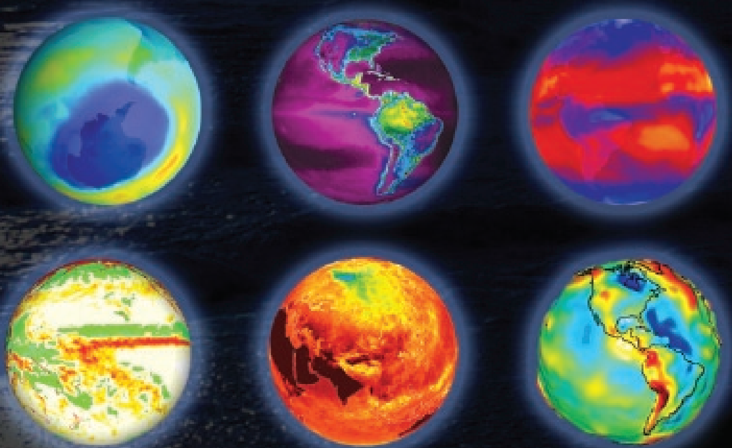
EARTH SCIENCE
VISION 2030



WORKING GROUP
REPORT


PREDICTIVE PATHWAYS FOR A SUSTAINABLE FUTURE

To the Reader:

As the human population increases and becomes more interdependent, so grows the demand on Earth to provide a safe haven and the resources that sustain life. As the demands on Earth increase, any major changes in weather and climate, the availability of food and water, the communication of disease, and many other issues become increasingly international topics. In response to these needs, the Earth sciences community has a new and heightened responsibility to address important social and policy needs for knowledge of the Earth as a system

In recent years, NASA Earth sciences research has provided a vastly improved understanding of the myriad of natural processes at work on Earth. With this movement towards understanding of the Earth as a complete system, we have progressed to the threshold of a fundamental new capability to observe the Earth system-the oceans and atmosphere, the biosphere, the habitability for life, the solid planet-and to predict future changes, whether they be due to natural changes or to human-induced effects. Truly an international effort, this whole Earth system focus provides a new predictive capability in which observations of all components of the Earth will feed into predictive computer models that can forecast future variability and changes in the Earth processes that affect life.

NASA has the responsibility for developing new space-based capabilities for observing and understanding the Earth, and for transitioning these new capabilities to national applications and decision support procedures that meet the social and policy needs of the nation. The NASA Earth Sciences Vision Team was asked to take a long-term view of NASA Earth Sciences, providing a future vision for NASA Earth sciences and suggesting major measurement goals that would help achieve this vision.

This report is the Earth Science Vision Team's response to our charge. In the course of our deliberations, we have sought the advice of experts from across the nation, and we have presented our results at several national and international meetings. We express our appreciation to all who assisted in our deliberations. The opinions and the future vision we express herein are our own, and do not represent the policy or plans of NASA. We hope that this report assists in defining the future vision for Earth sciences at NASA and elsewhere. We hope that it stimulates a strengthened effort to provide predictive pathways towards a sustainable future for life on Earth.

Sincerely,

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March 2004

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> *We have come to understand that the only way to really comprehend our climate and to protect the scarce resources of our planet is to look at the Earth as a single, whole system.*
>
> *Sean O'Keefe, NASA Administrator*

1. 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 continues to grow and to demand more of the Earth, the capability for quantitative prediction of the Earth system is becoming 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, combining the 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.

The mission of the NASA Earth Science Enterprise (ESE)[1] is to observe and understand the Earth environment with the goal of predicting both natural and anthropogenic change. ESE activities include research into climate and weather, biosphere, solid Earth, as well as cross-cutting science topics, such as chemistry, radiation, pollution, human impacts, water cycle, carbon cycle and more. Central to NASA Earth Science Enterprise research is the requirement for global observations, which are most efficiently implemented from space-based vantage points, and which provide the ability to monitor the variability of the Earth environment for life under the effects of climate change, human impacts and tectonic events.

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 through development of computer models that address specific Earth system processes. Significant progress has been made. Current observational systems include capable operational satellites operating in polar and geostationary orbits.

These operational satellite measurements are augmented by a fleet of eighteen NASA research satellites (Fig. 1.1) that observe a wide spectrum of Earth processes. Examples include: the Tropical Rainfall Measurement Mission (TRMM) precipitation measurement satellite with the proposed upgrade to the Global Precipitation Measurement (GPM) constellation, the Earth Observing System (EOS) Terra and Aqua satellites observing a spectrum of Earth processes and paving the way towards the future upgraded National Polar Orbiting Environmental Satellite System (NPOESS) polar orbiting satellites, the Gravity Recovery and Atmospheric Change Experiment (GRACE) Earth gravity measurement mission, ICESat (Ice, Climate and Elevation Satellite) glob-

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[1] Here and elsewhere, please see the list of references at the end of this report.

al topography, Landsat Earth surface observations, QuickScat ocean surface wind measurements, and the other missions illustrated in Fig. 1.1, and detailed on the NASA Web sites. Measurement systems scheduled for the near future will add to these capabilities to fill in critical observational gaps, and a new generation of data assimilation and fusion capabilities will enable greatly improved predictions. The nature of these observational and data assimilation and modeling systems is presently limited, because each Earth observation and modeling system component retains the viewpoint of that specific component of the Earth system. Future needs for enhanced observational and Earth system predictive capabilities require a new approach.

Figure 1.1
Eighteen NASA Earth Science Enterprise research satellites currently provide observations of Earth system components. Each satellite is designed to measure specific Earth system processes.

The Earth Science Vision (ESV) for 2030 establishes a paradigm in which the dynamic Earth system is fully observed using an international suite of Earth observation systems, and then represented in a family of interacting models that include all major Earth system components: atmosphere, oceans, biosphere and solid Earth. When implemented in its complete form, the Earth Information System[2] (EIS, Fig. 1.2) will provide a quantitative predictive capability of system interactions that will continually be evaluated against observations. Key attributes of the EIS are that it:

- observes the whole Earth system, such that the changes in any component system can be traced to measure the total impact;
- models the whole Earth system and all its components, such that effects of changes in any component can be predicted;
- dynamically evolves to define the system behavior that best describes ongoing observations; and
- yields predictions with quantitative uncertainties that are useful in the public decision-making process.

Achieving this Earth observation and modeling system is the grand, long-term challenge for the NASA Earth Science Enterprise. This long-term NASA goal is designed to support larger Earth science community goals (NRC, 2003). Achieving this challenge requires new approaches to observations, data analysis and modeling, in which data sets and models of all the system components are coupled. The present disciplinary approach to Earth observations and modeling

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[2] NRC (2003).

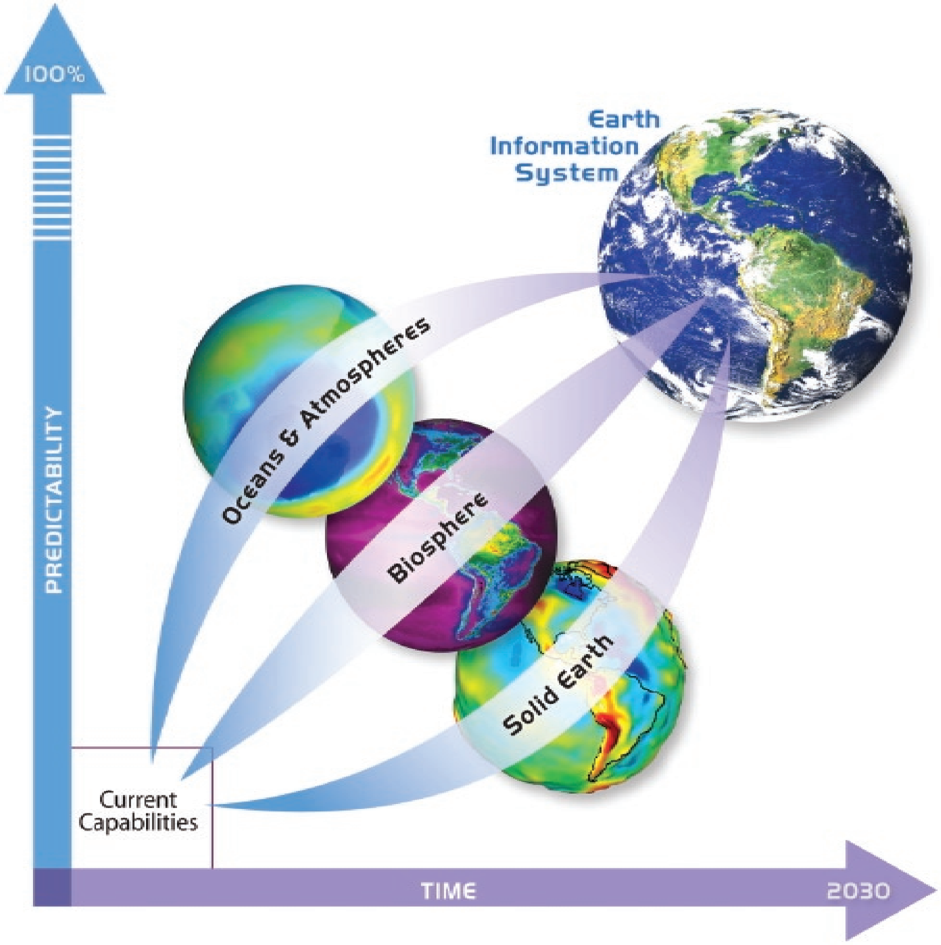


Figure 1.2 Illustration of the growth of predictive capability toward an Earth Information System prediction paradigm with integrated observational and modeling capabilities.

poorly assesses the feedbacks between diverse system components, thereby limiting the ability to make accurate predictions. The EIS approach will produce a measurement/modeling environment that couples the major and minor systems together to provide robust constraints on predictions. These constraints will define model performance and will drive model evolution. Once the models can simulate a closed system, each model component can be tested against the myriad of observations, providing quantitative evaluation of predictive capabilities. It is to be expected that the coupled models will initially perform poorly, relative to present models that are optimized for single component systems. However, in the long term, the potential for greater understanding and prediction is much greater for the full Earth system measurement and modeling environment. For this reason, integration of new knowledge into an EIS framework forms the overarching, long-term ESE goal that will strongly support the larger world-wide community effort to develop a global EIS.

A comprehensive Earth system observation and modeling capability will provide important benefits to society. It will enable a robust Earth system predictive capability that represents the community consensus of current knowledge. This addresses the critical need for science support of public activities and policy decisions. Such activities include the wide variety of public accommodations to the ongoing variability in the Earth system, such as weather and climate variability, or the consequent alterations in ecosystems, or other events. A robust Earth system predictive capability will also provide a test bed for new theories that will stimulate collaborative, interdisciplinary research. This capability will allow for rigorous, quantitative assessments of the value of each observation in driving model predictions, such that observational systems will be able to evolve toward an optimized suite, rather than monitoring everything on a continuous basis.

The observations from space will drive our modeling and predictive capabilities. This will require new instrument and technology investments that cover the entire electromagnetic spectrum, and include both passive- and active-sensing techniques. The strategic focus for instrument development is to promote advances that improve measurement precision while also enhancing spatial, spectral, and temporal resolution. Technologies that enable observations from geosynchronous orbits and the LaGrange vantage points are needed to allow continuous, global coverage of the Earth's surface. Finally, new technologies will provide advanced platform capabilities that will process data and share information in real time, thus leading the way towards a future where fully integrated systems collaborate autonomously to perform complex observations.

The long-term vision of a sensor-web observing architecture employs large numbers of frequency-agile sensors operating from multiple vantage points to simultaneously collect global observations. The capability to tailor the spatial, spectral and temporal resolution of the measurements will be accomplished by having a cooperating fleet of spacecraft operating intelligently. Such an architecture requires advanced on-board data processing systems capable of orchestrating real-time collaborative operations. For such observing systems, information technology investments are needed to develop the capability to observe autonomously in changing environments, and to rapidly convert vast amounts of sensor data into operational knowledge and information products.

A major paradigm shift accompanies the development of the EIS. Each building block of the EIS must be built and tested in a community modeling environment in which multiple models operate and 'learn' from each other. Based on this, a consensus model will emerge, representing the mean state of the model space. The competing models will continue to evolve, based on the stream of observations and model evaluations; the consensus model will be periodically updated, based on these evaluations. There will still be a spectrum of effort from pure research to 'operational' prediction, but rationalized into a robust system. In such a community modeling environment, paradoxes and unexplained phenomena will emerge, focusing research efforts on the highest payoff questions.

An EIS, such as described here, can only be developed by a large consortium of international partners and US agencies. However, we believe that NASA should and must take a strong role in framing and developing the EIS. NASA has made, and will continue to make, huge investments in the observational system technologies that provide the foundation for the EIS. NASA also has a large investment in computational technologies and models that can be directed at EIS development; indeed, many of the building block models are in early stages of development at the present. NASA has unique capabilities in this area and is well poised to take on a leadership role in bringing together the needed technologies and data from within and outside of the Agency to produce a resource for the global community.

2. The ESV Science Questions

The core new capabilities for the NASA Earth Science Enterprise can be summarized within three major subject areas: the Earth fluid system (consisting of the atmosphere and oceans), the biosphere, and the solid Earth (Fig. 1.2). In the balance of this section we will outline exemplary science questions within each of these three broad subject areas. Each of these exemplary areas for improved Earth predictive capabilities, is illustrative of the potential for major breakthroughs in scientific understanding. These breakthroughs will be based on new observational capabilities and predictive models that are integrated to enable new Earth system forecast capabilities.

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. Development of fundamentally predictive capabilities will be based on new understandings that we supported by observational and modeling capabilities that are not now available. Within the solid Earth research area are the examples of developing capabilities to predict changes in sea level, and the consequent effects on coastal zones in terms of their habitability and ecosystems, and the full spectrum of motions of the Earth's surface and subsurface, leading to useful earthquake forecasting. Within the biospheric processes research area are the examples of the availability of water as a global resource, and development of a comprehensive understanding of global biosphere-climate interactions, including the consequent human influences on 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. The following discussion reaches beyond the current program, using these six key examples to illustrate avenues

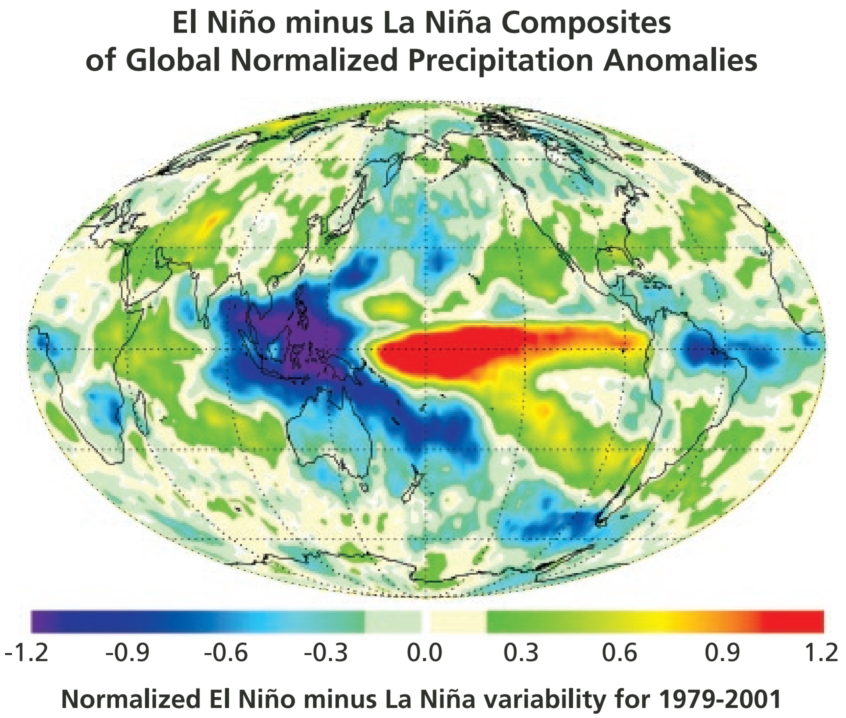


Figure 2.1
Precipitation anomalies associated with El Niño/La Niña. The anomalies (normalized variability) propagate poleward from their western Pacific Ocean origin.

of research that will push the frontiers of understanding, enabling a comprehensive Earth Information System to be realized.

There are important additional Earth science knowledge and predictability topics that are not discussed herein. Examples include 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, and the dynamics of the Earth's magnetic field. These and other important topics will also be addressed in the future program.

2.1 Atmosphere and Oceans

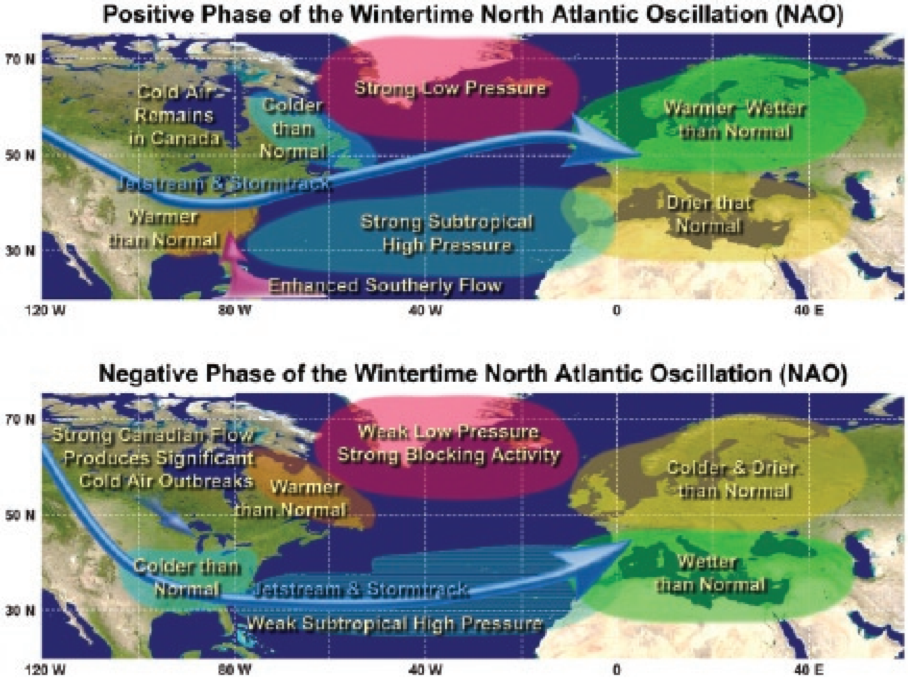
2.1.1 Climate and Intra-Seasonal Predictability

Science Knowledge and Capability

The Earth weather and climate system is driven by solar radiation, by the Earth's radiation budget, and by the motions of the atmosphere and oceans. In the most simplistic view, the Earth's climate system results from the process by which the planet redistributes solar energy. This redistribution involves moving large amounts energy, both sensible and latent heat, from the tropics to mid and high latitudes, and to higher altitudes where it is radiated to space. In addition to moving heat around the planet, the atmospheric motions distribute fresh water over the land, and result in the variability of weather and short term climate.

The many processes that affect the Earth's radiative balance and the energy transport process have impact upon climate prediction. These processes can be very subtle, and some have only recently become evident as observational data sets have improved. For example, there is an increasing appreciation for the importance of aerosols in affecting the radiative balance, and thereby precipitation and the hydrological cycle. There are complex connections between land ice, sea level, and oceanic circulations that link back to climate.

The whole system has many complex interactions, including anthropogenic forcing, and is highly nonlinear. Its predictability is therefore severely limited by the complex interactions between processes and temporal-spatial scales, and by the


Positive Phase of the Wintertime North Atlantic Oscillation (NAO)

Negative Phase of the Wintertime North Atlantic Oscillation (NAO)

Figure 2.2 The positive and negative phases of the North Atlantic Oscillation. These persistent, large-scale weather oscillations change the jet stream and storm track, thereby affecting regional weather in Europe and North America.

difficulty in observing and modeling the complete system. The theoretical limits for climate predictability are therefore not clear. Forecast model deficiencies can be attributed to three general problems:

- inadequate observations used to initialize the climate models,
- the need for improved simulation of key processes and the interactions between these processes (e.g. snow-ice cover, air-sea exchange, ocean evaporation, clouds, aerosol transport, etc.), and
- low model resolution caused by inadequate computational power.

The problem of inadequate observations is particularly important for the ocean models, because as mentioned above, the spatial scales for oceanic processes are small and the temporal scales for oceanic evolution are much longer than for atmospheric evolution thus having a strong influence on medium-term climate predictions.

The present approach to climate forecasting deterministically integrates the governing equations for the Earth system forward in time to predict future climate changes. These equations are highly nonlinear, and since neither the models nor the observations are perfectly accurate, and since the observations are not adequately distributed in space and time, these deterministic predictions cannot be depended on for "weather" forecasts, i.e., for instantaneous states beyond a certain period of time (about two weeks for large-scale weather phenomena). There is however, hope for climate prediction with the same deterministic models. As these models are integrated forward in time, the model climatologies eventually dominate the forecasts (i.e., the climatology of the forecast becomes independent of the initial conditions). These climatologies may, or may not, accurately reflect Earth's climatology, depending on the validity of the physics and numerical representations within the models. The research challenge is to improve the models through comparison of the climate predictions with observations, and also through comparisons of the components of the model output, such as the water and energy cycles, with satellite and other data, and through detailed examination of the underlying model physics and forcing functions.

Predictive Goals — Short-Term Climate

Today	2015	2030
Week to month, short-term climate predictions have little skill.	Initial success in forecasting short-term climate.	Short-term climate predictions have useful accuracy over week to month time periods.
First steps taken linking weather and climate to forecasts of flooding, crop and disease. First steps taken toward understanding of causative factors for El Niño occurrence.	Short-term climate predictions link to forecasts of adverse weather, flooding, crop, and disease outbreaks. Past El Niño occurrences can be reproduced, and experimental forecasts are routine.	Short-term climate predictions are sufficiently accurate that predict societal and economic decision-making. Routine 15-20 month El Niño prediction.
Predictions of annual rainfall on regional scales are based on climatology and persistence.	Useful predictions of annual rainfall on regional scales based on climate predictions.	Routine global forecasts of annual rainfall on regional scales accurate enough for agriculture and commerce.
First steps taken toward understanding of decadal climate variability.	Causative factors for decadal climate variations understood.	Routine decadal climate forecasts with useful accuracy.

Table 2.1 Short-term climate prediction goals enabled by an Earth Measurement and Modeling System by the year 2030.

Table 2.2
Key climate measurement needs that will be required as part of an Earth Measurement and Modeling System by the year 2030.

Measurement Needs — Short-Term Climate

Measurements	Frequency	Horizontal Resolution	Precision/Accuracy
Ocean evaporation rate	Daily	10 km	5 %
Ocean mixed layer depth	Weekly	10 km	10 %
Sea Ice thickness	Monthly	5 km	5 cm
Soil Moisture	Daily	< 1 km	10 %
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly To Weekly	< 1 km	NA
Stream flow	Daily	NA	10 %
Aerosol distribution and absorption properties	Hourly	< 1 km	10 %
Atmospheric ozone	Hourly	1 km (vertical)	5 %
Carbon dioxide and methane	Hourly	1 km (horizontal)	1 % (column)
Atmospheric gases	Hourly	1 km (H & V)	1-10 %

The prediction characteristics for climate variables are not specific forecasts, but statistical assessments, such as expected mean temperature, or mean precipitation, or the expected variance of these quantities. Even more useful is the generation of a Probability Distribution Function (PDF) for climate variables, from which the mean, the variance, and higher order moments can be derived.

There are many practical and useful applications of successful climate predictions. For example, subtle climatic shifts in storm tracks may increase the frequency of hurricane landfall, or episodes of beach erosion, excessive precipitation, or drought. Communities can use climatic predictions of periods of anomalous temperature or rainfall for energy and water management. In the last 20 years, analysis of the atmospheric and ocean database has led to the realization that outside of seasonal fluctuations, a significant portion of the climatic variation can be explained by the existence of characteristic climate patterns of variability. Prominent examples include the El Niño-Southern Oscillations (ENSO), which is now known to have a strong influence outside the tropics (Fig. 2.1), the North Atlantic Oscillation (NAO) (Fig. 2.2), the Pacific Decadal Oscillation (PDO) and the Madden-Julian Oscillation (MJO), among others.

A review of the present climate prediction capabilities and goals for 15 and 30 years from now, reveals a number of important areas of research that can be expected to produce important results of practical benefit to society. These short-term—week to seasonal—climate prediction goals are summarized in Table 2.1.

New Measurement Goals

Satellite measurements play an important role in understanding the climate. Many of the needed measurements for a climate observing system now exist and are planned to continue under the NPOESS and Global Precipitation Mission (GPM) programs. From the climate data users perspective, particular attention needs to be paid to the calibration and continuity of the satellite measurements. It is far cheaper and easier to plan for good calibration of multi-satellite measurements than it is to develop a calibrated data set long after the observations are taken. This issue is exemplified by the long struggle to calibrate the inter-satellite Microwave Sounding Unit (MSU) data in the search for global warming signals.

Figure 2.3
The ability to forecast tropical cyclogenesis—the initial transition of a disturbance into a tropical storm—is poor, and few observations are made of the causative atmospheric and oceanic processes. Accurate prediction would save many lives and mitigate economic damage.

Some of the new needed spaced-based measurements for short-term climate (Table 2.2) are in the queue for the near term (e.g., ocean salinity), but there are a number of new measurements needed that have not currently been considered. They include ocean mixed layer depth, ice sheet thickness, ocean evaporation and precipitation rate, soil moisture, stream flow, aerosol amounts, and aerosol absorption properties. For long-term climate estimates, measurements of the thermal-haline circulation, aquifer water storage, and soil carbon reservoirs are needed. Technologies that can obtain these measurements from space need to be investigated and developed.

New Modeling Goals

Community experience with coupled ocean-atmosphere-land models suggests that much higher resolution models are required to capture the subtleties of ocean heat transport, cloud processes, air-sea exchange, land hydrology and ice, and trace gas and aerosol transport. Credible climate models of the future must resolve the underlying physical processes, and hence will be required to run at 1/4° (~25 km) resolution for the atmosphere and 1/10° (~10 km) resolution for the ocean, improving over the current capabilities of 2° and 1/3°, respectively. Using current model formulations, this will require a more than 10^3 increase in computer speed.

2.1.2 Extreme Weather

Science Knowledge and Capability

The everyday variation of weather is one of the most evident aspects of the Earth system. Accurate prediction of the weather, particularly extreme weather, provides high value to the general public and to decision makers from all sectors of modern society. Today's weather prediction capabilities provide an excellent example of the application of NASA-developed technology and scientific knowledge that is being used by operational entities for the public benefit. It is anticipated that the useful range of medium-term weather forecasts can be doubled from those of the present, and for some phenomena, the useful prediction time can be much more than doubled. Table 2.3 lists some specific weather prediction goals for the next 10 to 25 years as inferred from recent NASA and NOAA planning documents.

Each of the forecast improvement goals listed in Table 2.3 is achievable, and will enable major reductions in the cost and disruption to human activities. Improvements in weather forecasting are a national priority, with significant international importance. Decisions with large economic impact are routinely influenced by weather expectations, including agriculture, utilities, construction, transportation, etc. It has been estimated that $500 million per year could be saved in commercial aviation fuel costs if wind fields over the oceans were more accurately known. Less frequent decisions with similar cost impacts-such as evacuation of coastal areas in the event of an impending hurricane-are felt worldwide.

The primary NASA role is to develop the technology for obtaining and validating the measurements necessary to achieve such prediction goals, and to develop the scientific understanding to permit improved predictive capabilities through better modeling and data assimilation. The activities that perform this function are called Observing System Simulation Experiments, or OSSEs. Through the use of models and simulated future observations, an evaluation is made on the relative value of various observations and their requirements (such as accuracy or coverage). This effort is generally performed in cooperation with the National Weather Service, and with the international community.

The Earth Science Vision effort has addressed the prediction of tropical cyclones (hurricanes), specifically their genesis, growth, and tracking, as the highest priority extreme weather topic. This selection is made on the basis of the needs for fundamentally new observational and modeling capabilities, new science understandings, and on the basis of the huge worldwide human and ecological impact of hurricanes and tropical storms. NASA technology and scientific knowledge (translating into advanced techniques) provide the needed capability improvements for operational applications.

The three key tropical cyclone issues are the predictability of storm formation, intensification, and track. Since tropical cyclones are long-lived, coherent vor-

Table 2.3 Weather predictive goals that will be enabled as part of an Earth Measurement and Modeling System by the year 2030. The Accuracy statistics are based on National Weather Service, Science and Technology Infusion Plan (NWS, 2003).

Predictive Goals — Weather

Today	2015	2030
3-day forecast at 93% accuracy	5-day forecast at > 90% accuracy	7-10-day forecast at >90% accuracy
3-day rainfall forecast not achievable	3-day rainfall forecast routine	7-day rainfall forecast routine
Winter storm forecasts provide 13 hours advance warning	Winter storms forecast 20 hours in advance	Winter storm forecasts >>1 day, with probabilistic guidance to 10 days
3-day regional, severe local storm forecasts have low-to-moderate confidence	5-day regional, severe local storm forecasts have moderate confidence	7-day regional, severe local storm forecasts, have moderate-to-high confidence
Thunderstorm occurrence (convective initiation) predictable to 16 min	Thunderstorm occurrence (convective initiation) predictable to 22 min	Thunderstorm occurrence (convective initiation) predictable >1-4 hrs
Tornado forecast lead time 12 min	Tornado forecast lead time 18 min	Tornado forecast lead time 60 min
Flash flood forecast lead time 47 min	Flash flood forecast lead time 1 hour	Flash flood forecast lead time 4 hours
Hurricane landfall forecasts accurate to 125 nm at 2 days	Hurricane landfall forecasts accurate to 90 nm at 2 days	Hurricane landfall forecasts accurate to 75 nm at 3 days
Hurricane intensity forecasts accurate to 16 knots at 2 days	Hurricane intensity forecasts accurate to 12 knots at 2 days	Hurricane intensity forecasts accurate to 9 knots at 2 days
Air quality day by day	Air quality at 2 days	Air quality at 7-10 days

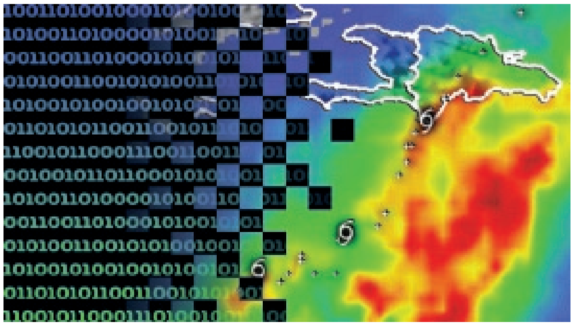


Figure 2.4
Incorporating recent data into models to predict complex weather phenomena is computationally intensive.

tices, they potentially have predictability limits that are significantly larger than for most mesoscale phenomena. Realization of this potential for predictability depends critically on our ability to observe the structure of the vortex and its environment, to assimilate this information into numerical models, and to adequately represent the scales of motion and the physical processes in the models.

Our ability to forecast tropical cyclogenesis—the initial transition of a disturbance into a tropical storm—is poor because of the lack of observations and of knowledge concerning the formation. Only a very small percentage of tropical disturbances develop into tropical cyclones. Significant observational, theoretical, and numerical modeling work is necessary to characterize the environmental conditions and internal structures that lead to cyclogenesis and to distinguish the characteristics of these few storms from those of the many that never undergo cyclogenesis.

Once a tropical storm forms, one of the most desired forecast capabilities is the prediction of storm track, particularly the timing and location of landfall. In the past 30 years, the 48-hour track forecast error has improved by about 2 percent per year, with the track error decreasing from about 250 nautical miles in 1970 to about 130 nautical miles in 2000. In the next 20 years, with currently planned research and observations the track error at landfall is expected to decrease to 100 nautical miles. A significantly greater improvement to 60 nautical miles or better would be possible if more accurate and detailed knowledge of the wind field through the troposphere over the ocean were available. Table 2.3 actually represents a compromise between these two expectations.

The prediction of tropical cyclone intensity has proven to be far more difficult than track predictions. Over the past 25 years, the 48-hour intensity error, mea-

Measurement Needs — Weather

Measurements	Frequency	Horizontal Resolution	Precision/Accuracy
Tropospheric wind profiles (20 levels in troposphere)	3 Hours	5 km	1 m/s per horizontal component
Wind vectors within storm systems (20 levels in troposphere)	1-3 Hours	5-25 km	3 m/s per horizontal component
Temperature and water vapor profiles in clear air (20 levels in troposphere)	1-3 hours	5 km	<1° C, T & Td (dew point T)
Temperature and water vapor profiles within storm systems (20 levels in troposphere)	1-3 Hours	5-25 km	<1° C, T & Td
Surface precipitation 3-D precipitation structure	Hourly	5-25 km	5-10 mm/h
(20 levels in troposphere)	3 Hours	5-25 km	5-10 mm/h
Ocean mixed layer depth	Weekly	10 km	10%

Table 2.4
Key extreme weather measurement that will be required as part of an Earth Measurement and Modeling System by the year 2030.

sured in terms of a storm's peak wind speed, has decreased by only about 3 knots (from about 18 knots in 1975 to 15 knots by 1999). Tropical cyclone intensity is affected by many factors including the underlying sea surface temperature, environmental influences such as vertical wind shear and trough interactions, and internal processes such as convective bursts and lateral eddy mixing by vortex Rossby waves. These processes span a wide range of spatial and temporal scales. Improved forecasting of intensity change requires improved understanding of the external and internal storm processes contributing to intensity change, improved observations of the storm and its environment, improved data assimilation, and development of highly sophisticated numerical forecast models.

New Measurement Goals

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 in the past decade. Such measurements need to be continued and improved. In addition, routine sounding of temperature and moisture in clear and cloudy areas is needed. Experimental use of rainfall data from the Tropical Rainfall Measuring Mission (TRMM) has shown great promise. It is presumed that precipitation data from the Global Precipitation Mission (GPM) will be routinely used to improve tropical cyclone forecasts. Clear-air soundings of temperature and moisture at high spatial and temporal resolution from the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) and its follow-on will be utilized within the decade. However, to meet the prediction goals for 2030, additional new measurements will be required (Table 2.4) beyond the current observational plans. The measurements giving the greatest impact, as determined by OSSEs, are tropospheric wind profiles. New technologies will be required to meet these measurement needs.

New Modeling Goals

Even with significantly improved observations, improved forecasting of tropical cyclones will require significantly more realistic numerical models with much finer horizontal and vertical grid resolution. Because of the critically important interactions between the storm and the underlying ocean surface, as well as the roles of boundary layer turbulent mixing, cloud microphysics, and latent heating, future numerical modeling systems must include:

A) Coupled ocean-atmosphere, high-resolution models with:

   1) Nested grids capable of resolving large eddy structures of storms;

   2) Sufficiently detailed explicit treatment of cloud and precipitation microphysics;

   3) Fully coupled ocean model with evolving ocean and wave structures;

   4) Accurate surface interactions and fluxes, including sea spray;

   5) Rapid and accurate mesoscale data assimilation.

B) Ensemble modeling systems that provide information on the range of variability in the expected forecasts (thus providing probability forecast information) and allow for rapid model improvement and improved mesoscale data assimilation:

   1) An evolutionary approach, applied over a large range of grid scales, will enable good models to survive, while poorly performing models either improve or are eliminated.

   2) Super-ensembles of numerical models will use information on model errors from a collection of independent models to produce an ensemble forecast superior to any of the individual model forecasts.

2.2 Solid Earth

2.2.1 Sea Level

Science Knowledge and Capability

Over the last several thousands of years we have been fortunate to live in a time of relative global sea level stability, but there is evidence that global sea level began rising in the middle of the 19th century at a rate that is about an order of magnitude faster than in the previous several millennia. If further global warming occurs in the 21st century, the world's coastal regions will be heavily impacted. Sea-level change results from complex interactions between the oceans, the cryosphere, the land hydrology, the atmosphere, and the solid Earth. A recent estimate places roughly 34% of the world's population within the first 100 m above sea level, with population density increasing exponentially towards the coast. More than 100 million persons live within one meter of mean sea level. In addition, coastal salt marshes and mangrove swamps, critically important ecological communities for their biological diversity and the protection they provide to coasts, will be severely impacted by increasing sea level. Currently, global sea level is projected to rise on average by tens of centimeters over the 21st century, more than double the rate of the 20th century. Local change, however, will be much larger in some critical coastal areas, such as the Gulf Coast of the United States. Where the rise is slow in human terms, mitigation strategies can be implemented to lessen its impact. Accurate measurement and prediction are keys to designing effective mitigation strategies, but there is great contention over the 20th and 21st century rates of sea-level rise and its regional variability making an intensive research program essential.

Figure 2.5
The potential rise in sea level caused by melting of the Greenland ice sheet would seriously jeopardize low-lying areas such as the Florida coast. Red shows where land would be submerged for an estimated 5-m sea-level rise.

There is clear evidence in the paleoclimate record that ice sheets can rapidly disintegrate, likely due to abrupt changes in oceanic thermohaline circulation. While thermal expansion of the oceans in a warming climate can be predicted with some certainty—and will definitely be a significant contribution to sea-level rise—the fate of the massive polar ice sheets is poorly understood. Indeed, at present it is not known whether the vast Antarctic ice sheet is growing or shrinking. Yet, these reservoirs

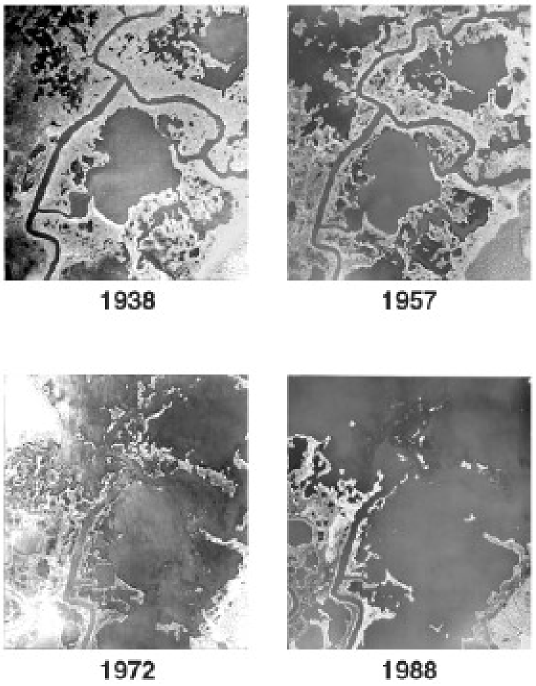


Figure 2.6
Aerial photo sequence spanning 50 years shows the progressive drowning and loss of coastal marshes in Maryland due to sea-level rise relative to local land.

hold the equivalent of meters of ocean volume (Figure 2.5) and might undergo rapid decadal changes, making their study a priority for enabling long-term sea level predictions.

Sea-level change is a highly interdisciplinary area of inquiry. At present, there is considerably less uncertainty and debate about the current rate of sea-level rise (1-2 mm/yr), than about its partitioning into different components (ocean, ice, solid Earth, hydrosphere, atmosphere, other) where sufficient observations are lacking. In order to build new predictive capabilities it is crucial to improve our determination and understanding of current sea-level rise and its contributing components.

Quantifying and predicting sea-level change, and understanding its causes, is a critical component of the NASA mission to understand and protect our home planet. Accurate estimates of rates of sea-level change, and spatial variability in that change, are critical to guide policies aimed at mitigating the effects of sea-level, quantifying changing vulnerability to severe storms, and preparing for long-term change in coastal regions. Such long-term change is seen in the Chesapeake Bay region (Figure 2.6), where local sea level rise has occurred over the last few decades. The highly interdisciplinary nature of the sea level question also supports the argument for an EIS that links the climate system, solid Earth, and biosphere into a dynamic interactive system.

Components of Sea-level Change and Future Prediction

The main contributors to sea-level change are: mass changes in the cryosphere (Antarctica, Greenland, and mountain glaciers), thermal expansion of the oceans, haleosteric (salinity) change of the ocean, atmospheric loading, ground water redistribution, liquid water retainment in land reservoirs, and post-glacial rebound or other types of crustal deformation processes.

The steric change (thermal expansion and salinity) of the oceans is believed to have contributed 0.6 mm/yr sea-level rise over the last half century. At the same time, satellite and in-situ measurements have demonstrated large decadal, interannual and spatial variabilities, the need for global, sustained monitoring strategies of the ocean surface over several decades in order to improve current estimates. A warming climate is expected to greatly increase the thermal expansion of the ocean and rate of sea-level rise over this century. Radar altimeter missions including: Geosat, European Remote Sensing [ERS]-1, TOPEX/POSEIDON, ERS-2, Geosat Follow On (GFO), Jason, ENVISAT, Cryosat, NPOESS will provide decadal and near-global measurements for accurate quantification of sea-level change.

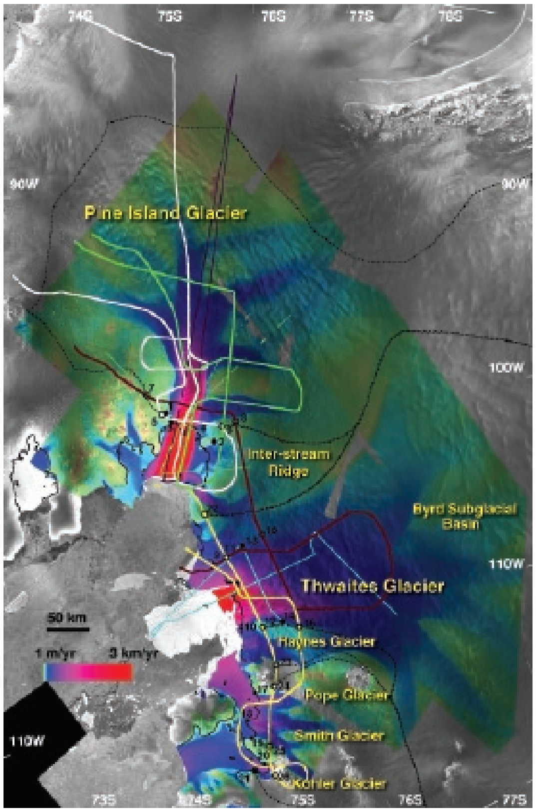


Figure 2.7
Mosaic of ice velocity of the in West Antarctica derived from InSAR data. Ice discharge from these glaciers significantly exceeds the mass input from snow accumulation, sea level rise. Recent InSAR data show that the outflow from Pine Island Glacier and Thwaites Glacier is accelerating.

Sea level has varied most significantly over the past million years in response to the waxing and waning of ice sheets, where

5% of the global water supply was stored as ice just 20,000 years ago. Thus, ice is likely to continue to influence sea level in major ways as climate changes. Presently, mountain glaciers have been estimated to contribute 0.3 to 0.5 mm/yr sea-level rise (recent evidence suggests even more); Less is known about the Greenland and Antarctic ice sheets. Much of the predictions of the future evolution of these ice masses in a changing climate will depend on how well we can understand the sequence of events taking place in West Antarctica and in the Antarctic Peninsula at present. The combination of GRACE, CHAMP (CHAllenging Minisatellite Payload), ICESat, Cryosat and GOCE (Gravity Field and Steady-State Ocean Circulation) missions should significantly improve our knowledge of the rate of mass loss from the polar ice sheets. Yet, a detailed understanding of these observations will require widespread interferometric synthetic aperture radar (InSAR) measurements of surface motion (example shown in Figure 2.7), lidar/radar altimetric height, ice thickness surveys, and targeted insitu measurements.

Land-ocean-ice sheet mass fluxes result in loading and unloading of the solid Earth. Part of the solid Earth deformation is purely elastic, resulting in an instantaneous response to changes in mass flux. Another part of the solid Earth response is viscoelastic deformation, characterized by changes over centuries to millennial time scales and over broad 1000-km or greater spatial scales. The viscoelastic response to past ice sheet mass changes (post-glacial rebound) must be understood in order to isolate the more subtle deformation associated with the instantaneous elastic response. GRACE and ICESat will vastly improve models of post-glacial rebound, especially over Antarctica, while future InSAR and ultra-precise time-varying gravity missions will monitor tectonic deformation causing coastal uplift or subsidence, including groundwater and oil extraction. Precise knowledge of post-glacial rebound and neotectonic motion is needed to determine the present-day mass changes of ice sheets, and the correction of tide gauges for crustal motion, thus improving the determination of sea-level rise.

The long-term vision is to determine ice mass change, ocean volume change, the hydrologic cycle, and solid Earth deformation in a calibrated sense that will allow precise and accurate determination of trends in system variables, leading to a reliable prediction capability. These predictive goals are outlined in Table 2.5. This requires improvement in existing measurement systems, invention of new systems, and the development of coupled models to interpret the observations in a way that will lead to a predictive capability.

Predictive Goals — Sea Level

Today	2015	2030
Knowledge of significant contributors to sea level rise (ice sheets and glaciers, coastal change, crustal rebound, steric effects)	Ice sheet state, evolution and dynamics understood	Accurate 10-yr and longer regional sea level prediction, including impacts on coastal erosion, coastal ecosystems and fresh water availability
Rudimentary knowledge of short-term ocean volume changes	Oceanic expansion is understood and tied to short-term climate prediction models	
Regional variability poorly understood	Variable coastal response to sea level change understood	
Rudimentary knowledge of adaptability of coastal ecosystems to changing sea level	Impact of sea level change on coastal region habitability coming into focus	

Table 2.5
Key sea level predictive goals that will be enabled as part of an Earth Measurement and Modeling System by the year 2030.

New Measurement Goals

To measure sea-level change and to understand and predict future changes will require sustained observations with increasing accuracy, plus a methodology and data system operational prediction capability. The measurements (Table 2.6) must be sustained in a highly calibrated sense, and for long periods of time, in order to sample all the relevant time scales of the processes. The measurements must also be absolutely calibrated so that trends in the time series can be confidently interpreted. The maintenance and improvement of the geodetic reference frame is thus required. Predicting future sea-level change requires short- and long-term climate prediction to quantify the steric sea-level change. Thus, high-resolution sea surface height, temperature, and ocean salinity measurements are needed; these should be routine in the 2030 time frame.

New Modeling Goals

There are two types of models needed to analyze the trends in variables contributing to sea-level rise. The first type of model needed seeks to measure, understand, and predict mass redistributions on the Earth, and predict relative sea level (the sum of sea-level and coastal height changes). Such a model integrates high spatial-resolution InSAR and imaging lidar measurements at frequent repeat interval with gravity change to derive mass changes and solid Earth deformation.

The second type of model seeks to understand and predict volume changes in the ocean and regional perturbations in the shape of the ocean surface (a feedback with the derived mass redistributions). This modeling effort is the same as that

Table 2.6 Measurement needs for sea level change that will be required as part of an Earth Measurement and Modeling System by the year 2030.

Measurement Needs — Sea Level

Measurements	Frequency	Horizontal Resolution	Precision/Accuracy
Ocean/Ice Mass Redistributions (gravity change)	Monthly	100s-1000s km (scale of drainage basin)	0.1 mm/yr sea level rise equivalent
Ocean altimetry	Weekly	open ocean: 50 km coastal: 5 km	1 cm absolute, 0.1 mm/yr rate
Bathymetry	Once	5 km	1%
Ocean mixed layer depth	Weekly	10 km	10%
Coastal zone topography	Monthly	2-5 m pixels	<10 cm (height)
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams - ice sheet)	1 cm (height)
Ice Sheet dynamics	Monthly	100 m	1 m/yr (rate)
Ice Sheet Bed Characteristics	10 Years	100 - 1000 m	Bed topography to <10 m
Crustal Deformation (uplift/subsidence)	Daily To Weekly	10 m	1 cm (range) 0.5 mm/yr (rate) on annual basis
Soil Moisture	Daily	< 1 km	10%
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equiv.
Reservoir and Aquifer	Monthly	Scale of storage basin	0.1 mm/yr sea level rise equiv. Impoundment

needed for medium-term climate forecasting, and indeed steric sea-level rise is an outcome of the medium and long-term climate modeling effort within the EIS framework. The contribution of vertical mixing to sea level and general ocean circulation could be assessed with improved knowledge of bathymetry (accuracy and spatial resolution).

The goals of the modeling effort are to produce 10- to 30- year forecasts of sea-level rise, on global and regional scales. These forecasts will be evaluated and updated annually, and split into contributions from ocean volume changes (tied to climate forecast), and mass redistributions (mainly ice sheet mass changes and coastal uplift/subsidence). Uncertainties of the short-term (1-5 year) forecast should be at the 10% level of accuracy, and longer-term forecasting should be at least 30% accurate. The projected changes in ice sheets will feed back into the climate forecasts within the dynamic EIS, allowing the predictive model capability to respond to evolving conditions. A further goal must be to determine more accurately the response of the land-water boundary to increases of sea level. Coastal erosion appears to take place at a rate about two orders of magnitude greater than the vertical rate of sea-level rise; thus, any increase in the rate of sea-level rise will exacerbate the already critical erosion occurring globally. In addition, coastal marshes are already drowning in many areas (see Figure 2.6) because the plants cannot keep up with rising water levels. Migration and loss of coastal marshes will have a severe impact on ecosystem health and the services that humans derive from it. These issues will be elucidated within the EIS framework and allow an integrated, multi-faceted strategy to be developed to mitigate the effects of sea level rise.

2.2.2 Earthquakes

Science Knowledge and Capability

Earthquakes have been observed and studied for centuries. Although numerous methods have been proposed to predict earthquakes, truly accurate and methodical earthquake prediction remains elusive. Developing a reliable forecasting capability is important, for a large portion of the world's population inhabits seismically active regions, including the megacities of Los Angeles, Tokyo, and Mexico City, and heavily populated regions in Asia. Economic losses from a magnitude (M 8) earthquake in California or Japan could top one trillion dollars and have global impact. The 1994 Northridge, California (M 6.7), and 1995 Kobe, Japan (M 7.2) earthquakes resulted in significant economic and infrastructure losses (Fig. 2.8) and devastating loss of life in the case of the Kobe event.

Improved seismic risk analysis, coupled with strict adherence to building codes and disaster mitigation and contingency plans, will help reduce the human and economic losses from future earthquakes. Dynamic earthquake hazard assessments at a range of spatial scales (large and small fault systems) and time scales (months to decades) will

Figure 2.8
A collapsed section of highway from the Northridge, California earthquake. (Courtesy of Robert Eplett, California Office of Emergency Services)

Table 2.7 Predictive goals for solid Earth processes that will be enabled as part of an Earth Measurement and Modeling System by the year 2030.

Predictive Goals — Solid Earth

Today	2015	2030
30-yr probabilistic earthquake assessments	Experimental 5-yr regional earthquake forecasts	Monthly earthquake hazard assessments at scale of major fault systems
Earthquake physics poorly understood	Models of earthquake physics yielding reasonable success in representing observed fault system interactions	Time-dependent models of crustal deformation due to tectonic loading and hydrology
Basic knowledge of the space-time spectrum of crustal deformation	Aseismic and transient strain budget coming into focus	Full spectrum of deformation understood
Daily to weekly volcanic activity warnings	Weekly to monthly volcanic activity warnings	Monthly and longer volcanic activity warnings
Magma dynamics models in development	Evaluation and validation of magma dynamics models to predict eruptions	Impact of potential eruptions on atmospheric composition factored into climate models

allow a more systematic approach to prioritizing the retrofitting of vulnerable structures, relocating populations at risk, protecting lifelines, preparing for disasters, and educating the public. At the same time, the understanding of the earthquake cycle and the assessment and prediction of earthquake hazards (Table 2.7) is a topic of increasing potential for scientific advancement and of social urgency, and long term goals for earthquake prediction can be defined, based on present knowledge and progress.

Fortunately, powerful new tools to observe tectonic deformation have been developed and are being deployed on the ground with encouraging results for improving knowledge of fault system behavior and earthquake hazards. The evolution of ground-based geodetic GPS networks from regional-scale and from dense, continuous networks such as the Southern California Integrated GPS Network (SCIGN) has resulted in significant advances in understanding crustal deformation and seismic hazard. An example of a high-resolution deformation time series from the Cascadia subduction zone in the Pacific northwest is shown in Figure 2.9. Continuous GPS monitoring of a site in North America above the dipping oceanic plate has revealed that deformation, occurring on ~14-month cycles, results from the continuous motion of the oceanic plate attempting to drag the North American plate with it. The build-up of stress (red lines) terminates in a slip event that produces no earthquakes, and hence was not previously recognized. This stress-strain relationship illuminates the nature of the coupling between the North American plate and the subducting Juan de Fuca plate, and improves evaluation of the seismic hazard there. Spatially dense information of this type is needed for all seismically active regions, and

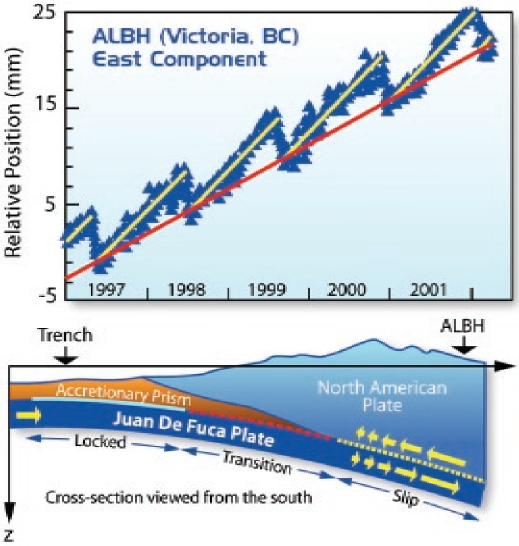


Figure 2.9 14-month stress-strain cycle is observed by GPS at the Cascadia margin. (Courtesy of Herb Dragert, Geological Survey of Canada)

Measurement Needs — Solid Earth

Measurements	Frequency	Horizontal Resolution	Precision/Accuracy
Crustal Deformation	Daily To Weekly	1-10 m	5 mm instantaneous, 1 mm/yr (rate over 10 yrs) accuracy
Crustal Mass Redistributions (gravity change)	Weekly	50-100 km	0.1 milligal accuracy
Subsurface sounding	Weekly	100 m/ 10 m depth	5% saturation

Table 2.8 Earthquake observing system measurement needs that will be required as part of an Earth Measurement and Modeling System by the year 2030.

therefore space-based measurements are critical to achieving major advances in scientific understanding and predictive capabilities. Serendipitous Interferometric Synthetic Aperture Radar (InSAR) images of recent earthquakes from ERS-1 and -2 have demonstrated the power of spatially continuous deformation measurements for measuring earthquake rupture parameters and monitoring transient strain fields associated with post-seismic stress redistribution. Achieving spatially and temporally continuous deformation measurements, coupled with advanced models of fault system interactions, will lead to revolutionary leaps in knowledge of earthquake physics and evaluation of seismic risk.

New Measurement Goals

Surface Deformation

Efforts to advance understanding of earthquake physics require detailed observations of all phases of the earthquake cycle (pre-, co-, and post-seismic), across multiple fault systems and tectonic environments, with global distribution. Systematic measurements of surface deformation with a frequent repeat interval are needed to obtain four-dimensional maps of deformation, continuous in space and time. The sampling of the time series is dictated by the tectonic environment, and should be sub-daily for plate boundary environments and other recognized highly deforming regions, but might be monthly to annually for more quiescent environments. Satellites offer the best way to achieve global coverage and consistent observations of the land surface. While ground seismometer and GPS networks will remain critical, the synoptic view of the deforming crust that is possible using satellite data calls for a global observing system to infer crustal stress. Detailed system requirements for a surface deformation observing system have been determined and are reported in Table 2.8.

Subsurface Sounding

The type of material in the shallow subsurface, and its saturation, affect the ground acceleration experienced as a result of a particular earthquake. Directivity of seismic energy during fault rupture can result in quite different patterns of deformation. Liquefaction, the sudden release of water from saturated, permeable layers, is of particular concern in coastal landfill areas and on steep slopes. Mapping the degree of saturation in the shallow subsurface (Table 2.8) 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. Radar sounders, along with InSAR displacements, can provide data to characterize the subsurface material and its degree of saturation.

Mass Redistribution

Changes in the crust due to stress and strain result in subtle mass redistributions. These signals could be monitored to provide validation and improvement to models of strain accumulation. Gravity measurements accurate to 0.1 milligal (10^{-3}m/s^2) over length scales of tens to hundred km (Table 2.8) would yield significant constraints on the stress field. Gravity changes would also result from fluid flow in the crust and would serve to constrain the sources of electromagnetic or thermal signals.

New Modeling Goals

The underlying stress-strain dynamics of fault systems are generally unobservable, but this obstacle can be surmounted by comparing observations to numerical simulations to test and improve models of fault system behavior. Developing and evolving models of complex fault systems and creating a community modeling environment will be key to exploiting the revolutionary advances in observing capability that are expected within the next 20 years. The goal is to produce earthquake forecasts at the scale of faults and fault systems updated monthly to annually. Capable models will ingest the observations in real time and may adjust the earthquake hazard assessments based on the emerging system behavior. Grid-based computing and data mining are planned attributes of the community modeling environment, as well as dynamic archives of a spectrum of data products. Data systems to provide tailored products in a timely fashion to disaster management agencies need to be developed. While predicting the time, location and size of a particular earthquake will remain elusive, much higher fidelity earthquake forecasts appear within reach, and can be widely disseminated to impact the safety of the general public.

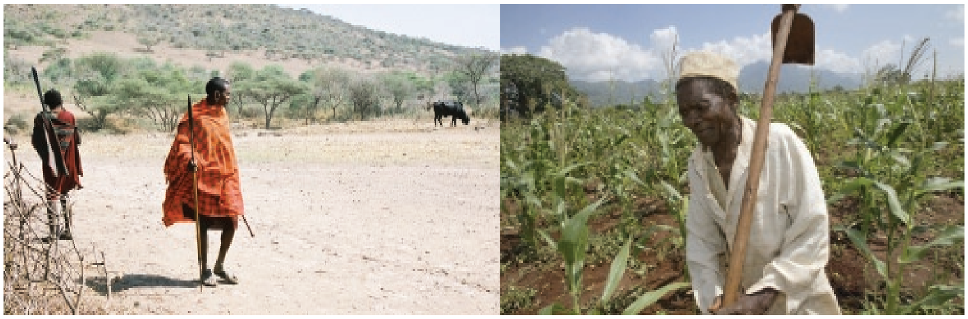
2.3 The Biosphere, Climate, and Human Interactions

The biosphere, the living ecosystems on land and in aquatic environments, the product of billions of years of evolution, is strongly coupled to the climate system, its variability and change. The terrestrial biosphere is currently home to Earth's dominant species, humans, who now appropriate nearly one half of the biosphere's net primary production, and regularly convert entire ecosystems to their (nearly) exclusive use. It is therefore crucial to understand and predict the effects of these human transformations so as to possibly adapt and sustain the living Earth system upon which we depend for our existence.

Greenhouse gases such as carbon dioxide and methane have recently increased in concentration to levels well beyond that for natural processes alone; this increase can largely be attributed to burning of fossil fuels and other human activities. The generation of aerosols, the generation and transport of water vapor, and the surface energy balance, are also strongly affected by the biosphere. Human activities are altering these processes at a staggering scale, through conversion of the ecosystems, excessive fertilization, over utilization, fire, discharge into the oceans, and other processes.

The climate system, in turn, affects the biosphere through changes in precipitation delivery and timing, changes in minimum and maximum air temperatures, changes in cloudiness and surface humidity affecting solar energy at the surface and more. These sources of climate change contribute to a myriad of variations in ecosystems including disruptions in the availability of nutrients and water, ecosystem development or senescence, increases or decreases in carbon exchange, disease patterns, migrations, plant and animal species invasions, and more.

While the understanding of many components of the biosphere is improving, other critical areas are lagging. For example, although human populations are growing in coastal regions worldwide, the ecosystems of the coastal zone—extending from tidal marshes down to 200 meters depth—are poorly understood. Our understanding of ocean biology, an important source of human nutrition, lags due to lack of knowledge of global variations in the ocean mixed layer



Figures 2.10a and b. Fresh water for human use and agriculture is not readily available in many parts of the world today, such as many regions of Africa. It is essential to understand future water availability in light of predicted climate changes. (left photo courtesy of Peter Hildebrand, right photo courtesy of Stig Stasig)

depth, nutrient fields, and even global deep ocean circulation patterns. Our understanding of global land ecosystem health and productivity lags because of, for example, the need for improved knowledge of all aspects of land surface hydrology, including root zone soil moisture, water table levels, snow water storage, runoff rates and storage, of pollution effects, and of the timing of leaf expansion and senescence in individual ecosystems.

By 2030 we expect to have a better understanding of the biosphere, with the ability to predict how the biosphere will respond to the major forces of change. Between now and then, substantial progress will be required to understand how the biosphere and climate interact, including all biosphere components (land, ocean, and coastal zone ecosystems). We will be able to assess the availability of fresh water and the major aspects of the land, ocean, and coastal zone ecosystems. Each of these components has unique and important relationships with the climate system and with human activities and impacts. The following discussion addresses the development of new knowledge for each of these major components of the biosphere, and the new observational and data assimilation and modeling capabilities that will enable new predictive capabilities for a stable ongoing human relationship with our planet.

2.3.1 Water as a Global Resource

The availability of water is an essential component of life on Earth. Truly the water planet, Earth has 71% of its surface covered with liquid water or ice. Of all the water on Earth, approximately 97% is seawater, and 2% is in the polar ice caps and glaciers. The remaining 1% is fresh water, of which only a small portion is available for human use. Mirroring the growth of human population and technology, human use of water for agriculture and household purposes has grown dramatically during the past 50 years. About 70% of human water use is for agricultural purposes, 20% for industrial purposes, and 10% is used for household purposes. Although the state of knowledge of the global water cycle is presently fairly rudimentary (Table 2.9), significant improvements in our ability to predict the availability of water on regional and global scales is expected to improve greatly over the next decade. The requirements noted in (Table 2.9), detail many of the components of the water cycle that will need to be accurately predicted in order to meet the societal needs of a growing population and increasing demands on the availability of water by circa 2030.

The continual availability of freshwater should not be considered to be a future certainty. With the world population increasing by 50% over the next half-century, the demand for fresh water will have a similar increase. It is well demonstrated that short-term climate variability, for example, that associated with ENSO, can strongly alter seasonal climate, thus changing availability of water in North America and around the world. The predicted climate warming and the resulting changes in the hydrologic cycle will have similar effects on the global availability of water. As the demand increases, even the variations in availability of fresh water are becoming

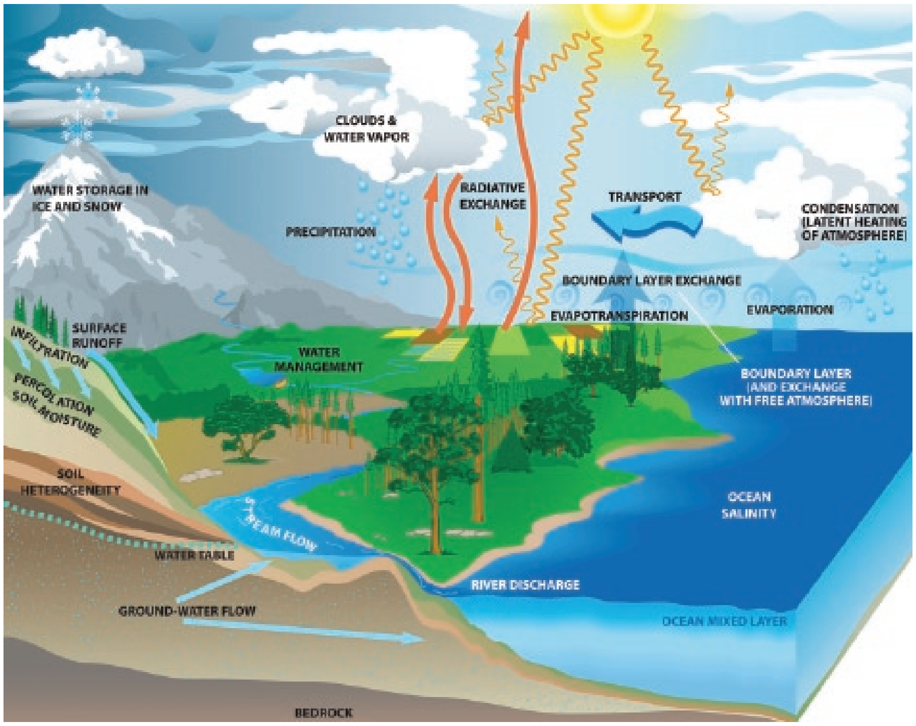


Figure 2.11
The hydrological cycle of the Earth is a complex interaction between the biosphere, oceans, atmosphere, and land.

a growing problem extending to most countries, affecting habitability, the availability of food, human migrations, and consequently, social stability.

By 2030 we will understand and be able to predict the availability of water on regional to global scales (Table 2.9). We will have the ability to forecast changes in the availability of water as may occur due to climate variability and change, or due to the impacts of human activities. This new knowledge and predictive capability for water resources will enable planning for changes in human populations or societal policies and practices. In order to achieve these new capabilities, NASA will work with partner agencies and institutions to develop an array of new observational and modeling capabilities. The needed advances in observational and modeling capabilities will be addressed in the last two portions of this section.

Table 2.9
Predictive goals for availability of water that will be enabled as part of an Earth Measurement and Modeling System by the year 2030.

Predictive Goals — Water

Today	2015	2030
Understanding of the role of clouds and precipitation in weather and climate.	Credible progress towards predicting clouds and precipitation in weather and climate models.	Routine predictions of clouds and precipitation in weather and climate models.
Prediction of land surface state-snow, soil moisture, surface water, evapo-transpiration-at a micro level.	Land surface state can be reliably predicted independently of the weather and climate variability.	Land surface state predictions include linkages to weather, climate and biosphere.
Components of the water cycle understood, but water budget not accurately closed.	Water cycle budget closed on continental-to-global and seasonal-to-annual scales.	Can routinely predict water cycle variability and extreme events on regional and global scales.

2.3.2 The Biosphere on Land and at Sea

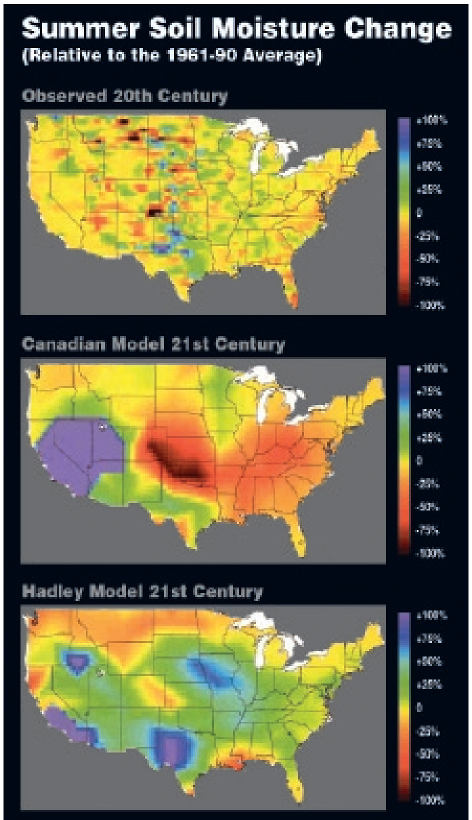
The Earth's biosphere is complex and diverse, and is strongly coupled with the availability of water and the state of the climate. Due to the strong variability of ecosystems, it is most convenient to individually address the important scientific issues relative to the land, the coastal zone, and the open ocean ecosystems.

Terrestrial Ecosystems.

The terrestrial ecosystems are diverse and complex, and although they cover only about a third of the Earth's surface, they are strongly coupled to the climate and weather systems. The health and nature of these ecosystems is highly dependent on the variability of climate and weather processes, particularly in terms of precipitation (kind, timing, intensity, and composition), land surface processes (moisture availability in soil, pollution, invasive species, etc.), the state of the atmosphere (air temperature, humidity, winds), and radiation loading (direct and diffuse components). In recent years, advances in understanding land surface climatology have dominated the research agenda and are making significant progress.

It is on land that the human transformational power is most clearly dramatic and recognized. The singular human power to alter ecosystems rivals that of natural processes. The effects of human activities must be understood, for there are a variety of possible outcomes to changes in ecosystems; some are reversible, some not, some of them are advantageous to human activity, others are serious problems. Among the many important biosphere issues, are the biosphere-climate system linkages and the effects of pollution. As progress is made, the links between solid-Earth processes, sea-level rise, and natural hazards will emerge. Attention can then be devoted to forecasting the myriad of ways in which the aquatic and terrestrial ecosystems respond to changes in forcing (Table 2.10). These understandings will contribute to the formation of sound science policy to sustain the living systems on Earth.

The present scientific attention to the carbon cycle and the role of terrestrial ecosystems is focused on carbon cycling and the controls exerted by water availability. This research addresses our understanding of net carbon exchange, carbon respiration, terrestrial sources and sinks for trace gases, and on the fluxes between the biosphere and the atmosphere. Developments in the near future will allow measurement of carbon storage of above-ground components, of standing biomass, and estimates of soil carbon (Table 2.10). Future research will address the availability of nutrients such as nitrogen, land use change and its consequences, and subtler effects, such as species replacement, disruption of pollination, pollution, land degradation, and toxin buildup.



Soil moisture has tended to increase in the central US with decreases in some localized areas. In the Northeast and in the western third of the country, there has been less change in soil moisture, despite the increase in precipitation, due to compensating temperature increases.

The Hadley and Canadian models project strong increases in soil moisture in the Southwest. For the rest of the nation, the Hadley model projects mostly increases while the Canadian model projects mostly decreases, with large decreases in the Central Plains. The contrasts between the two models result from the combination of greater precipitation in the Hadley model and higher air temperatures in the Canadian model.

Figure 2.12 Observed 20th century changes in soil moisture, and predictions of 21st century changes in soil moisture change from two models. The difference between these two different predictive models illustrates the need for improvement. (Courtesy of Marty Mylnczak)

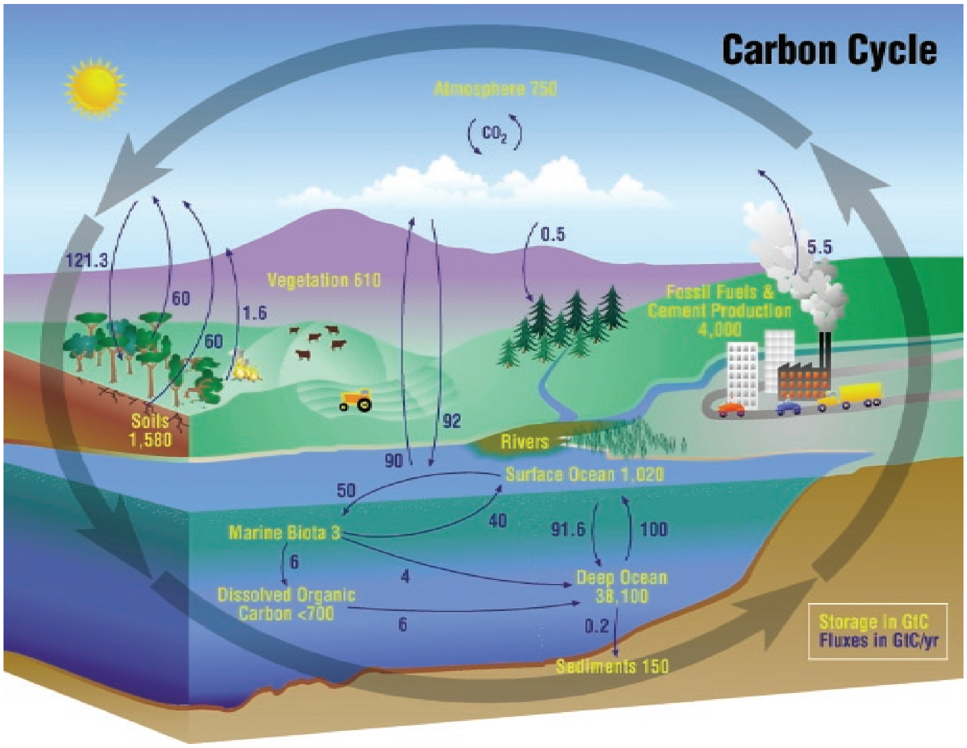


Figure 2.13 The carbon cycle exchanges carbon between elements of the Earth system. The numbers indicate carbon storage (black) and flux (blue).

The coupling of the above-ground ecosystems to those below ground and to the hydrological cycle that redistributes water throughout the landscape is less well understood. At the present time, the quality of simulated land surface quantities, particularly in the hydrologic cycle, is a strong function of the availability of insitu observations. Little capability exists to measure these properties from space. Measurement of the topographic variation of the land surface is now advancing well enough that modeling of hydrologic routing is improving. A key variable for modeling is the wetness of soils in the full root zone, with kilometer-scale spatial resolution. This measurement goal, using a combination of remote and insitu observations plus data assimilative models, will be an important achievement for the next decades.

Coastal Zone

The coastal zone—the components of the land and ocean along the land margins, from wetlands out through the continental shelf—is an area of increasing pressure and human impact. This zone is sensitive to ocean currents, to upwelling events, to precipitation, runoff, and pollution from the land, to exchanges with the freshwater systems in estuaries. The coastal zone is also a main source of food for humans, as it is easily accessible and has unusually high biotic primary production, relative to the open ocean (about 25% of total oceanic net primary productivity occurs in the coastal zone, which has only 6% of the ocean surface area). Coastal zone wetlands are also a major source of trace gases, especially methane.

While some existing satellite sensors observe this narrow and highly dispersed region, such data were never optimized for coastal zone observational problems, such as the turbid waters, bottom signals, the high spatial and temporal variability, the small spatial scales, and the high biodiversity. By 2030 we will have developed the needed suite of high resolution sensors and the predictive capability needed to address these problems. Many of the required measurements are those of the land or open ocean, but here the extremely high spatial variability places highly stringent demands on the spatial resolution of the measurements.

Predictive Goals — Biosphere-Climate

Today	2015	2030
Observations allow relating net primary production with carbon balance.	Carbon sources and sinks for North America are quantified well enough to allow carbon management decisions.	Prediction of global, high resolution, monthly carbon exchange by oceans, coastal zone, and terrestrial biosphere
Accurate characterization of annual biogeochemical cycling and biospheric processes in ocean and terrestrial models based on remote sensing data.	Understand the effects of land use recovery on carbon balance, including explicit understanding of biomass, soils, and coastal zone.	Capability to understand and predict the natural regulatory controls on biosphere processes.
Teleconnections between climate variability and ecosystem response understood on a statistical basis.	Capability to forecast ecosystem response to climate and weather variability on interannual and longer time scales.	Capacity to forecast ecosystem response to human influences on biosphere-atmosphere exchanges.
Capability for coarse resolution, global net primary production modeling.	Capability for ecosystem-specific, carbon management modeling and forecasting.	Capability to model fine space and time scales of biosphere response to climate variation (adequate for public applications).

Table 2.10 Predictive goals for the biosphere-climate interactions that will be enabled as part of an Earth Measurement and Modeling System by the year 2030.

Open Ocean

The knowledge of the state of the biosphere and carbon exchange processes at the surface of the open ocean is advancing fairly well. Recent satellite launches provide key global observations at the appropriate temporal and spatial scales, including sea surface temperature, height, and winds; ocean circulations; and biological indicators such as PAR irradiance, fluorescence, and pigments. These data are already used both in fisheries activities and in the regulatory arena for evaluation of fishing stocks on regional through global scales. Improvement in this arena is important due to our dependence on the products of the open ocean (mainly the top of the food chain, fisheries) and the increasing threat from over fishing, pollution, increased ultraviolet radiation due to ozone depletion, and sea temperature rise due to global warming.

By 2030 we will have added measurements of the oceanic characteristics, nutrients, aerosol deposition, mixed layer depth, and functional groups of organisms. Measurement and accurate prediction of oceanic thermo-saline circulation variability will provide a key to understanding the sudden seasonal changes in climate that have profound consequences for land and coastal zone ecosystems. The contribution of the open ocean to the carbon cycle in terms of net primary production and sequestration into the long-term slow pools of settling carbon will be well in hand, once these missing variables can be added.

New Measurement Requirements

In order to achieve the water cycle, biosphere and human interaction goals, major aspects of the global water cycle and of global biotic activity will need to be observed. Many of the required measurements are listed in Tables 2.11 and 2.12, along with the required update rate, the horizontal resolution on the Earth surface, and the precision of the measurement. Many of these same measurements are required for other long term science goals. Seemingly a tall order, strong present steps towards most of these measurements assure realization of this goal. These broad observational capabilities will include global precipitation and evaporation on land and at sea, water vapor transport in the air and clouds, oceanic circulations and air/sea boundary layer effects including sea ice, polar ice and melting processes, land surface fluxes and storage, subsurface water storage and flow, freeze/thaw conditions, and ecosystem health. For some types of measurements, e.g., soil type, there may never be practical global observational capabilities. There, innovative combinations of insitu observations, plus global remote measurements coupled with new modeling approaches, may meet the needs of predictive models.

These observations (Tables 2.11 and 2.12) must all be made at the spatial/temporal resolution and with the precision required by the geophysical processes being observed and forecast. Given the needs for precise measurements, remote measurements from satellites will be calibrated against insitu sensors on the ground or in the air, using data assimilation models that assess the measurement characteristics of each instrument. By 2030, new approaches to data assimilation will use diverse measurements at a variety of scales to sharpen the spatial and temporal resolution of the measurements in question. For example, although global remote measurements of soil moisture through the root zone may be made at too coarse a scale due to instrumental limitations, higher resolution knowledge of surface wetness, precipitation history, soil type and of other variables may enable clever data assimilation models to calculate the needed measurement.

These observations, coming from the network of new sensors, will directly feed into a global network of computers upon which models of the Earth system run continuously. A key focus of this future computational and predictive capability will be analysis of all components of the full water cycle down to a local level. This local level would correspond to the needs of a nation, a community or an in-

Table 2.11 Global water measurement needs that will be required as part of an Earth Measurement and Modeling System by the year 2030.

Measurement Needs — Water

Measurements	Frequency	Horizontal Resolution	Precision
Crustal Deformation	Daily To Weekly	1-10 m	5 mm instantaneous, 1 mm/yr (rate over 10 yrs) accuracy
Soil Moisture	Daily	< 1 km	10 %
Precipitation	Hourly	5-25 km	5-10 mm/h
Stream flow	Daily	100 m	10 %
Sea Ice thickness	Monthly	5 km	5 cm
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly to Weekly	< 1 km	NA
Ocean evaporation rate	Daily	10 km	5%
Reservoir and Aquifer Impoundment	Monthly	Scale of storage basin	0.1 mm/yr sea level rise equivalent
Ice sheet elevation	Weekly	< 1 km	1%
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams - ice sheet)	1 cm (height)

dividual. This capability will improve our ability to forecast regional water availability and to predict areas at risk due to climate change.

Two 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. This capability will enable competitive evaluation of new measurement and modeling approaches, resulting in continual and gradual adoption improved approaches that are more accurate, more efficient, and less costly. Second, long-

Measurement Needs — Biosphere Climate

Measurements	Frequency	Horizontal Resolution	Precision/Accuracy
Mixed layer depth, coastal zone Ocean Nutrient fields (N, Si, Fe), aerosol deposition, functional groups	Weekly Weekly	10-100 m 10 km	10% 30%
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%
Ocean Physiological state (fluorescence)	Daily	100 m	20%
Bathymetry	Daily-Weekly	100 m	10%
Phenological state (leaf out, senescence)	Diurnally	1 km	Less than one day
Biochemical composition of plant canopies (N, lignin, pigments, chlorophylls, etc.) Responses to multiple stressors (long-term)	Weekly	100-200 m	25%
Fire properties (energy release rates, rate of spread, gas/aerosol loading, soil heating)	Daily	100 m	20%
Standing biomass over time	Monthly-Annual	100 m	10%
Vegetation structure, successional state, primary & secondary vegetation condition	Monthly	100 m	20%
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly To Weekly	< 1 km	NA
Aerosol distribution and absorption properties	Hourly	< 1 km	10%
Atmospheric ozone	Hourly	1km (vertical)	5%
Carbon dioxide and methane	Hourly	1km (horizontal)	1% (column)
Atmospheric gases	Hourly	1km (H & V)	1-10%

Table 2.12 Measurement needs for the Biosphere on Land and Sea that will be required as part of an Earth Measurement and Modeling System by the year 2030.

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 to develop an understanding of the causative forces.

The open ocean and the coastal zone share several key variables not presently observed including salinity, mixed layer depth, wind and nutrient fields, aerosol deposition, and biotic functional groups. In general, the temporal resolution is similar for the open ocean and coastal zone, but the required spatial resolution in the coastal zone is much more stringent. The coastal zone has special needs for hyperspectral measurements, plus accurate and stable calibrations. The spatial resolution must be tens of meters or less (as opposed to hundreds in the open ocean). The needed high temporal resolution for some properties may require the use of geostationary platforms and, due to the rapid changes that can occur, a special events imager. Special attention to removal of atmospheric effects for the coastal zone is necessary because simplifying assumptions about upwelling reflectance cannot be assumed.

The terrestrial ecosystems requirement of a long, continuous record of well-calibrated data at appropriate spatial resolution, usually about 100 meters or less, has been a demand of the science community for some time and is being achieved for some variables. Little has been achieved to study diurnal and shorter time resolution characteristics for specific variables. Much of the land mass has such small scale relief that removal of topographic and atmospheric effects is critical. To elucidate the processes of biogeochemical cycles, such as the roles of nitrogen, sulfur and other elements, will require the continued advancement of the difficult problem of remote sensing of biochemical composition and related variables amenable to high spectral resolution sensors and the ability to make repeat observations on a reasonably short time scale, monthly. An ability to measure such properties as phenologic state—i.e., the time of leaf bud burst and expansion, as an indication of the growing season being initiated as well as senescence—may be dependent on a satellite with virtually constant whole disk observation. Measurement of land disturbance and its recovery (fire effects, land succession and trajectory, soil loss, etc.) remain as future challenges.

New sensor designs will be required to meet these observational needs. The measurements encompass those of the water cycle and the carbon cycle, and add strong demands for measurement of the state of the ocean, the weather and climate effects, the health of terrestrial and oceanic biota, the changing topography, and the presence and effects of runoff and pollution. Modeling of these complex bio-physiological processes will progress in the next decades to encompass both the global view as well as highly site-specific measurements across large regions and time.

2.3.4 New Modeling Requirements

Gross Primary Production models of the open ocean are based on absorption of PAR in the photic zone and SST. The future models will include functional groups with different rates of efficiency, mixed layer depth, nutrient fields (N, Si, Fe), and aerosol deposition. The sequestration of carbon to the deep ocean is based on in situ knowledge and modeled. Future modeling capabilities will integrate mixed layer depth, composite cloud free imagery, to elucidate the trophic levels of fish and microbiotic species. Atmospheric corrections for optical imagery of the turbid waters and bottom reflectance of the coastal zone and freshwater systems are needed or need to be generalized. New bio-optical models (generalized and region specific) for the water column will account for the biological variability of the zone. Improved models will permit prediction of the high-resolution physical transport (horizontal and vertical) typical of this aquatic ecosystem.

Ecophysiological modeling of terrestrial ecosystems is improving and is on track to predict Net Primary Production (NPP) and related indices of carbon exchange based on remotely sensed variables. These models are based mainly on short-term processes and while they are being used to predict the production of a host of biogenic gases to and from the atmosphere, they are now based too heavily on correlates to NPP. Modeling of life cycle community structure, based on remote sensing, is less well developed. Future community structure models will predict trajectories of ecosystem response to change, including climatic, land use, multiple stressors, species invasions, and so forth, and will couple with ecophysiological models. These ecophysiological models will dominate the research agenda to 2030, and will enable prediction of land disturbance from all sources; selective harvesting, agriculture, grazing, land conversion, fire, acid rain, climate variation such as precipitation timing and kind, and more. This area of modeling is crucial for predicting the performance and services the ecosystems can deliver for humans and all other life on Earth, and the relation of these ecosystems to the Earth’s climate.

3. Applications and Benefits of an Earth System Observational and Modeling Capability

Today, we recognize the benefits and applications of weather and climate forecasts on public and private sector decisions. The variation of weather is one of the most evident aspects of the Earth system where accurate predictions provide significant value to the public in their daily lives and to managers with their management responsibilities. For example, improved weather forecasts allow city managers to more accurately purchase energy contracts—if the accuracy of 30-hour weather forecasts improves 1°F, the annual cost of electricity can decrease by over $1 billion.

Climate forecasts are now improving to the point that they provide significant information across broad economic sectors. Water resource boards use near-term climate forecasts to design policies to conserve water in anticipation of impending droughts. Climate and weather predictions help disaster managers anticipate the frequency and onset of events to alert the public to prepare at appropriate times. Thus, data and predictive knowledge of the Earth’s systems have significant economic consequences in policy and management at the human dimension.

Similar improvements are being made in ocean measurements and models, and application of these measurements provides information concerning ocean biological productivity and fish stocks of growing importance to the maritime industry. Developing knowledge of ocean state and circulations is assisting in forecasting the onset and intensity of tropical storms and changes in short-term climate.

New capabilities in biological productivity observations and modeling are enabling evaluation of ecosystem health on land and at sea. These evaluations are now beginning to be linked to the spread of disease and pestilence.

The Earth Science Vision for the year 2030 centers on development of a complete observational and predictive capability for the whole Earth system. The EIS will incorporate our observations and knowledge of all system components—the atmosphere and ocean, the solid Earth, and the biosphere—and will provide the world with the technological capability to move beyond understanding of the Earth and its environment to a quantitative predictive capability which has broad application to human needs. To illustrate the development and utility of the EIS, we describe several application scenarios for the EIS:

Scenario 1: The EIS will be used by the agricultural industry to predict temperature, rainfall, and crop damage potential from disease and pests, on time scales ranging from weekly to multi-year. This information will be used to proactively adjust agricultural practices and activities, thereby optimizing land productivity, crop selection, planting schedules and water management.

Scenario 2: The EIS will be used by land use planners to predict hazard threats from fire, flood, earthquake, volcano, tropical storms, severe storm outbreaks, storm surge, sea-level rise, etc. This information will be used to begin emergency response preparations prior to events through raising alerts, repositioning resources and managing key infrastructures.

Scenario 3: The EIS will be used to evaluate economic impacts and environmental effects of changes in agricultural and other ecosystem productivity that results from proposed non-agricultural use of land. This information will facilitate improved decisions concerning the placement and building codes for long-term infrastructure, and will enable trade-offs of revenue from development projects against loss of ecosystem productivity.

Scenario 4: The United Nations and the global community will use the EIS to support development of environmentally relevant global protocols, to evaluate the effects of harmful emissions, and to monitor compliance and effectiveness of international protocols.

In these and other future applications, our knowledge and understanding of the Earth will be embodied in an EIS that allows us to predict future changes and to evaluate the impact of various human responses to these changes. With the enormous human capability to alter the Earth, we will greatly benefit from this predictive tool which will allow evaluations of alternative responses to human needs and environmental events.

Achievement of this future capability is just now within our grasp. However, to take this step will require improved, and even revolutionary, measurements of all the components: for climate, ocean, weather, biosphere, water cycle, atmospheric composition, radiation budget, Earth surface movement. Then they must be incorporated into a comprehensive Earth Information System that can link causes, effects and relationships into one complete understanding of the Earth system.

4. Integration with ESE Planning

The NASA Earth Science Enterprise (ESE) Research Strategy defines the current and future measurement and research requirements for the Enterprise. The ESE Research Strategy is based on the science understandings and issues of the present and on the current technological horizon. It therefore identifies the science measurements that will be required over the next 10 to 15 years in order to improve our understanding of the planet Earth as an integrated system. The strategy also motivates the Earth science technology, applications, and education strategies that support and apply the results of the NASA Earth science effort. These science goals and activities are therefore the driving forces that direct NASA Earth sciences technology investments. The education and applications strategies serve to apply the results of the Earth science and technology efforts to national educational activities and to the agency and policy-setting needs of the nation.

The Earth Science Research Strategy is divided into six major research theme areas, which are embraced within the Vision themes. These six theme areas include: climate variability, weather predictability, the global water cycle, atmospheric composition, solid Earth deformation, and the global carbon cycle. Each of these

theme areas cuts across traditional scientific disciplines to apply scientific knowledge to a major cyclic Earth process. Each of these six ESE Research Strategy theme areas maps into a set of highly specific roadmaps that lay out comprehensive scientific development pathways which will lead the NASA ESE to meeting the specific science and technology goals.

The ESV 2030 effort provides the farther-out view that will require new observational capabilities based on fundamentally new technological approaches. The ESV 2030 themes reflect the critical interactive nature of Earth science components that must be recognized to provide needed future predictive capabilities. This longer term viewpoint also makes possible addressing extremely difficult scientific goals, such as the EIS, that are so difficult, yet so important and so potentially achievable, that a multi-decadal, national and international effort is needed to achieve success.

Implementation of the ESV 2030 goals is facilitated by the close similarity of the ESV goals with the ESE Research Strategy, and by existing NASA technology development activities. The ESV science themes are an outgrowth of the ongoing ESE research effort, primarily addressing longer term, interrelated science issues. The natural cycle of long-term planning begins with an evaluation of the state of science knowledge and of the needs for new technology. From this come the long-term science goals, plus descriptions of required new observational and computing capabilities.

This period of scientific emphasis should be followed by a technology cycle, during which investigations of the technological underpinnings for new obser-

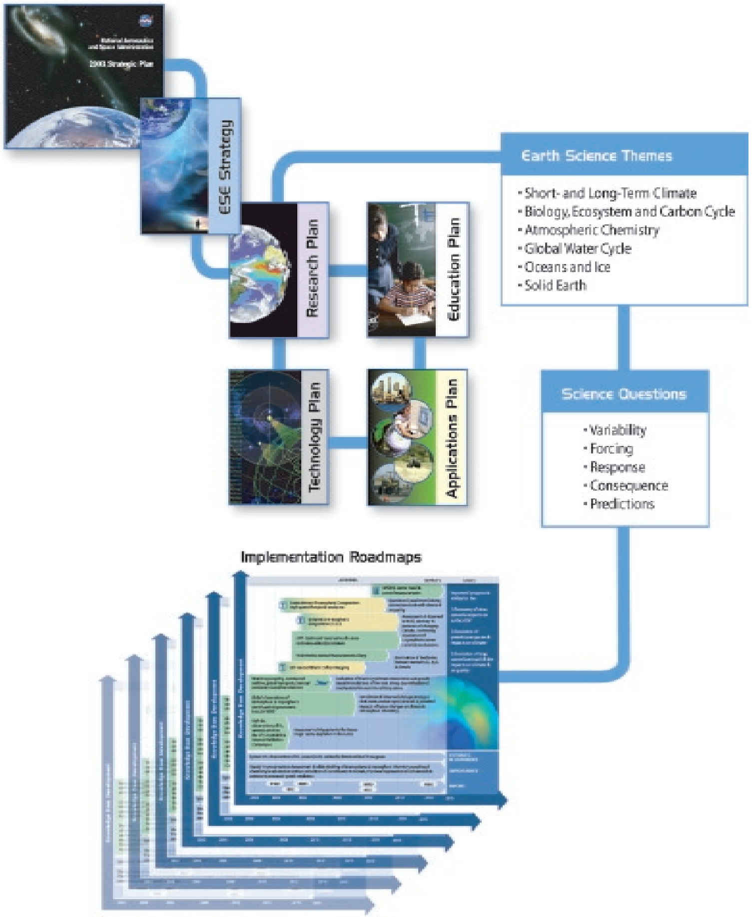


Figure 4.1 The Earth Science Vision report and other working group reports provide input into the Enterprise Strategic plan, and to, the future research strategy and long-term roadmaps.

vational and computing technology come to the fore. During this time, the long range science planning activities will provide occasional feedback and oversight of the technological goals and proposed new capabilities. The cycle time for the full science and technology planning cycle is several years. As time passes new science discoveries and technological breakthroughs will alter the scientific priorities and the process will continue.

5. Strategic Implementation

5.1 NASA Role

The observational systems required for the Earth measurements described herein, and for the Earth Information System (EIS) itself, are scientific and technological challenges for NASA. Meeting these challenges will require strong agency commitment, plus cooperation and integration across US government agencies, academia, industry, and institutions in other countries. As we become more aware of the links between Earth systems and human actions, and the resultant impacts on human welfare, the scientific breakthroughs and predictions enabled through the EIS will be increasingly critical to national and international decision support and related policy making.

NASA, with its expertise in the Earth sciences and in integrated Earth observation and modeling systems, will play a major role in development and implementation of the Earth Information System. Through partnerships with government agencies, international organizations, and researchers across the world, NASA is uniquely positioned to provide the required technological capabilities. With its broad research and development relationships, NASA has unique abilities to effectively coordinate the national and international activities of diverse sources of new science knowledge and technological capabilities. Given its role as a research and development agency, NASA will facilitate integration by operational agencies through merging and coordinating the EIS objectives from many organizations. The result will ensure that validated Earth system predictions are delivered in a timely manner and in a usable form. Through its systems analysis, engineering, and international leadership NASA can provide the breakthrough scientific missions and modeling efforts that, through partnerships, can be transitioned to operational agencies at the appropriate time.

NASA can provide critical, experienced leadership for each of the scientific themes identified by the Vision team. For example, as outlined above, climate predictive goals require improved measurements of tropospheric trace gases, ocean altimetry, atmospheric moisture, improved resolution temperature and humidity profiling, and more. For weather measurements, as is shown in every theme, the global perspective of space is critical. Additionally though, NASA must lead breakthrough scientific missions and modeling efforts that can then, through partnerships, be transitioned off to operational agencies at the appropriate time.

Sea level studies require a multi-disciplinary approach and a large-scale perspective. Current projections of sea-level rise by the Intergovernmental Panel on Climate Change (IPCC) are heavily model-based, with very limited observations and poor spatial sampling. NASA can make a strong and unique near-term contribution by supporting development of new observations and models that produce accurate near-term and far-term predictions of sea-level change. Further, working in partnership with NOAA, other government agencies, and international agencies, NASA can build an effective interface to ensure that validated predictions, endorsed by the scientific community, are delivered to operational agencies effectively.

Figure 5.1.
The NOAA ships, Ronald H. Brown and John N. Cobb, at the pier at Pacific Marine Center in Seattle. Partnerships between agencies such as NOAA and NASA will combine critical ground-based and space-based measurements. (Courtesy of NOAA)

Observation and prediction of the global hydrologic cycle requires a synthesis of space-based remote sensing technology, ground-based measurements, and Earth system models. Ideally, NASA's role would be complimentary to other efforts, and could help in organizing observations made on more local scales. For example, NASA could provide area-averaging for such local measurements made as part of a hoped-for global observation hydrologic network for climate, recently proposed by the World Meteorological Organization.

Monitoring earthquake hazards from space is a challenging, technology-rich endeavor. NASA has played a leadership role in developing space-based radar systems and new information technology approaches, and continues to invest in In-SAR capabilities. New satellite orbits, plus extremely precise satellite orbit determination will improve the accuracy of Earth surface displacement observations. Data from networks of distributed observational systems must then be located, retrieved, and merged to provide the needed measurement of Earth surface displacements. NASA's role will be to push these observational and information technology envelopes, thereby supporting new predictive capabilities.

The Earth's biosphere and the carbon cycle present unique new challenges. Subtle effects must be monitored-often over the full diurnal cycle and over highly diverse spatial scales-in order to evaluate the state of the biosphere, the effects of pollution, human activities, and climate variability. NASA leadership in innovative measurement technologies will be required to attain the behavioral discriminations needed to make essential progress in predicting these changes.

5.2 Partnering and Transition to Operations

NASA has major responsibilities and new opportunities to initiate and implement key aspects of this future vision. These include both the essential global observing concepts and major components of the highly integrated Earth Information System. It is also clear that other national and international agencies and organizations bear the major responsibilities for operational activities, including the ultimate decision-making and policy-setting. NASA's role is to provide the new technological and scientific capabilities in collegial and cooperative relationship with these other agencies and organizations.

For example, the operational weather analysis and forecasting systems are in the charter of the National Weather Service (NWS). NASA's role is through development of new weather observational and data analysis capabilities. This is accomplished in partnership with the NWS, as well as with the Federal Aviation Administration (FAA) and the Department of Defense (DOD). Through these partnerships NASA contributes to the national goals for new weather forecasting observational technologies, through setting priorities for the development goals, determining how advances can be made through NASA-developed technology and knowledge, and by transferring the technology and knowledge to NOAA and other operational agencies.

NOAA is the operational agency most closely aligned with the research goals of a sea-level rise monitoring initiative. The oceanographic measurements collected by NOAA, including the tide gauge networks and GPS reference system, greatly

Figure 5.2. Homes, businesses, and personal property were all destroyed by the Midwest floods of June 1994. A total of 534 counties in nine states were declared for federal disaster aid. As a result of the floods, 168,340 people registered for federal assistance. Future monitoring of precipitation, topographic mapping, and new modeling capabilities will allow for improved flood prediction that will be of great benefit to society. (Courtesy of FEMA)

contribute to the goal of monitoring and predicting sea-level change. The DOD/NOAA/NASA Integrated Program Office will be responsible for the operational ocean observing system of the future that will monitor ocean volume, while NASA will be responsible for developing and deploying critical measurement systems to probe the mass redistributions that reflect changes in the cryosphere and Earth's interior. Cooperation with international agencies engaged in land-based hydrological monitoring will be important to provide information on water storage at local scales to augment and validate space-based monitoring.

FEMA is responsible for preparing for and mitigating national disasters, but state and local governments will be the primary beneficiaries of sea-level rise predictions to support policy decisions on mitigation strategies. Sea-level rise predictions, generated by the Earth Information System, will be provided to these agencies, along with high-resolution digital topography. Predictions of severe storm frequency and intensity will also be provided to federal, state and local agencies so that they can assess the risk to coastal communities from the combination of changing sea level and changes in storm characteristics and develop effective short-term and long-term mitigation strategies.

One of the primary applications that requires NASA partnership will be in the area of agriculture and food production. Accurate forecasts of regional water availability will help produce a better understanding of the degree to which irrigation will be feasible under warming conditions. It would also help in assessing cost-benefit ratios for policy options to mitigate or adapt to a changing climate.

Of the twelve themes of the NASA Applications Division, the role of the biosphere is a key component in most thematic areas. These include carbon management, ecosystem forecasting, coastal ecosystem management (and land-ocean margins), agricultural competitiveness, public health, biological invasive species, homeland security, water management and conservation, air quality management, and energy forecasting.

The span of capabilities provided by the NASA Earth Science Enterprise provides a myriad of applications that will assist the nation in the development of programs and policy. The present number of partners for these application areas is large. These include: NOAA National Marine Fisheries Service (NMFS), NOAA National Environmental Satellite, Data, and Information Service (NESDIS), several elements of DOD, the Environmental Protection Agency (EPA), United States Department of Agriculture (USDA), US Geological Survey (USGS), National Institutes of Health (NIH), Center for Disease Control (CDC), US Fish and Wildlife Service

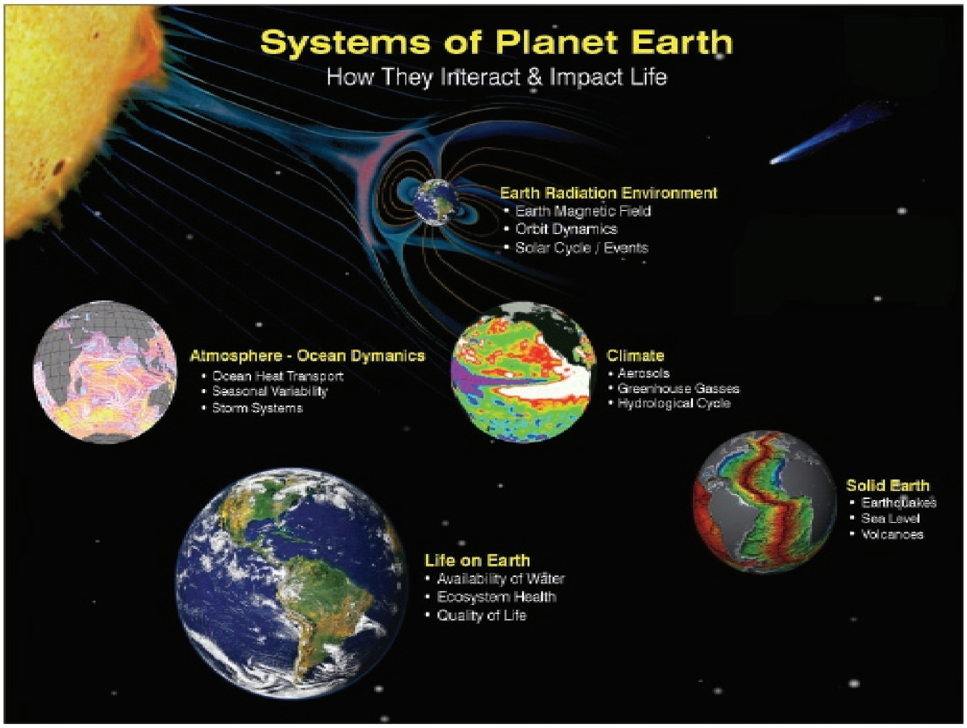


Fig. 6.1. The systems of planet Earth are schematically illustrated beginning with the Earth radiation environment and its various components, the atmosphere - ocean dynamics, the resulting Earth climate, the solid Earth processes, and finally the biosphere which is strongly affected by the availability of water which, with the climate, results in ecosystem health and the quality of life.

(USFWS), Bureau of Land Management (BLM) and Federal Emergency Management Agency (FEMA). State and local agencies-Departments of Environmental Quality, Divisions of Materials Research, etc.-are all potential users of a wide variety of information concerning the state of the Earth and of forecasts for future variability and change. Technology transfer and infusion of NASA capabilities and information into the wider public and private sectors will further develop the value of the public investment in NASA. Along with continued scientific discovery the extended application and commercial utilization will provide feedback to the evolution of the EIS capabilities to further improve forecasts.

6. Conclusions

This report summarizes the Earth Science Vision Team's view of NASA's role in developing new capabilities for understanding the Earth and for predicting future changes in the habitability of Earth. The field of Earth Sciences is now on the threshold of fundamental new capabilities to observe the whole Earth-its oceans and atmosphere, the biosphere and habitability for life, and as a solid planet-and to predict future changes in the Earth system, whether they be due to natural changes or to human-induced effects.

The predictive goals envisioned for the 2030 era were summarized in Section 2. The tables therein indicate the opportunities for significantly improved predictions of individual aspects of the Earth, as well as the full Earth as a system. In reviewing the current state of Earth science capabilities, the Earth Science Vision Team found that the current goals for the 2010 time frame are ambitious, providing concrete steps toward the future capability envisioned for the 2030 era. However, in order to achieve the 2030 era goals, several things must happen. As the interrelationships among forecast variables becomes more apparent, interdisciplinary science will become more critical. Forecast models must become more robust and temporally responsive, linking the various Earth system processes through an internationally supported modeling and Earth information

exchange framework. New multi-sensor observational capabilities will provide the essential measurement sets to feed the modeling framework. Key elements of the observation system will respond to dynamic model forecasts, in which the data demand driven by derived forecast uncertainties. These components will all gather and share information through the international Earth Information System construct. The observational capabilities described in the individual sections of this report are summarized in Table 6.1. As the needed precision and temporal/ spatial resolution are attained and experience is gained, these individual capabilities will produce a new observational paradigm in which all major aspects of the Earth are measured.

These measurements will then feed the comprehensive Earth Information System, a huge international undertaking with computational capabilities (Table 6.2) that are just now being addressed internationally, and with approaches to evolutionary software development that are also just now being developed, again internationally. We see the Earth Information System as an enormous and truly international effort, but an effort that has a strong NASA role that leads development of new capabilities to observe all components of the Earth, and to, thereby, feed scientific knowledge into predictive computer models that can forecast future variability and changes in the Earth.

The NASA role will be to provide development of new capabilities for observing all components of the Earth, and to assist with the highly interactive computer data handling and modeling capabilities that forecast the future variability and changes in the Earth. This NASA role extends and builds upon the existing NASA Earth Science Enterprise (ESE) mission: to observe and understand the Earth environment, with the goal of predicting both natural and anthropogenic change. The ESE activities and research into climate and weather, biosphere, solid Earth, and the cross-cutting science topics, such as chemistry, radiation, pollution, human impacts, water cycle, carbon cycle, and more will continue, but with new focus and direction as they apply to the overarching goal of the Earth Information System. Achieving this Earth modeling capability and the supporting observation system is the long-term grand challenge for the NASA's Earth Science Enterprise.

Measurement Requirements — All

Measurement	Frequency	Horizontal Resolution	Precision/ Accuracy	Climate Measurement	Extreme Weather	Sea Level	Surface Displacement	Global Water	Biosphere
Ocean evaporation rate	Daily	10 km	5%	●				●	
Ocean mixed layer depth	Weekly	10 km	10%	●	●	●			●
Mixed layer depth, coastal zone	Weekly	10-100 m	10%						●
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent			●		●	●
Ice sheet elevation	Weekly	< 1 km	1%	●				●	
Sea Ice thickness	Monthly	5km	5cm	●				●	
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams - ice sheet)	1 cm (height)			●		●	
Ice Sheet Dynamics	Monthly	100 m	1 m/yr (rate)	●		●			
Ice Sheet Bed Characteristics	10 Years	100-1000 m	Bed topography to <10 m			●			
Soil Moisture	Daily	< 1 km	10%	●		●		●	●
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly To Weekly	< 1 km		●				●	●
Stream flow	Daily	NA	10%	●				●	●
Reservoir and Aquifer Impoundment	Monthly	scale of storage basin	0.1 mm/yr sea level rise equivalent			●		●	
Aerosol distribution and absorption properties	Hourly	< 1 km	10%	●					●
Atmospheric ozone	Hourly	1km (vertical & horizontal)	5%	●					●
Carbon dioxide and methane	Hourly	1km (H) boundary layer & 2 km (V)	0.3% (column)	●					●

Table 6.1. Summary of the measurement goals discussed in this document. This table lists the measurement goals that would be required to meet the observational and predictive capabilities described in the text. See the text for detailed discussions of the expected goals and the observational and modeling breakthroughs that will be required to meet these goals. The grouping of the required measurements in the last six columns provides links to the discussions in the various sections of the text.

Measurement Requirements — All

Measurement	Frequency	Horizontal Resolution	Precision/ Accuracy	Climate Measurement	Extreme Weather	Sea Level	Surface Displacement	Global Water	Biosphere
Atmospheric source gases (N2O, CFC's, NMHC)				●					
Atmospheric radicals (N2O, OH, ClO,...)	Daily	2km (H), 5 km (V)	1-10%	●					●
Carbon Monoxide	Daily	50 km (H), 1 km (V)	10%	●					
Water Vapor	1-3 Hours	5 km (H) 0.5 km (V)	5%		●				
Tropospheric wind profiles (20 levels in troposphere)	3 Hours	5 km, 0.5 km (V)	1 m/s per horizontal component		●				
Wind vectors within storm systems (20 levels in troposphere)	1-3 Hours	5-25 km, 0.5 km (V)	3 m/s per horizontal component		●				
Temperature profiles in clear air (20 levels in troposphere)	1-3 hours	5 km (H) 0.5 km (V)	< 1° C, T & Td		●				
Temperature and water vapor profiles within storm systems (20 levels in troposphere)	1-3 Hours	5-25 km	< 1° C, T & Td		●				
Surface precipitation	Hourly	5-25 km	5-10 mm/h		●			●	●
3-D precipitation rate (20 levels in troposphere)	3 Hours	5-25 km	5-10 mm/h		●				
Ocean Nutrient fields (N, Si, Fe), aerosol deposition, functional groups	Weekly	10 km	30 %					●	●
Ocean Color, dissolved organic matter, Chlorophyll and other pigments	Daily-Weekly	100 m	10%					●	●
Functional groups Coastal shallow bathymetry and bottom reflectance	Daily-Weekly	100 m	10%					●	●
Nutrient concentration (N, Si, Fe, P)	Daily-Weekly	100 m	10%					●	●
Ocean Physiological state (fluorescence)	Daily	100 m	20%						●
Coastal zone topography	Monthly	2-5 m	<10 cm (height)			●			

Measurement Requirements — All

Measurement	Frequency	Horizontal Resolution	Precision/ Accuracy	Climate Measurement	Extreme Weather	Sea Level	Surface Displacement	Global Water	Biosphere
Crustal Deformation (tectonic motion, coastal uplift/subsidence)	Daily To Weekly	10 m	5 mm (range) 0.5 mm/yr (rate) on annual basis			●	●		
Ocean/Ice Mass Redistributions (gravity change)	Monthly	100s-1000s km (scale of drainage basin)	0.1 mm/yr sea level rise equivalent			●	●	●	
Crustal Mass Redistributions (gravity change)	Weekly	50-100 km	0.1 microgal				●		
Phenological state (leaf out, senescence)	Diurnally	1 km	< one day						●
Biochemical composition of plant canopies (N, lignin, pigments, chlorophylls, etc.) Responses to multiple stressors (long-term observations)	Weekly	100-200 m	25%						●
Fire properties (energy release rates, rate of spread, gas/aerosol loading, soil heating)	Daily	100 m	20%						●
Standing biomass over time	Monthly-Annual	100 m	10%						●
Vegetation structure, successional state, primary & secondary vegetation condition	Monthly	100 m	20%						●

Table 6.2. Estimated computational environmental goals for Earth Systems Modeling capabilities as described for circa 2030.

Computational Goals

	Today	2010	2030
Models	Single Discipline Models Coupled Ocean-Atmosphere Models for Climate Prediction Single Discipline Data assimilation	Coupled Ocean - Atmosphere - Land Surface Models with multi-model data assimilation - 4X resolution improvement Multi-component solid earth models with data assimilation	Integrated multi-discipline Earth System Models with 10X additional resolution improvement, fully consistent all-component data assimilation, validated prediction capability for 2 week weather, interannual climate, moderate confidence fault hazard predictions
Dedicated Networks	1Gb/s sustained	100Gb/s sustained	10 Tb/s sustained
Performance	1 - 10 TeraFLOPS Sustained (Japan Earth Simulator)	100s of TeraFLOPS - PetaFLOPs Sustained	100s of PetaFLOPS
Memory (RAM)	40 GB	5 TB	1 PB

Acknowledgements

This report is the result of the efforts of the numerous individuals on working groups who considered the future of Earth science and the great potential of satellite observational systems to advance the state of knowledge. Their efforts, devotion of time and their willing support of an inquiry into a seemingly poorly bounded problem is gratefully acknowledged. This report summarizes their work and discussions, as interpreted in the context of a possible future path for the NASA Earth Science Enterprise.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. This independent review was intended to provide candid critical comments and to ensure that the report meets standards for completeness, objectivity and thoroughness. We wish to thank Mark R. Abbott, Richard A. Anthes, Dennis L. Hartmann and Thomas A. Herring for their thoughtful, helpful reviews. Although these reviewers were asked for their candid documents, they were not asked to endorse the conclusions of this report, nor were they sent a final draft prior to publication. Responsibility for the final content of this report rests entirely with the Earth Sciences Vision Team.

Bibliography

Foody, G.M. and Curran, P.J. (eds) , 1994: *Environmental Remote Sensing from Regional to Global Scales*. Wiley, New York, 250pp.

Douglas, B.C., M.S. Kearney, and S. P. Leatherman (Eds.) , 2001: *Sea Level Rise: History and Consequences*, Academic Press, San Diego, 232pp.

Gattuso, J.-P., M. Frankignoulle and R. Wollast. 1998. Carbon and carbonate metabolism in coastal aqautic ecosystems. In: Fautin, D.G. (ed.), *Annual Review of Ecology and Systematics* **29**, Palo Alto, California: Annual Reviews, p. 405-434.

GCRP (U.S. Global Change Research Program), 2003: Our Changing Planet: *The FY 2003 U.S. Global Change Research Program and Climate Change Initiative*. Washington, D.C.: While House Printing Office:

Global Carbon Project, 2002: Summary available at: http://www.globalcarbonproject.org.

International Geosphere-Biosphere Programme, 2003: Links to IGBP programs and interactions with the climate system available at: http://www.igbp.kva.se/cgi-bin/php/frameset.php.

Koblinsky, C.J., and N.R. Smith, (Eds), 2001: *Observing the Oceans in the 21st Century*, GODAE Project Office, Bureau Of Meteorology, Melbourne, 604pp.

Langenberg, H. (Ed.), 2001: *Nature Insight: Climate and Water*, Nature, **419**, London, U.K., 187-232.

Lubchenko, J., A. Olson, L. Brubaker, S. Carpenter, M. Holland, S. Hubbell, S. Levin, P. MacMahon, P. Matson, J. Melillo, H. Mooney, C. Peterson, H. Pulliam, L. real, P. Regal and P. Risser. 1991. The sustainable biosphere initiative: an ecological research agenda. *Ecology* **72**:371-412.

Malthus, T. and P. Mumby (eds.). 2003. Remote sensing of the Coastal Marine Environment. *International Journal of Remote Sensing* **24**:2585-2815.

NASA (National Aeronautics and Space Administration) / ESE (Earth Science Enterprise) Website: http://www.earth.nasa.gov/

NASA/ESE Science: http://www.earth.nasa.gov/science/index.html

NASA/ESE Missions: http://gaia.hq.nasa.gov/ese_missions/

NASA/ESE, 2002: Report from the Earth Science Enterprise Computational Technology Requirements Workshop. Available at:

http://esto-doc.gsfc.nasa.gov:8080/documents/Information_Systems/CT/ESE-CT-Workshop/2002/ctreqreport.pdf

NASA/ESE, 2000: *Exploring our Home Planet: Earth Science Enterprise*. National Aeronautics and Space Administration, Washington DC. Available at: http://www.earth.nasa.gov/visions/stratplan/

NASA/ESE, 2000: Research Strategy for 2000-2010. National Aeronautics and Space Administration, Washington DC., Available at: http://www.earth.nasa.gov/visions/researchstrat/

NASA/ ESE, 2001: Advanced Weather Prediction Technologies: NASA's Contribution to the Operational Agencies, Mike Kalb and Bob Atlas (Eds.). National Aeronautics and Space Administration, Washington DC., Available at:
http://esto.nasa.gov/files/2001/14%20Day%20Weather/2025_Wx_Study_Final_Report_5-31-2002.pdf

NASA/ ESE, 2001: Socio-Economic Value of Improved Weather and Climate Information, Ray Williamson (ed.). National Aeronautics and Space Administration, Washington DC., Available at:

http://esto.nasa.gov/files/2001/Economic%20Study/Socio-EconomicBenefitsFinalREPORT1.pdf

NASA/ ESE, 2002: Living on a Restless Planet: Solid Earth Science Working Group Report. National Aeronautics and Space Administration, Washington DC., Available at: http://solidearth.jpl.nasa.gov/seswg

NASA/JPL, 2003: Global Earthquake Satellite System Study Report, Pasadena, CA, Available at: http://solidearth.jpl.nasa.gov/gess

NASA/ ESE, 2002: *Earth Science Enterprise Applications Strategy for 2002-2012*. National Aeronautics and Space Administration, Washington DC., Available at: http://www.earth.nasa.gov/visions/appstrat2002.pdf

NASA/ESTO (Earth Science Technology Office), 2003: IGARSS 2003 Earth Science Vision Sessions: Global Understanding of the Complexities of Our Planet. National Aeronautics and Space Administration, Washington DC., Available at: http://esto.nasa.gov/conferences/igarss03/vision.html

NASA/ESTO, 2003: IGARSS 2003 Earth Science Technology Sessions: Technology Challenges for the Coming Generation of Earth Explorers. National Aeronautics and Space Administration, Washington DC., Available at:

http://esto.nasa.gov/conferences/igarss03/architectures.html

Nemani, R.R., C.D. Keeling, H. Hashimoto, W.M. Jolly, S.C. Piper, C.J. Tucker, R.B. Myneni and S.W. Running. 2003. Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. *Science* 300:1560-1563, June 6.

NOAA, 2003: Turning to the Sea: America's Ocean Future, Available at www.publicaffairs.noaa.gov/pdf/ocean_rpt/

NRC (National Research Council), 1995: *Natural Climate Variability on Decade-to-Century Time Scales*, Washington D.C.: National Academy Press. 644pp.

NRC, 1997: Satellite Gravity and the Geosphere. National Academy Press, Washington D.C., 1997. 112 pp.

NRC, 1999a: *Global Environmental Change: Research Pathways for the Next Decade*. Washington D.C.: National Academy Press. 595pp.

NRC, 1999b: *Adequacy of Climate Observing Systems*. Washington D.C.: National Academy Press, 66pp.

NRC, 2001: *Climate Change Science: An Analysis of Some Key Questions*, Washington D.C.: National Academy Press. 42 pp.

NRC, 2003: Satellite Observations of the Earth's Environment; Accelerating the Transition of Research to Operations. National Research Council, Washington, DC, 163pp.

NWS (National Weather Service), 2003: NOAA/National Weather Service Science and Technology Infusion Plan 2003 - Roadmap to 2025. NOAA/NWS Office of Science and Technology. 17pp., 2001.

NWS, 2003: *National Weather Service, Science and Technology Infusion Plan: 2003, DOC/NOAA/NWS; Science and Technology Infusion Plan (STIP) Review, September 17-18, 2002* National Weather Service, Washington, D.C. Available at: http://www.nws.noaa.gov/ost/stip02/stip02agenda.html)

Peterson, D.L. J.A. Brass, W.H. Smith, G. Langford, S. Wegener, S. Dunagan, P. Hammer, and K. Snook, 2003: Platform options of free-flying satellites, UAVs or the International Space Station for remote sensing assessment of the littoral zone, *International Journal of Remote Sensing*, in press.

Potter, C., S. Klooster, R. Myneni, V. Genovese, P.-N. Tan, and V. Kumar. 2003. Continental-scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982-1998. *Global and Planetary Change* **39**, 201-213.

Prentice, I.C, et al. 2001. The Carbon Cycle and Atmospheric Carbon Dioxide. Chapter 3 of *Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, pp. 183-238.

Richard L. Miller, Carlos E. Del Castillo and Brent A. Mckee (eds). 2004. *Remote Sensing of Coastal Aquatic Environments: Technologies, Techniques and Applications*. Kluwer Publishing, Fall 2004 release.

Rignot E., and R. H. Thomas. 2002. Mass balance of polar ice sheets. *Science*, **297**, 1502-1506.

Schubert, S., R. Dole, H. van den Dool, M. Suarez, and D. Waliser, 2002: Proceedings from a Workshop on “Prospects for improved forecasts of weather and short -term climate variability on subseasonal (2 week to 2 month) time scales. Co-sponsored by NASA Seasonal-to-Interannual Prediction Project and NASA Data Assimilation Office, Goddard Space Flight Center, Greenbelt, MD., 16-18 April 2002. NASA/TM 2002-104606, vol 23.

Skidmore, A. (Ed.), 2003: *Environmental Modeling with GIS and Remote Sensing*. Taylor and Francis, London, 293pp.

Vernadsky, V.I., D.B. Langmuir, (translator), M.A.S. Memenamin (editor), and L. Margulis. 1998: *The Biosphere*. Copernicus Books. 192pp.

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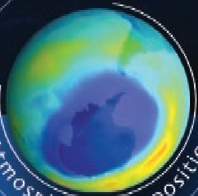
Acronym list

BLM	Bureau of Land Management
CDC	Center for Disease Control
DEQ	Department of Environmental Quality
DMR	Division of Materials Research
DOD	Department Of Defense
EIS	Earth Information System
ENSO	El Niño-Southern Oscillations
EOS	Earth Observing System
EPA	Environmental Protection Agency
ESE	NASA Earth Science Enterprise
ESV	Earth Science Vision
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
GFO	Geosat Follow On
GPM	Global Precipitation Measurement
GPM	Global Precipitation Mission
GRACE	Gravity Recovery and Atmospheric Change Experiment
ICESat	Ice, Climate and Elevation Satellite
InSAR	Interferometric Synthetic Aperture Radar
IGARSS	International Geosciences and remote sensing Symposium
IPCC	Intergovernmental Panel on Climate Change
MJO	Madden-Julian Oscillation
MSU	Microwave Sounding Unit
NAO	North Atlantic Oscillation
NESDIS	National Environmental Satellite, Data, and Information Service
NIH	National Institutes of Health
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar Orbiting Environmental Satellite System
NPP	Net Primary Production
NRC	National Research Council
NWS	National Weather Service
PDF	Probability Distribution Function
PDO	Pacific Decadal Oscillation
SCIGN	Southern California Integrated GPS Network
TRMM	Tropical Rainfall Measurement Mission
USDA	United States Department of Agriculture
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey

Notes

Notes



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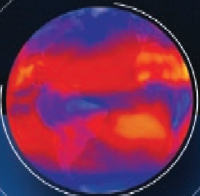

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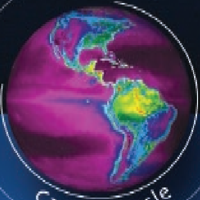

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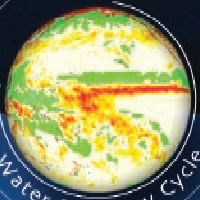

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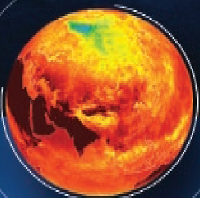

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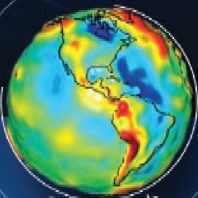

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