocean thermohaline circulation. Continuing development of ensemble-based approaches will be essential in order to improve probability estimates of extreme events. Finally, it is essential that the Ocean Observing System for climate be completely implemented as currently planned through FY 2010.

Capacity building from the U.S. and other developed countries to meet the needs of the developing world will continue to be critical. Landsat observations have helped developing nations better understand usage of their land resources, and maintenance of this long satellite heritage is a high priority. The future Landsat system must maintain global seasonal cloud-free sampling with a long-term acquisition strategy, provide for wide and open distribution, and for information and decision support tools.

Networks to measure atmospheric constituents have contributed a global database of important information on greenhouse gases. The oceanographic community has successfully engaged coastal nations to participate in observing. International programs addressing terrestrial processes have demonstrated similar successes in observing ecosystems. The United States can contribute further by evaluating existing networks' capability to meet established climate requirements; improving existing networks through direct contributions to international programs; forming partnerships with other developed countries to make directed investments to meet developing country inadequacies; providing direct assistance through U.S. programs of aid to specific developing country activities; and continuing to expand collaborative international scientific programs that address critical climate variables.

Understanding the current extent and future impact of the human impact on climate change represents one of the most important objectives in modern scientific research. The two to fourfold uncertainty in estimates of the aerosol radiative forcing via the direct and indirect aerosol effects is one of the major sources of errors in climate change simulations. Major improvements to climate model treatments of aerosol-cloud-radiation interactions are needed to reduce the large uncertainties in climate model predictions of the human impact. Direct observations of aerosol physical and chemical properties and their interaction with clouds and precipitation are urgently needed to estimate the aerosol forcing directly from observations and to improve model treatments of aerosol forcing.

A program such as the Atmospheric Brown Cloud (ABC) project coordinated by the Scripps Institution of Oceanography at the University of California, San Diego is an excellent example of international research effort involving NOAA as well as partners from India, Japan, China, and other associated nations. ABC focuses on linking together long-term aerosol and radiation measurements with remote sensing and computer modeling, which could be considered in this area. The Brown cloud phenomenon is a worldwide phenomenon that does affect the U.S., and while ABC's first emphasis is on Asia, it is envisioned that the program articulated by the ABC science team will become a template for other regions of the world including Africa, America and Europe. A primary focus of the project over the short-term is to set up regional aerosol-chemistry-climate observatories. The major goal of these observatories is to estimate the aerosol radiative forcing and to relate the forcing to anthropogenic emissions from the region. The observatory system includes 10 new observatories in the Indo-Asia-Pacific region, half of which are being funded by NOAA and the other half by the governments of China, India, Japan, and other associated countries. Currently, three sites are coming online with sites in the Republic of the Maldives operational as of October 2004. When these new observatories are combined with three alr eady existing observatories in the region, adequate coverage will exist to characterize the aerosol radiative forcing of the South and East Asian region.

The major scientific objectives of the ABC observatories are to: (1) establish continuous chemical and microphysical aerosol measurements at key locations in the Indo-Asian-Pacific region with a particular emphasis on black carbon, organics and cloud condensation nuclei;
(2) use regional scale source-receptor models in conjunction with the data from observatories and validated satellites to identify the relative contribution of the various Asian regions to the observed aerosol loading; (3) determine direct short-wave and long-wave aerosol radiative forcing at the surface and top of the atmosphere based on aerosol data in conjunction with comprehensive *in situ* and remote radiometric measurements; and (4) relate the aerosol forcing to regional sources of aerosol emissions.

8. Conclusions

GCOS, in consultation with its partners, has developed an implementation plan that, if fully implemented, will provide most of the observations of the Essential Climate Variables (ECV) listed in Table 1. That plan is in response to the GCOS Second Adequacy Report and has considered existing global, regional and national plans, programs and initiatives. The plan was developed in consultation with a broad and representative range of scientists and data users, including an open review of the implementation plan. There was close collaboration with the *ad hoc* Group on Earth Observations in developing their respective implementation plan. The plan identifies implementation priorities, resource requirements and funding options, and includes indicators for measuring progress in implementation.

The goal of the GCOS Implementation Plan is to specify the actions required to implement a comprehensive observing system for the ECVs that would, if fully implemented provide for:

- Global coverage.
- Free and unrestricted exchange and availability of observations of the ECV required for global-scale climate monitoring in support of the UNFCCC.
- The availability of integrated global climate-quality products.
- Improvements to and maintenance of the global *in situ* surface and airborne networks and satellites required to sustain these products, including system

improvements and capacity building in developing countries, especially in the least developed countries and small island developing states.

- Internationally accepted standards for data and products especially in the terrestrial domain and adherence to the GCOS Climate Monitoring Principles.
- Characterization of the state of the global climate system and its variability.
- Monitoring of the forcing of the climate system, including both natural and anthropogenic contributions.
- Support for the attribution of the causes of climate change.
- Support for the prediction of global climate change.
- Projecting global climate change information down to regional and local scales.
- Characterizing extreme events important in impact assessment and adaptation, and to the assessment of risk and vulnerability.

As the U.S. plan for climate observations moves forward, it should strive to build on the GCOS Implementation plan by addressing the following elements over the near-term (2-4 years); mid-term (4-7 years), and long-term (7-10 years), which are in line with goals of the CCSP Strategic Plan.

Maintenance and Standards: A high priority is to maintain and extend the records of key climate variables such as global carbon dioxide, ozone, temperature, and other essential climate variables now being monitored by current systems. The climate quality of these records must be assured by adherence to the GCOS climate monitoring principles, as extended by the CCSP Strategic Plan to cover satellite systems.

Modeling and Integration: Continued development and improvement in climate analyses and periodic reanalyses is required for integration of climate observations. Continued development of ensemble forecasting for climate is needed for applying and evaluating observations, and for better definition of requirements for future observations.

The following address each of the nine challenge themes identified in Table 2. In agreement with priorities of the CCSP Strategic Plan, near-term (2-4 year) enhanced observations and research are recommended for the first four themes, while enhancements to address the last four are recommended for phase-in over the latter part of the 10 year planned period. A detailed phase-in plan is needed that provides efficient integrated implementation to address all climate change challenge themes within realistic budget constraints, taking advantage where possible of governmental and non-governmental partnerships as discussed in section 6.

Near-term (2-4 years):

Land/Ecosystems/Human Dimensions: Improve monitoring, measuring, and mapping of land use and land cover, and the management of these data; Determine cycling of nutrients such as nitrogen and how these nutrients interact with the carbon cycle; launch a follow-on Landsat satellite at the earliest possible date, and continue the Landsat long-term acquisition plan.

Polar/Feedback: Enhance capacity to observe land and sea ice parameters including ice thickness; develop continuous high-resolution altimetry over the ice sheets, and SAR capability to monitor glacial advance/decline; improve resolution of global gravity measurements; integrate modeling of global climate and glaciers/ice sheets.

Aerosol: Reduce uncertainties in the changing aerosol radiative forcing of climate. This requires reduced uncertainty in the sources and sinks of aerosols and their precursors, in aerosol solar absorption, and in aerosol effects on cloud radiative fluxes and precipitation. Direct observations of aerosol physical and chemical properties and their interaction with clouds and precipitation are urgently needed to estimate the aerosol forcing directly from observations and to improve model treatments of aerosol forcing.

Water: Planned satellite measurements and focused field studies to better characterize water vapor in the climate-critical area of the tropical tropopause (the boundary between the troposphere and the stratosphere)

Carbon: Determine North American and oceanic carbon sources and sinks; the impact of land-use change and resource management practices on carbon sources and sinks; secure the measurements needed for the North American Carbon Program (NACP); enhance the ocean carbon observing network.

Mid-Term (4-7 years):

Water: Improve accuracy and global diurnal sampling of precipitation and water vapor to identify trends in the intensity of the water cycle; improved global/regional ocean and terrestrial observing systems and data exchange; improved technology (satellites and *in situ* , including suborbital, surface, and sub-surface) to measure soil moisture and evapotranspiration; improved observations and modeling of water vapor-cloud-climate-radiation feedback processes; closure of terrestrial hydrological budgets; impacts of climate change on the global/regional water cycle; and studies related to physical/biological and socioeconomic processes to facilitate efficient water resources management.

Radiation Budget: Provide for continuity of solar and Earth-emitted radiation budget observations at the top-of-atmosphere and surface, to continue the satellite record that began with Nimbus 7 and continues with SORCE and CERES, and maintain the related network of surface stations such as SURFRAD, Baseline Surface RadiationNetwork (BSRN), SURFX, and DOE/Atmospheric Radiation Measurement (ARM) sites. Supplemental radiation flux observations with coordinated observations of detailed wavelength spectra of solar and Earth-emitted radiation, are required to better identify mechanisms leading to changes in solar forcing and cloud-radiation feedbacks.

Long-term (7-10 years):

Temperature: Reducing uncertainties in the evaluation of temperature trends will require: (1) implementing an improved climate monitoring system designed to ensure the continuity and quality of critically needed measurements of temperature, and concentrations of aerosols and trace gases: and (2) making raw and processed atmospheric measurements accessible in a form that enables a number of different groups to replicate and experiment with the processing of the more widely disseminated data sets such as the MSU tropospheric temperature record. A number of possible research strategies for improving the understanding of uncertainties inherent in the various measurement systems and the relationship between surface and upper air temperature trends are actively being pursued by the CCSP and the international community, and these activities need to continue. For example, effective use of independent atmospheric sounding systems (MSU, IR, and RO) will produce atmospheric temperature and water vapor fields more accurate and reliable than any one sounding system by itself.

Paleoclimate: Enhance and where possible regularly update paleoclimate observations and data management systems to generate a comprehensive set of variables needed for climate change research; enhance tree ring, coral and ocean core records. Gaps in paleoclimate observations can be categorized in three areas dealing with: (1) physical observations, (2) data management, and (3) scientific stewardship. Regarding actual physical observations, the following three areas represent the greatest gaps for paleoclimate observations: (1) Collect and analyze 500-2000 year long coral records to reproduce temperature and salinity in the tropical oceans; (2) Collect and analyze high sedimentation rate deep sea cores; and (3) Produce marine geochemical proxy records of temperature trends for the past 2,000 years using corals, mollusks, and marine sediments from around the globe.

Earth Information System

The integration of a widely diverse system of systems that provides climate quality data is a central need. This requires the coordination of climate measurements from across domains in a way that provides for seamless access to the data, and appropriate tools for analysis and decision support. This coordinated system must be designed to continuously monitor the vital signs of the planet, and to provide tools needed to know what is going on in the climate system, to provide for full and open access to the data, to support the identification of the forcings and feedbacks, and to relate these to the decisions being made by the diverse community of users. The observations must be linked together in a synergistic manner, to enable the collection of individual observations to produce results than would not have been possible by use of the separate observations by themselves. This climate portion of an Earth Information System should establish benchmarks, provide for quality control and assurance, and support a seamless continuum of climate prediction products on multiple time scales.

Because of the multiple time scales involved in climate variability and climate change, an area requiring future development is the ability to not only track climate anomalies but also to attribute them on multiple time scales to:

- External forcings (solar, volcanoes, atmospheric composition)

- Internal forcings (e.g., ENSO, SSTs and ocean heat content, soil moisture anomalies, state of vegetation, sea ice)

- Natural variability (essentially unpredictable)

This will require an operational numerical experimentation program running ensembles of Earth system models. At present, this activity is carried out in an *ad hoc* fashion, often not in real time. Institutions such as the NOAA's Climate Prediction Center, the European Centre for Medium range Weather Forecasts, and the International Research Institute for climate prediction, as well as many other national meteorological or climate centers, may perform limited experimentation in near real time as part of the process of issuing monthly forecasts, or retrospectively to understand major anomalies. However, models now appear to have improved sufficiently that results are becoming more definitive; such attribution examples include the Sub-Sahara African drought beginning in the 1960s and the "Dust Bowl" era in North America in the 1930s.

Climate observations need to be taken in ways that satisfy the climate monitoring principles and ensure long-term continuity and ability to discern small but persistent signals. The health of the monitoring system must be tracked and resources identified to fix problems. Satellite observations must be calibrated and validated, with orbital decay and drift effects fully dealt with, and adequate overlap to ensure continuity. Reanalysis of the records must be institutionalized along with continual assessment of impacts of new observing and analysis systems. Such an end-to-end Earth information system will be key to the success of the U.S. effort in supporting the GEO over the next 10 years.

APPENDIX 1 ESSENTIAL CLIMATE VARIABLES FROM THE GCOS 2nd ADEQUACY REPORT CROSSWALKED AGAINST THE 9 IWGEO THEMES

IWGEO THEME	Weather	Disasters	Ocean	Clim	Agric	Health	Eco	Water	Energy
Aerosol Properties	X	X	X	X	X	X	X		X
Air Pressure	X		X	X		X	X		
Air Temperature	X	X	X	X	X	X	X	X	X
Albedo	X			X	X		X	X	X
Biomass				X	X		X		
Carbon			X	X	X	X	X		X
CFCs				X					
CH4				X					X
Cloud Properties	X			X					X
CO2	X			X					X
CO2 Partial Pressure			X	X	X		X		X
Earth Radiation Budget (incl. solar irradiances)	X	X	X	X	X	X	X	X	X
Fire Disturbance	X	X		X	X	X	X	X	
Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)				X	X		X	X	
Glaciers and Ice Caps		X	X	X			X	X	
Ground Water	X	X		X	X	X	X	X	
Lake Levels	X	X		X	X	X	X	X	
Land Cover (incl. vegetation type)	X			X	X		X		
Leaf Area Index (LAI)				X	X		X		

Nutrients			X	X	X	X	X	X	
Ocean Color (for biological activity)			X	X		X	X		
Ocean Sub-Surface Temperature		X	X	X			X		X
Ocean Tracers			X	X			X		
Other long lived GHGs (N2O, CFCs, HCFCs, SF6 & PFCs)			X	X	X	X	X		X
Ozone	X	X		X	X	X	X		X
Permafrost and Seasonally Frozen Ground		X		X			X	X	
Phytoplankton			X	X			X		
Precipitation	X	X	X	X	X	X	X	X	X
River Discharge	X	X	X	X	X	X	X	X	X
Sea Ice		X	X	X			X	X	
Sea Level		X	X	X			X	X	
Sea State		X	X	X		X	X		
Sea Surface Temperature	X	X	X	X			X		X
Sea-Surface Salinity		X	X	X			X		
Snow Cover and snow water equivalent	X	X	X	X	X	X	X	X	
Sub-Surface Current			X	X			X		
Sub-Surface Salinity			X	X			X		
Surface Current		X	X	X			X		
Surface Radiation Budget		X		X	X	X	X		X
Upper air temperature (incl. MSU radiances)	X			X	X		X		X
Water Use		X		X	X	X	X	X	X

Water Vapor (Surface)	X			X	X		X		X
Water Vapor (Upper Air)	X			X	X		X		X
Wind Speed & Direction (Surface)	X	X		X	X	X	X	X	X

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