The Future Global Earth Observing System: System requirements and architecture

Peter Hildebrand, Mark Schoeberl, Warren Wiscomb, Mariann Albjerg
NASA/Goddard Space Flight Center, Greenbelt, MD 20771
Martin Mlynczak
NASA/Langley Research Center, Hampton, VA, 23665
Carol Raymond, Robert Ferraro
Jet Propulsion Laboratory, Pasadena, CA,09109
Tim Miller
NASA/Marshall Space Flight Center, Huntsville, AL, 35812
Richard Miller
NASA/ Stennis Space Center, MS 39529
David Petersen
NASA/Ames Research Center, Moffett Field, CA, 94035

ABSTRACT: This paper summarizes the observational requirements for a future Earth System Observational and Modeling capability, in terms of the observed variables, the needed precision, and spatial-temporal resolution. Architectural approaches are discussed, including an open-systems, evolutionary, sensor-web approach.

I. Introduction

The Earth environmental system—the interconnected oceans and atmosphere, the biosphere, the solid Earth—influences all aspects of life on the planet. The Earth's comfortable environment, with its moderate temperatures and relatively abundant fresh water, has provided for the development of the remarkable and diverse forms of life we find on Earth.

The natural variability of the Earth's environment links to life in a myriad of ways, affecting human activities, the availability of water, the production of food, atmospheric composition, ecosystem and human health, and even human migration. As the human population grows, the links between the ever-changing Earth environment, human needs, and environmental impacts also grow. As our society grows and demands more of the Earth, the capability for quantitative prediction of the Earth system is becoming more and more important. In the decades to come we must move beyond the basic understandings of the components of the Earth system, to develop an accurate and quantitative predictive capability for the Earth system as a whole. We must develop the ability to understand and to accurately predict future changes of Earth's atmosphere, oceans, biosphere and solid Earth. These predictions will enable informed societal decisions that will enhance the quality of life, economic sustainability, and global social stability.

During the past 20 years Earth science research has focused on understanding the components of the Earth system. This has been accomplished through new global observations and computer models that address specific Earth system processes.

The circa 2030 future Earth System Observational and Modeling capabilities will extend beyond the present weather, ocean, land surface, and biosphere observations to include comprehensive Earth observation. This will include a global perspective of the ocean and atmospheric systems, their states, processes, heat transport, and evolution, and the coupling between ocean and atmosphere, and understanding of the complex linkages between climate and the water cycle. It will include a global perspective of the solid Earth, crustal movement and processes, ice processes and sea level, Earth inner circulations, and the linkages between solid Earth processes, climate and the water cycle. It will include a global perspective of the biosphere and ecosystem health, and their linkages to ocean-atmosphere, climate and the water cycle. These aspects of the Earth system will require routine global observations, all made with appropriate precision and with the required temporal and spatial resolution.

These complex observations will be achieved through a mixture of remote sensing and direct measurements, ingested into data assimilation models which can evaluate their precision and timeliness, placing appropriate weight to their application to the Earth system model. The model will, itself, be a composite of components that address each aspect of the Earth system, and the linkages between components.

This paper summarizes the future Earth system observational requirements in terms of the science needs for observed variables, the needed precision, and the spatial-temporal resolution. Since implementation of these observational capabilities will be a complex international effort, it will be important to develop architectural approaches that enable an evolutionary, open-systems approach to the total Earth observational system. We will discuss our view of the observational requirements and some possible approaches to developing an acceptable, international system architecture.

II. Earth Science Observational Needs

The core future Earth system observational and modeling capabilities can be summarized within three major subject areas: the Earth fluid system consisting of the atmosphere and oceans, the biosphere, and the solid Earth. Within the area of atmospheric and oceanic phenomena are the examples of the predictability of intra-seasonal climate, such as the El Niño and the north Atlantic Oscillation, and the prediction of extreme weather, specifically hurricane track and intensity. Within the research area of the solid Earth are the examples of the predictability of changes in sea level, and the consequent effects on coastal zones and their habitability and ecosystems, and the development of the ability to measure earth crustal movements and to forecast earthquakes. Within the research area of biospheric processes are the examples of the availability of water as a global resource; and development of a comprehensive understanding of global biosphere-climate interactions, and the links to human influences on the biosphere and climate. For each of these research topics, new global observational capabilities must be developed. New scientific understandings, derived from the observations and predictive models, will yield a complete picture of the Earth system.

The vision for 2030 outlined in this document assumes that many fundamental phenomena and processes that are currently under study, or are high priority for the near future, are likely to be well advanced by 2015. There are important additional Earth science research topics, including the role of aerosols and atmospheric chemistry in the Earth's radiation budget, variability in global heat transport by the ocean's abyssal circulation under the effect of climate change. These and additional topics will need to be addressed in the future. The following discussion reaches beyond the current program to illustrate some avenues of research that would push the frontiers of understanding and enable a comprehensive Earth System Model to be realized.

A. Intra-Seasonal Climate

The challenge of intra-seasonal climate predictions relates to the understanding of the critical scales for short-term climate—the mean states and variability of the weather patterns that determine temperature, precipitation, availability of water, etc—rather than the predicting instantaneous realizations, such as are used in our current weather forecasts. Using this paradigm, the circa 2030 predictive goals will center on accurate predictions of weekly to monthly climate, 15-20 month cycles, and decadal climate variability. The forecasts on these long time scales must be accurate enough for societal action.

Some of the new needed spaced-based measurements for short term climate are in the queue for the near term (e.g., ocean salinity), but many needed new measurements are in the proposal stage or have not yet been considered. The short tem climate observational needs (Table 1) include hourly measurements of aerosols and critical atmospheric chemical components; daily measurements of ocean evaporation rate, precipitation, soil moisture and stream flow; weekly measurements of ocean mixed layer depth; monthly measurements of sea ice thickness and soil properties. For long-term climate estimates, observations of the thermal-haline circulation, aquifer water storage, and soil carbon reservoirs are needed.

For each measurement, the same precision as current in-situ technology is required. For most variables, this requires accuracies in the 5-10% of the total value of the variable. Due to the required hourly sampling rate for the aerosol and atmospheric chemistry measurements, geostationary platform instruments will be required. With their long temporal scales, most ocean variables, sea ice, soil moisture and other variables can be measured from Low Earth Orbit (LEO) or as is convenient, given the instrumentation. Measurements of aerosols and atmospheric chemical constituents will have to be made from a geostationary location due to the required hourly temporal update rate.

A major consideration for all these measurements will be maintenance of the consistency and integrity of the observations across many years and decades. This requirement places stringent requirements on maintaining the history, the calibration, and the access to data over the very long periods associated with climate change and variability.

B. Extreme Weather – Tropical Storms

The challenge of extreme weather predictions, as exemplified by tropical cyclogenesis, centers on extending weather prediction capabilities to their theoretical limits, and on developing an understanding the genesis of extreme events. Extreme weather events have enormous societal impact, particularly with due to the effects of extreme precipitation and winds on human life, infrastructure and transportation.

The measurement of sea surface temperature (SST), water vapor, and cloud-drift winds from satellites, in combination with significantly improved numerical and statistical models, has enabled much of the improvement in tropical cyclone forecasts during the past decade. A series of Observing System Simulation experiments (OSSEs) have indicated that the additional measurement having the greatest impact on weather forecasts, and tropical storms in particular, will be measurements of global tropospheric wind profiles. Additional needed measurements (Table 1) include hourly measurements of global temperature and humidity profiles, and precipitation. In-storm measurements of winds, temperatures and hydrometeors will provide an additional challenge. All oceanic storm forecasts will benefit greatly from knowledge of the ocean mixed layer depth. The observations will be required to meet the same accuracy requirements as present in-situ measurements (~1-3 m/s, ~1°C T & Td, a few mm/h precipitation, ~10% ocean mixed layer depth). This will be a major technological challenge.

A additional technological challenge for all these measurements is the need for high resolution (5-25 km), and a high update rate (1-3 hours, with the exception of ocean mixed layer depth—1-7 days). The 1-3 hour and longer update rates suggest the use of either a network of LEO spacecraft, or new geostationary capabilities, with either approach augmented by in-situ calibration and data assimilative models.

C. Changes in Sea Level

The challenge of sea level prediction is to transition from the present knowledge of the major causative factors—ice sheet volume and melting, water cycle variability, steric effects, and ocean basin volume changes—to the ability to measure the effects of changes in these factors. Although the effect of changing sea level is slow, the impact, due to human migration toward coastlines, is large.

To measure sea-level change and to understand and predict future change requires sustained observations of many variables (Table 1). The observational requirements include weekly measurements of ocean mixed layer depth, soil moisture, and snow pack, monthly observations of ocean-ice gravity distributions, ice motion dynamics, land water storage, and coastal zone topography; and annual to multi year observations of ice sheet topography, ice bed characteristics and ocean bathymetry. Each of these measurements needs to be made on the scales of the processes, which dictates scales ranging from 1-100 km. The slow update rate needed for ice and sea level processes suggests that single LEO satellite systems could provide the needed space-based measurements.

Each measurement requires a precision that is similar to current in-situ precision. The measurements must also be sustained and be highly calibrated, for very long periods of time, in order to sample all the relevant time scales of the processes and their interactions, and in order to maintain the integrity of the measurement calibration across the evolution of observational instruments and data assimilation algorithms.

D. Earthquakes

The challenge of earthquake prediction is to make the huge leap from basic knowledge to observation, understanding and prediction of these events. Although infrequent, earthquakes (and volcanic eruptions) have such a large human and social infrastructure impact that they are remembered for many generations.

The efforts to advance understanding of earthquake physics will require detailed observations of all phases of the earthquake cycle (pre-, co-, and post-seismic), across multiple fault systems and tectonic environments, and across the full globe (Table 1). Systematic measurement of surface deformation on a variable, daily-to-monthly scale, at a few *m* resolution, and with high precision are needed. The selection of the temporal sampling is dictated by the tectonic environment, and should be sub-daily for plate boundary environments and other recognized highly deforming regions, but might be as long as monthly to annually for more quiescent environments. Gravity measurements on a weekly basis, with 50-100 km spatial resolution and 0.1 milligal accuracy will be required. Mapping the degree of saturation in the shallow subsurface will help determine landslide hazards, and may allow the liquifaction hazard to be folded into the overall dynamic earthquake hazard assessment, scaled by the degree of saturation of the vulnerable layers.

Due to the weekly and longer time scale of most of these measurements, a combination of individual LEO satellite observing systems (InSAR and gravity, augmented by GPS coordinates), plus critical in-situ measurement systems could provide the needed observational capabilities.

E. The Availability of Water

The fundamental problem in developing a full understanding of the water cycle and the global availability of water is that most aspects of the water cycle are very poorly measured on the global scale. The conceptual framework for the global water budget has been developed and a few well-instrumented locations around the world are measured accurately. However, fundamentally new global measurement capabilities of many variables—precipitation, stream flow, land and oceanic evaporation, retention of water in land, snow, and ice—will be required in order to develop a viable predictive capability that accurately links to climate variability.

The observational challenges (Table 1) include global precipitation and water vapor transport in the air and clouds every few hours, daily measurements of soil moisture, stream flow, evaporation rate over land and at sea; weekly measurements of water storage in snow and ice, and freeze/thaw conditions; and monthly observations of changes in soil properties, land water storage, sea ice thickness and ocean circulations. The scales of these measurements are typically 1-10 km, and the required precision is 5-10% of the total value as measured over the sampling period. Strong present steps towards many of these measurements assure realization of this goal.

Due to the low temporal sampling rate of most of these observations, many can be made from LEO satellites, plus addition of critical in-situ measurements and data assimilative models. For some types of measurements, e.g. soil type, there may never be a practical global observational capability and innovative combinations of in-situ observations plus global remote measurements, coupled with new modeling approaches, may be necessary.

F. Biosphere-Climate Interactions and Human Influences

As with the global availability of water, the grand challenge of predicting changes in biosphere-climate interactions and human influences centers on the need for new measurement capabilities. The Earth's biosphere is complex and diverse and varies greatly across the Earth's surface. Fundamental new observational capabilities (Table 1) will be required to understand processes including biosphere-land-ocean carbon exchange, biosphere-climate linkages, the natural regulatory controls on the biosphere, and human influences.

The requirements for new terrestrial ecosystem measurements include diurnal assessments of atmospheric aerosols, critical chemical constituents, radiation and pollution; daily observation of phenological state (leaf out and senescence) and fire properties; and weekly or longer assessments of soil moisture, precipitation and evaporation, the biogeochemical composition of plant canopies, and soil properties. Additionally, weekly measurements will be required of the biogeochemical composition of plan canopies, as well as monthly assessments of the standing biomass and of land surface properties. These measurements must be made on the ~100 m scales of ecosystems, and with 10%-20% accuracies.

These diurnal and daily measurements may be amenable to high spectral resolution sensors that could be operated in geostationary orbit. The longer term measurements might be more amenable to LEO observational systems, augmented by in-situ and sub-orbital calibration measurements.

The open ocean and the coastal zone share several key variables that are not presently observed, including salinity, ocean mixed layer depth, wind and nutrient fields, aerosol deposition, and functional groups. Most of these variables require observation on a daily to weekly time scale, with the dissolved organic matter and ocean physiological state measurements needed at daily scales, and other variables, generally at weekly scales, both in the ocean and on land. The coastal zone has special needs for hyperspectral measurements, with spatial resolution that are related to ecosystem sizes (10s – 100s m). Due to the relatively low temporal requirements, LEO observational platforms plus possible use of instrumented aircraft, coupled with critical in-situ instrumentation, will likely meet the needs of these observational requirements.

III. Earth System Observation and Modeling Considerations

The Earth system measurements listed in Table 1 will provide the measurements required by the range of science topics that have been discussed. As noted, other science topics will add additional required observations, and as more is learned, additions will be required for this list, but for the current and future Earth science topics. The long-term vision is a *sensor-web* observing system architecture that employs large numbers of sensing systems, operating from multiple vantage points—LEO, GEO, LaGrange points, and the Earth—to collect observations at the spatial/temporal resolution and with the precision required by the geophysical processes being observed and forecast.

Implementation of all these measurements from satellite platforms will likely be accomplished with several different satellite systems. The design of the satellite systems will be determined by the required temporal and spatial resolution for the data and by the remote sensing wavelengths needed to make the measurements. For the high temporal update rate measurements—hourly, diurnal, daily—it is most likely that the needed measurements must be collected from a geostationary vantage point, using visible or very high microwave frequencies in order to provide reasonable antenna sizes. Examples include the measurements of aerosols, atmospheric chemical constituents, biomass characteristics on land and at sea, and at some aspects of precipitation and atmospheric wind observations. For those variables that require multi (~3) hour to daily update rates, a constellation of 6-8 LEO satellites, such as that proposed for GPM could provide the needed measurements. Due to the much lower orbit altitude, a considerably wider range of frequencies, extending down to a few tens of GHz, can be implemented on a reasonably sized spacecraft. Examples of such measurements include precipitation and cloud water, ocean evaporation, physiological state and dissolved organic matter, fire properties, crustal deformation, and aspects of soil moisture. The longer temporal update rate measurements on the order of a week and longer can all make use of single LEO satellite systems that provide a weekly or longer full observation of the full Earth. Examples include root zone soil moisture, snow pack, ocean salinity, sea ice coverage and thickness, topography for global ice, coastal zones and other areas, crustal deformation, global gravity fields, ocean mixed layer depth.

Although this list of measurements (Table 1) and satellite systems (above) is somewhat daunting, it is important to note that there is considerable overlap between the observational needs of science and the orbits and instruments that will be required. Some of the overlap is indicated in the last column of Table 1. Additional overlap will be provided through application of the same sensor technology on a single platform (e.g. the geostationary) to a long list of different measurement needs. A third level of overlap will be provided through application of the measurements from the higher temporal update rate instruments to support the lower update rate observational needs. This will be the essence of the future sensor-web of Earth observing satellite systems. The net result of all this will be not unlike the present fleet of geostationary, LEO polar orbiters and the many research satellite systems. The difference will be that the composite of the whole will be designed to operate as a symbiotic system; each part supporting the rest of the system, and the total system providing reliability through redundancy.

Two additional concepts are central to achievement of these goals. First, our measurements and models must continuously evolve as observations improve, scientific understanding advances and the computer models become more clever. The concept of observational and modeling evolution is a central element of the long term future, for this capability will enable competitive evaluation of new measurement and modeling approaches, and for continual and gradual adoption improved approaches that are more accurate, more efficient and less costly.

Second, long-term calibration stability must be maintained as the measurement and predictive modeling capabilities evolve. In order to achieve the desired predictive capability, the required observations must be maintained long term, including precise and continuing re-calibration of the measurements as the technology evolves and improves. This is required in order to understand long term trends, to be able to discern variability versus change in the earth system, and in order to develop an understanding of the causative forces for either.

Acknowledgments

We would particularly like to thank the panels of experts across the country who supported the NASA Earth Science Vision activities, and the management at NASA Headquarters and at the Centers where we work, for providing the support and encouragement necessary for this effort to be concluded.

Table 1. Key Climate Measurement Goals that will be required as part of an Earth Measurement and Modeling System by the year 2030. The predictive goals are indicated for climate (C), extreme weather (EW), sea level (S), earthquake (E), water (W) and biosphere (B).

Measurement	Frequency	Horizontal Resolution	Precision/ accuracy	Predictive Goal
Ocean evaporation rate	Daily	10 km	5%	C, W
Ocean mixed layer depth	Weekly	10 km	10%	C, EW, S
Ocean mixed layer depth, coast al zone	Weekly	10-100 m	10%	B
Ocean/Ice Mass Redistributions (gravity change)	Monthly	100s-1000s km (drainage basin)	0.1 mm/yr sea level rise equivalent	S
Aerosol distribution and absorption properties	Hourly	< 1 km	10%	C, B
Atmospheric ozone	Hourly	1km (V)	5%	C, B
Carbon dioxide and methane	Hourly	1km (H)	1% (column)	C, B
Atmospheric gases	Hourly	1km(H&V)	1-10%	C, B
Tropospheric wind profiles (20 levels)	3 Hours	5 km	1 m/s	E
Wind vectors within storm systems (20 levels)	1-3 Hours	5-25 km	3 m/s	E
Temperature and water vapor profiles in clear air (20 levels)	1-3 hours	5 km	1º C, T & Td	E
Temperature and water vapor profiles within storms (20 levels)	1-3 Hours	5-25 km	1º C, T & Td	E
Surface precipitation	Hourly	5-25 km	5-10 mm/h	E, W
3-D precipitation structure (20 levels in troposphere)	3 Hours	5-25 km	5-10 mm/h	E
Sea Ice thickness	Monthly	5km	5cm	C, W
Soil Moisture	Daily	< 1 km	10%	C, S, W
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly - Weekly	< 1 km	NA	C, W, B
Stream flow	Daily	NA	10%	C, W
Bathymetry	Daily-Weekly	100 m	10%	B
Coastal zone topography	Monthly	2-5 m pixels	<10 cm	S
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams & sheets)	1 cm (height)	S, W
Ice sheet elevation	Weekly	< 1 km	1%	W
Ice motion (dynamics)	Monthly	100 m	1 m/yr (rate)	S
Ice Sheet and Bed Characteristics	Yearly	10 – 100 km	Bed topography to <10 m	S
Crustal Deformation (uplift/subsidence)	Daily To Weekly	10 m	1 cm (range); 0.5 mm/yr (rate) on annual basis	S, E
Crustal Mass Redistributions (gravity change)	Weekly	50-100 km	0.1 milligal accuracy	E
Subsurface moisture sounding	Weekly	100 m/ 10 m depth	5% saturation	E
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent	S, W
Reservoir and Aquifer Impoundment	Monthly	Scale of storage basin	0.1 mm/yr sea level rise equivalent	S, W
Ocean Nutrient fields (N, Si, Fe), aerosol deposition, functional groups	Weekly	10 km	30 %	B
Ocean Colored dissolved organic matter, Chlorophyll and other pigments, Functional groups, Bathymetry and bottom reflectance, Nutrient concentration (N, Si, Fe, P)	Daily-Weekly	100 m	10%	B
Ocean Physiological state (fluorescence)	Daily	100 m	20%	B
Phenological state (leaf out, senescence)	Diurnally	1 km	Less than one day	B
Biochemical composition of plant canopies (N, lignin, pigments, chlorophylls, etc.) Responses to multiple stressors (long-term)	Weekly	100-200 m	25%	B
Fire properties (energy release rates, rate of spread, gas/aerosol loading, soil heating)	Daily	100 m	20%	B
Standing biomass over time	Monthly-Annual	100 m	10%	B