CHAPTER 7

EARTH SYSTEM OBSERVATIONS AND MODELING

7.0 INTRODUCTION

The Earth science research agenda described in the previous chapters makes use of two broad classes of activities: observational and modeling. Continued progress in the study of the Earth as an integrated system requires their application and improvement so that aspects of the Earth system, or linkages among them, not addressed previously can be studied in detail. Further, it is critical that the observational and modeling activities be linked together, as observations that do not exist in the context of a model-based hypothesis can provide data but little insight, while models unconstrained by observations are frequently of little use in explaining the past or present, let alone for predicting the future. Thus, NASA's Earth science research planning places particular emphasis on maintaining a close linkage between observations and models so that the benefits of both sets of activities are maximized. A key method that is used for linking observations to models is model-based assimilation of heterogeneous observed data, described below. NASA is committed to development and application of model-based data assimilation, with particular emphasis on demonstrating, through assimilation, the value of spaced-based observing systems.

Observations are the important starting point for Earth science research. Several classes of observational activities are identified. First are the space-based measurements that form the largest part of NASA's program. As discussed earlier, major space missions fall into one of three categories: systematic, exploratory, and operational precursor. In addition, some space-based measurement activities exist mainly for purposes of technology demonstration; these are described in more detail in the ESE Technology Plan. The next category includes sub-orbital measurements, which include ground-, airborne-, and balloon-based observations. The sub-orbital measurements are carried out mostly for detailed study of Earth system processes, but some are designed for global characterization of environmental parameters and, in a small number of cases, for development of long-term data sets suitable for trend analysis. Laboratory measurements are carried out to characterize fundamental properties and processes. These observations and measurements both support the development of technology and algorithms for future sensors (sub-orbital and space-based) and provide the needed information for accurate representation of processes in models. Observations also are used to determine initial states for model predictions and to verify model predictions and simulations. Finally, it is important to recognize the linkage between different types of observations, especially in the context of the validation of space-based observations and the coordinated deployment of satellite, airborne, balloon-, and/or ground-based measurements in process-oriented field campaigns.

Mathematical models play several critical roles in Earth Science. First, they provide a framework for testing our understanding of the processes that govern the behavior of the Earth system and its individual components: the atmosphere, oceans, lithosphere, mantle, core, cryosphere, land hydrology, and biosphere. Second, they provide a means for simulating the observed changes in the Earth system and its components, including the effects of external forcings of the Earth system and internal interactions within the system to system responses. Such simulations can be focused on the present day Earth or can be applied retrospectively to simulate the prior evolution of the Earth system. They are especially useful for establishing consistency in our knowledge of the time evolution of planetary forcings, interactions, and corresponding Earth system responses. Third, they provide a method for predicting the future evolution of the Earth system and its components. When run in a prognostic mode, models calculate the time-dependent responses of the Earth system to a postulated set of time-dependent forcings. Multiple simulations with different assumed forcing functions or different representations of various processes allow the range of Earth system responses expected in the future to be explored. The results are important for assessing the sensitivities of the various components of the Earth system to future forcing and ultimately for evaluating environmental and other human-related impacts of future changes.

Finally, significant scientific advances arise from the combination of models and observations. Three significant ways in which they are combined include inverse modeling, data assimilation, and model/observation intercomparison. The first of these, inverse modeling, is useful when the forcing factors of interest cannot be unambiguously determined from independent sources and must be inferred instead from the known evolution of one or more components of the Earth system. Inverse modeling has been applied to a broad range of environmental problems, for example inferring sources and sinks of long-lived trace gases in the Earth's atmosphere. The second joint application of models and observations is data assimilation, a mathematical method whereby observed data are combined with model predictions to provide optimal, physically consistent, and geographically well-distributed fields of environmental parameters. These fields are used as input for diagnostic studies of Earth system changes and underlying mechanisms, for the initialization of numerical forecast procedures, for evaluation of model forecasts, for evaluating the usefulness of new observing systems in model simulations and predictions, and for determining needed improvements to the global observing network. They can also serve as a basis for trend analysis of Earth system variables when prepared in a consistent way over time. The third joint application of models and observations is model development and evaluation, especially in focused intercomparison studies in which the results of different model simulations are compared with corresponding observational data.

In general, a hallmark of NASA's Earth Science research strategy is ensuring close linkage between observation programs, data analysis, and predictive Earth system modeling at all relevant spatial and temporal scales. In particular, developing the means for full utilization of global observational data acquired by the agency (e. g. through systematic data assimilation) and analysis of discrepancies between observed and modeled fields is considered an essential component of the program, aiming to verify the scientific robustness of the models that encapsulate our knowledge of Earth system processes. In this respect, NASA's research strategy fully subscribes to the recommendation of the National Research Council/Board on Atmospheric Sciences and Climate (NRC, 1998) to: "Apply the discipline of forecasting… in order to advance knowledge, capabilities for prediction, and service to society". Synergy between global Earth observation, analysis, and modeling is perceived as an essential means to answer the following scientific questions and a specific contribution of NASA to the U. S. Global Change Research Program.

7.1 SCIENTIFIC QUESTIONS

To what extent can weather forecasting be improved by new global observations and advances in satellite data assimilation?

While weather prediction is the primary responsibility of operational agencies, such as NOAA in the US, scientific advances made in developing more accurate climate and/or Earth system models, as well as more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Synergy between operational weather forecasting practice and the development of new observation systems or products is an effective engine of progress in both domains. The principal thrusts of ESE's cooperation with operational weather services are participation in the development of precursor operational instruments for application to various operational environmental satellite systems, development of new data products originating from space-based observing systems, and contribution to the development and experimentation of improved atmospheric circulation models and data assimilation schemes.

To what extent can transient climate variations be understood and predicted?

Extended-range weather forecasts (for periods from a season to a year) are of considerable value to businesses, resource management agencies, and farmers. Improved atmospheric circulation models and coupled ocean-atmosphere models have demonstrated predictability in weather patterns up to several months in advance for some regions of the world. Numerical simulations have also demonstrated the sensitivity of such predictions to a number of land surface and ocean circulation parameters. An essential condition for capitalizing on these scientific advances is access to the relevant geophysical information and the ability to ingest this information through more effective data assimilation methods. The information most useful for this application includes, in order of increasing persistence or "memory": *ocean surface winds*; *continental soil moisture*; *sea surface temperature*; *ocean sub-surface temperature and currents* (alternatively, *ocean surface topography*). Initial values of tropical ocean parameters are principally useful for ENSO prediction, while continent-scale soil moisture data are expected to significantly enhance the predictability of summertime precipitation over the interior of continents. Recent progress in seasonal prediction has come from realistic representation of mesoscale weather systems in coupled global atmosphere-ocean models (to be expected since the principal manifestations of transient climate anomalies are changes in storm track, frequency, and strength).

To what extent can long-term climatic trends be assessed or predicted?

The long-term prediction of potential changes in global climate is the most daunting challenge of all, because such predictions depend critically on accurate representation of all relevant "feedback processes" in the atmosphere, ocean, soil and ice, and the biosphere, as well as realistic guesses about future changes in primary forcing factors. Among the most critical problems are understanding the atmospheric processes that vertically redistribute energy, water and other constituents in the atmosphere; the relationship between cloud radiative properties and the underlying meteorological conditions; the partitioning of rain and snow among evaporation, storage and runoff; the effects of changes in land surface and land use on the latter; the exchanges of energy, fresh water, and trace constituents between the atmosphere and the ocean; the formation and evolution of sea ice; the influence of physical climate on biogeochemical cycles; and the trace gas composition of the atmosphere and response to changes atmospheric circulation. Building confidence in such predictions requires success in all four preceding steps in the science strategy. Another piece of information, that will eventually be needed for deterministic predictions of multi-decadal climate changes, is the initial state of the deep ocean circulation globally. Systematic observation of the global ocean circulation will be necessary for this purpose.

To what extent can future atmospheric chemical impacts be assessed?

Prediction of the evolution of atmospheric trace constituent composition is intimately linked to that of the meteorological conditions under which chemical and transport processes occur. The chemical constituent of greatest interest is ozone, which both protects the Earth from biologically damaging solar ultraviolet radiation, and is an active chemical agent pollutant that affects both plant and animal life. Ozone responds (for both production and destruction) to the concentration of many precursor species coming from both natural and anthropogenic sources. Accurate modeling of atmospheric composition requires knowing or forecasting the future evolution of these chemical forcings as well as relevant changes in climatic conditions. In the case of sufficiently large changes in atmospheric composition, interactions with resulting changes in atmospheric circulation and physical properties cannot be ignored (the chemistry of the polar stratosphere is an important case in point). Processes of particular importance for model assessments of potential atmospheric chemical composition impacts include the transport of material between the troposphere and stratosphere; the formation of aerosols and cloud particles and of their interactions with gas phase species; the natural variability in biological sources and sinks; and the balance between chemical removal and long-range tropospheric transport.

To what extent can future atmospheric concentrations of carbon dioxide and methane be predicted?

To predict future climate changes and global productivity patterns, it will be necessary to develop realistic projections of the atmospheric concentrations of carbon-containing gases such as carbon dioxide and methane. These projections require understanding the interactions between the biosphere and the physical environment (especially temperature, precipitation, and carbon dioxide concentration for the terrestrial biosphere; ocean circulation for the marine biosphere; and changes in nutrients for both), as well as the basic relationships between the physical environment, human management activities (e. g. land use, fishing), and biological activity. A combination of global observation of the biosphere (including vegetation cover, above-ground biomass, and the distribution of chlorophyll in the ocean) and global biosphere models will be needed.

In order to predict future atmospheric concentrations of carbon dioxide and methane, observations and representations of carbon cycling processes must be incorporated into terrestrial and oceanic ecological and biogeochemical models, as well as land cover change models. In addition, new and improved carbon cycle models will be necessary to calculate emissions for different landscapes, regions, oceans and the entire Earth system. Inverse modeling may be used to test our understanding of trace gas emissions in the light of observed atmospheric distributions and knowledge of carbon cycling processes. Such models will be important to assess our ability to simulate the past evolution of trace-gas concentrations and build up confidence in prediction capabilities for the future. The ESE will rely largely on information developed by NASA's partners in the USGCRP about future carbon dioxide emissions from fossil fuel combustion and methane emissions (e. g. from landfills, cattle, rice paddies, and natural gas production).

How is the Earth's surface being transformed and how can such information be used to predict future changes?

Recent advances in space geodesy make it possible to characterize land and ocean topography and it’s change to centimeter or better accuracy. This accuracy is sufficient to estimate the risk of flooding in river plains and coastal zones. Space geodesy enables us to follow the subtle effects of crustal deformation through the earthquake cycle, monitor the slow inflation of volcanoes and follow the subsidence of land from the pumping of wells. Though these geodetic technologies have been demonstrated, there is still much to do to achieve timely acquisition of space geodetic data with the required temporal and spatial resolution and to provide the necessary data analysis tools. Though we have the ability to monitor crustal deformation with great accuracy we have much to do in describing the physics of the earth’s crust associated with violent earthquakes and volcanic eruptions. A thorough understanding of this physics is required to achieve reliable disaster forecasting . Space borne observations of the solid Earth whether they be measurement of gravity, geomagnetism , or

Earth rotational dynamics provide the unique global perspective to better understand these forces which drive our restless earth.

Computer models are particularly useful to understanding solid Earth dynamics. Models transcend the limitations of time and space by simulating the entire earthquake cycle over thousands of years and span complete fault systems to provide a better understanding of how earthquakes occur and how faults interact. Complex three-dimensional models with millions of unknowns are required to adequately model regional tectonic systems. High performance computing has recently passed the milestone of replicating a self reversing magneto hydrodynamic geodynamo with the suggestion of a differential higher rotation rate for the inner core – a model derived observation that has stimulated the interest of seismologists. Three dimensional models for mantle convection based upon observation can be played forward to describe the evolution of the Earth’s outer layers. As we approach realistic models for the internal dynamics of the Earth, we gain new insight into the powerful forces which shape the Earth’s surface.

7.2 OBSERVATIONS

As noted in the introduction, the observational approaches used in ESE programs include space-based measurements, sub-orbital measurements using ground-, airborne-, and balloon sensors and laboratory-based investigations of basic physical or chemical properties relevant to remote sensing methods.

7.2.1 Satellite Observations

From both programmatic and scientific strategy perspectives, the NASA flight missions program distinguishes three basic types of missions– exploratory scientific missions, systematic scientific observation missions, and operational precursor and technology demonstration missions. These categories were first introduced in the "post-2002 mission scenario" developed in 1998-99 by soliciting specific research questions and associated measurement concepts from the science community, and integrating them into a slate of mission concepts reviewed by representatives of this broad community. The identification of three categories of satellite missions represents a significant departure from the prior programmatic outlook of the Office of Earth Science. The original architecture of the Earth Observing System attempted to combine all three types of missions: a series of three identical platforms were to be flown successively, carrying the same complex instrument payloads designed to study processes, provide long-term continuity of measurement, and demonstrate innovative measurement techniques that could be transitioned to operational partners. Under the current approach, a determination needs to be made early in the planning cycle concerning the specific purpose and category of each mission. The basic characteristics of these three mission categories were defined in the Overview (section 3.2) and are summarized briefly below.

Systematic Measurement Missions

The systematic measurement program is designed to provide consistent time-series of observations of the key environmental parameters that best characterize the natural and forced variations of the total Earth system and changes in relevant forcing factors. The goal of ESE is to define a limited set of parameters for systematic measurement that includes only enough parameters to characterize the key independent forcing and response factors that cannot be inferred from measurements of other parameters based on knowledge of the processes that connect them. To this end, it is critical that systematic measurements include those of parameters governing the physical, chemical, and biological state of the Earth system along with external forcing factors. Within a given category, the list of systematic measurements will typically not include parameters that can be calculated unambiguously from one or several parameters that are observed. For example, it is desirable to reduce the number of chemical constituents that must be observed systematically, but not so much that the number of truly independent basic physical state parameters is reduced. As another example, global precipitation must be observed systematically because it cannot yet be precisely inferred from systematically observed meteorological parameters such as temperature and moisture.

The intent is to acquire long enough records, with the required sampling density and measurement accuracy, to characterize specific Earth system variations and their causes. The systematic measurement missions typically build on existing observation methods and aim for consistency with previous measurement series. While new systematic observation missions may take advantage of improved measurement techniques, the continuity objective usually implies that technological innovation will be restricted to incremental changes, driven more by the need for reduced cost than performance upgrade. (It is important to note that technology improvements may be made through technology-oriented missions, such as the New Millennium Program described in the ESE Technology Plan.) Whenever possible, NASA will seek to leverage the related global measurement programs of national and international environmental agencies that are mandated to deliver operational services, and/or acquire the data needed to achieve its scientific research objectives from commercial information providers.

Systematic measurement is not synonymous with continuous measurement, although the simplest way to assure systematic measurements is to have a continuous series of measurements, ideally with adequate overlap between successive sensors that questions about inter-instrument differences can be answered. The strongest requirement for continuity (overlapping measurement records) between successive measurement series occurs when the variability in a given parameter is small relative to the ability to provide accurate calibration for a satellite sensor, either in terms of pre-launch laboratory calibration or, where appropriate, through comparison with closely related ground-based or in situ observations. Thus, for example, total solar irradiance (TSI) is a parameter for which the overlap requirement is extremely important, given the small variability in TSI and the difficulty in assuring exact calibration of radiometric sensors in space. On the other hand, when a geophysical signal is varying relatively slowly and sensors can be well calibrated, gaps between successive measurements may be acceptable. For example, Synthetic Aperture Radar (SAR) mapping of the major continental ice sheets only needs to be done about every five years to check for major changes in the ice shelves.

The maintenance of a stable and accurate terrestrial reference frame is an example of a systematic measurement which must be made over decadal time scales. How do we measure the millimeter per year change in sea level or ice volume when everything on Earth is moving- even the continents? The terrestrial reference frame captures the Earth’s constantly changing shape change over time to allow for the comparison of physical measurements of Earth over decadal time scales. NASA developed the space geodetic techniques that now serve as the supporting measurements for maintenance of the terrestrial reference frame. The terrestrial reference frame enables satellites to navigate with centimeter precision providing clear images of the El Nino and La Nina, revealing the first complete measurement of the global ocean floor, allowing the comparison of millimeter scale sealevel rise over decadal time scales. Society is becoming increasingly dependent upon the terrestrial reference frame for the long term registration of data within geographic information systems (GIS), land surveying , timing, and other similar civilian applications. Discovery has been enabled by the continuing improvement in the accuracy of the terrestrial reference frame by nearly a factor of one thousand over the past thirty years.

In general, the ESE plans for continuity of key systematic measurements, with the understanding that gaps or discontinuities may occur in the case of premature failure of a sensor or spacecraft. The ESE plan does not provide for instantaneous (in-orbit) replacement of systematic measurement missions. However, through close interactions with its domestic and/or foreign partners (including participation in pre-launch calibration, algorithm intercomparison, etc.), contingency dispositions can be made to complete a measurement record with data from non-NASA assets, should a gap develop in a systematic measurement series. A significant component of the ESE scientific research program is the development of integrated, long-term, multi-sensor/multi-platform data sets for environmental parameters will be particularly useful in such cases, as well as the more typical cases of transition from one sensor to its replacement. Such contingency measures have, in fact, been a long-term feature of the ESE program applied to data sets as diverse as the total ozone from the Total Ozone Mapping Spectrometer and Solar Backscatter Ultra-Violet instruments, or sea surface temperature from the Advanced Very High Resolution Radiometer data and ship or buoy measurements.

Exploratory Satellite Missions

Exploratory missions are focused on scientific discovery and are designed to acquire new or dramatically improved global-scale measurements and to yield new or deeper insight on a specific component or process of the Earth system. The intent is that each exploratory satellite project should be a one-time mission that would deliver conclusive scientific results concerning a focused set of scientific questions. In some cases, this may involve measurement of several related parameters so that closure tests may be carried out (as has frequently been the case in the past in atmospheric chemistry measurements, in which simultaneous observations of long-lived source gases, reservoir species, and free radicals are made), while in others it may involve a pioneering measurement of one or a small number of new environmental properties (such as will be the case with the upcoming GRACE mission, in which the spatial and temporal variation of the Earth's gravitational field will be mapped with unprecedented accuracy).

No commitment for long-term measurement is made with this class of mission, although it is possible that the results of an exploratory project could result in the recognition that it would be beneficial for scientific and/or operational purposes to initiate a continued observational program to fulfill the scientific objectives of the ESE. For example, the success of the space-based precipitation measurements made with the TRMM satellite have led to a proposed project to undertake systematic measurements of global precipitation in the future, in conformity with the original plan for the EOS program.

The guiding principle for the exploratory satellite program is the promotion of new scientific ideas and technical innovations. For this reason, the exploratory satellite program cannot be rigidly planned: successive flight projects will be chosen on the basis of periodic calls for proposals and a selection process involving peer review. The solicitations for exploratory satellite missions will indicate those scientific questions of greatest interest at any given time but will allow for possible selection of a mission addressing any scientific question if that mission best meets the criteria established in the Overview, Section 2.1. In particular, the ESE needs to allow for the possibility that advances in technology may enable a new class of measurement not previously possible. It is essential that the selection process for exploratory missions have sufficient flexibility to undertake promising new measurements.

Operational Precursor and Technology Demonstration Missions

The ESE recognizes that requirements for ever more comprehensive and accurate measurements place increasing pressure on environmental agencies and require major upgrades of existing operational observing systems. In order to enable such advances, NASA will invest in innovative sensor technologies and make available more cost-effective versions of its pioneer scientific instruments, such as can be used effectively by operational agencies or commercial operators. The Implementation Plan identifies several operational precursor or "bridging" missions that will lead to future operational deployment in low Earth orbit or geostationary orbit during the next decade, principally within the framework of the NPOESS and GOES programs. Active participation of operational user agencies or partners is essential in the definition and development of these new observing systems and their transition to operational deployment. The currently planned NPOESS Preparatory Project (NPP) is a particular example, as it will not only provide early flight opportunity for two instruments selected by NPOESS but also provide the first flight of the Advanced Technology Microwave Sounder (ATMS) instrument being built by NASA.

The primary objective of technology demonstration missions is to promote and validate breakthrough technical innovations in new sensor concepts and spacecraft components. Technology demonstration missions may also constitute a major first step toward the realization of future operational instruments that may be deployed as part of operational observing systems (e. g. high-resolution land cover imaging radiometer; geostationary atmospheric sounder). Technology demonstration missions are normally conducted under NASA's New Millennium program and are part of the ESE technology program that parallels the scientific research program.

The first operational precursor mission likely to be implemented is one for the direct determination of tropospheric winds. Other potential missions which have been identified in this category include lightning detection from a geostationary platform (Lightning measurements have been demonstrated from low earth orbiting platforms, but not from a higher altitude platform that provides the opportunity for better temporal sampling than the twice a day measurements available from low earth orbit.); high resolution gravity change measurement to track the movement of water from the ocean to land or ice cap; high spatial resolution, steerable, multi-spectral imaging for use in geostationary orbit for focused observation of rapidly-evolving events or phenomena ("special events imager"); and improved geostationary soundings of the temperature and humidity of the atmosphere (first being tested through the New Millennium Program via its selection of the Geostationary Infrared Fourier Transform Spectrometer (GIFTS) instrument for launch in 2003).

7.2.2 Sub-orbital Observations

The ESE recognizes that a coherent Earth science research strategy must combine findings from global observations with insight gained from specialized studies, especially *in situ* measurements or airborne remote sensing at much higher spatial and temporal resolutions than currently possible from space. Sub-orbital observations supported by the Earth Science Enterprise are largely of four types – ground-based, oceanic, airborne, and balloon-borne. These are used for a variety of purposes, including detailed process-level understanding, calibration and validation of space observations, proving the feasibility of measurement approaches designed for new types of space-based observations, and in a limited number of cases providing information on long-term trends (e. g. aerosol optical depth data from atmospheric transmission measurements). The ways in which sub-orbital measurements contribute to studies of the different components of the Earth system and linkages between have been described in the previous chapters, but it is helpful to review the contributions which they make to the ESE program.

The sub-orbital measurements contribute unique scientific information in several areas. The surface-based observing programs of Federal agency partners in the USGCRP are especially important for the advancement of Earth system science. Examples include NOAA's TOGA array of ocean buoys that complement satellite altimetry in observing ENSO events, DOE's Atmospheric Radiation Measurement (ARM) program complementing satellite measurements of radiation transfer in the Earth's atmosphere, and DOE's Ameriflux network of towers whose carbon dioxide flux measurements are useful to validate space based measurements of primary productivity (e.g., NDVI).

Ground-Truth and Comprehensive Process Observations

In situ and remote sensing measurements made at the surface of the Earth, in the ocean, or in the atmosphere provide "ground truth" against which space-based measurements are compared. They also help strengthen our knowledge of processes through comprehensive characterization of active sites or specific regions at a given time, which is not usually possible with remote sensing techniques. This is particularly true of measurements in the area of chemistry, radiation, and biology. The large number of chemical species whose concentrations are related by photochemical, transport, and microphysical processes (and are needed if quantitative tests of chemical mechanism sets are to be carried out) cannot typically be observed from satellites, and in situ observations (most typically made from airborne platforms) provide the completeness necessary for such tests. For atmospheric radiation studies, such measurements that may include information on the concentration of aerosol and cloud precursors, the physical and chemical properties of aerosol and cloud particles, and measurements of the radiation field which is strongly affected by the presence of particles. In biological studies, observations may include detailed characterizations of the distribution and availability of the chemical nutrients necessary for supporting organisms, of the range of biological species present at a site, and of the transfer of material between organisms and the environment.

These comprehensive data sets can form the basis for critical tests of models used to represent key physical, chemical, and biological processes. These "process models" can be applied to a range of geophysical conditions and can also be included in global models, either directly or in parameterized form. The role of process models is described in section 7.2.1 below. These ground-based observations can also help identify "surrogate measurements" that can be made globally through space-based remote sensing techniques.

Time Resolution

Sub-orbital measurements may allow for intensive sampling in the temporal domain, ranging from the resolution of diurnal variations (not possible from space-based observation in low earth orbit), to the characterization of seasonal and interannual variability at a limited number of sites. They can also provide continuous measurements under a range of conditions, including observation of surface parameters in unfavorable (e. g. rainy or cloudy) weather that can block space-based remote sensing. The temporal sampling can be particularly important for those parameters that are significantly affected by clouds, such as those involving the surface radiation budget and the surface flux of UV radiation. Without such temporal sampling, it can be difficult to determine diurnally averaged quantities given the large variability that clouds can introduce and the limited temporal sampling of most space-based systems, i.e., those in low Earth orbit.

Spatial Sampling

In situ and surface-based remote sensing techniques may provide capability for vertical sampling not possible from space. These include probing the detailed vertical structure of the lower atmosphere, the oceans, soils, vegetation canopies, and ice. Detailed vertical resolution not only provides process-level information but also constrains and tests algorithms used in remote sensing observations. An example of the latter is the use of shallow ice probes on ice sheets to evaluate the relationship between snow accumulation rates and space or aircraft-based microwave measurements.

In situ sampling also can provide information about the detailed spatial (both horizontal and vertical) variability that is averaged over in many remote sensing observations. This is a particular problem with atmospheric limb sounding, which involves a very long measurement pathlength through the atmosphere. Any inhomogeneity in the composition of the air masses viewed by the sensor can complicate the interpretation of the satellite observations. Such inhomogeneities can arise in particular when the atmospheric ray path cuts across strong gradients or encounters the presence of clouds or aerosols in part of the field of view. Sub-orbital measurements that are made coincident with such satellite observations can be very useful in aiding the interpretation of the space-based measurements. *In situ* sampling can also characterize spatial heterogeneity in surface properties that occurs at scales finer than the spatial resolution of surface images (i.e., sub-pixel variability).

Calibration Consistency

Sub-orbital measurements allow the possibility for assuring consistency of calibration over time because accurate laboratory calibrations can be performed either during the measurement sequence for ground-based sensors or for both pre- and post-flight for aircraft- and balloon-based sensors. This contrasts with the calibration possibilities for space-based measurements from free-flying satellites, for which laboratory-based comparisons with fixed standards are only possible before launch.

7.2.3 LABORATORY AND/OR PROCESS MEASUREMENTS

The intellectual capital for both the planning and exploitation of Earth system observations is vested in an active research and analysis program. The ESE research and analysis program is conducted along both traditional discipline lines and selected interdisciplinary themes. It includes activities driven by current Earth science questions as well as opportunities to exploit the data from specific observing systems. The ESE research and analysis program is strongly focused on Earth System Science, has defined the Earth System Science issues identified in preceding chapters, has developed strategies to bring fundamental Earth science research to bear on these issues, and has laid the interdisciplinary groundwork for the modeling activities described below.

While the physical, chemical, and biological laws that underpin Earth system phenomena are well known for the most part, there are needs for specialized theoretical or laboratory investigations to strengthen the existing knowledge for quantitative modeling and the formulation of algorithms that relate the desired environmental properties to remote sensing data. Furthermore, remote sensing techniques often rely on very specific and still insufficiently determined properties of electromagnetic signals observable from space. Specialized laboratory measurements are needed, for example, to determine with needed accuracy molecular and particle optical properties, chemical reaction rates, reflectance, emittance, and scattering properties of surface materials, and metabolic rates of organisms under various environmental conditions. The results of such focused laboratory measurements frequently comprise critical input into process-level models that are used to represent the detailed operation of processes in the environment.

7.2.4 Observation Inter-comparison, Validation and Integration

The different types of observations available through the Earth Observing System are frequently used in a coordinated way and typically involve pairing of satellite-based and sub-orbital observations. The two main reasons for this are (1) the validation of space-based sensors and (2) the joint application in field campaigns in which the "top down" and typically larger-scale observations from space-based sensors are combined with higher spatial resolution and more comprehensive observations available from ground-based or in situ platforms.

Satellite validation can involve both surface-based and airborne measurements. The most straightforward approach to validation is to compare the results of measurements of the same quantity made concurrently by different methods to see if they agree within their respective known errors. Where widely distributed ground-based networks are available, such comparisons can provide a good first-order check of new sensors as well as an objective test of the differences between related satellite instruments. In many cases, comparisons of this sort are conducted using operational networks of other organizations. For example, total ozone observations are typically compared with total ozone measurements from the International Dobson network, while ozone vertical profile measurements are compared with corresponding measurements from the international ozonesonde network (both those networks are coordinated through the World Meteorological Organization's Global Atmosphere Watch program). Similarly, ocean altimetry measurements are compared with sea-level measurements from precision tide gauges. Other measurements may be compared more directly with NASA-provided ground-based instruments; examples of networks used at least in part in this way include the Network for Detection of Stratospheric Change (NDSC), used for comparison with space-based atmospheric chemistry measurements, and the Aeronet network, used for comparison with space-based atmospheric radiation and aerosol studies.

Another type of validation is the direct comparison of space-based and airborne measurements. Such comparisons are of particular interest when new remote sensing observations are made for the first time and comparison with observations from similar airborne instruments with substantial heritage can provide confirmation of the operation of the space-based sensor. The validation of the TRMM precipitation radar measurements using airborne radar is such an example. In a number of cases, dedicated airborne simulators of space-based instruments are constructed and used to establish significant experimental heritage prior to the flight of the space-based sensor. Airborne simulators have been built for several EOS instruments, notably MODIS, MOPITT, and MISR; these airborne simulators have been widely used within the ESE airborne observation program for a range of environmental studies.

Most process-oriented ESE field campaigns make active use of space and sub-orbital measurements. The space-based measurements frequently provide the wider spatial context for the more focused (and geographically localized) surface-based and/or airborne observations. The comprehensive measurement capability available from surface-based and/or airborne observations complements the broader spatial picture (but typically more limited parameter suite) observable from space. Thus, field campaigns in various areas, such as BOREAS, LBA, and the various FIRE campaigns, were all planned from inception to combine surface-based, airborne, and space-based sensors.

Finally, it is worth noting that as new surface-based and airborne measurement capabilities become available, it is frequently necessary to carry out detailed intercomparison of related measurement techniques. This is particularly important in those cases where different measurement techniques obtain different values for what should be the same quantity. An example of this has been the past inconsistency in measurement of total odd nitrogen in the upper troposphere, for which multiple instruments have been flown side-by-side on aircraft to help characterize the nature of the inter-instrument differences. Such intercomparisons will be made in the future as circumstances demand.

7.3 EARTH SYSTEM MODELING

The development of models that can simulate the full Earth system, including the key processes that link the different components is the ultimate aim of the modeling component of the Earth Science Enterprise. Such fully interactive models can only be developed through the linkage of less ambitious models that simulate individual components of the Earth system and critical coupling processes. Thus, the ESE modeling strategy is to build up from focused process models that are designed to simulate some particular mechanism in great detail, through component models that simulate the behavior of a major component of the Earth system, to interactive multi-component models that simulate the coupled behavior of two or more components of the whole system. Process and component modeling efforts need to be balanced by larger scale modeling efforts focused on linkages and coupling between several components. Models can be used in a diagnostic way as a test of our understanding, based on observations and a view of how the system works. They can indicate gaps in observational data and help identify critical variables requiring better characterization. Models also can be prognostic, or predictive, and assist in guiding future actions or policies.

Although the focus of the modeling effort is on the science associated with the conception and evaluation of models, significant technical challenges also exist associated with the development of numerical codes and the exploitation of the models. The extreme demands placed on high-end computing by long-range climate simulations with state-of-the-art atmosphere-ocean-land models cannot be met by faster and more powerful computer equipment alone. Corresponding investments are needed in numerical analysis, development of faster model codes, and implementation of faster application software, optimized for running on the massively parallel supercomputer systems that are likely to become prevalent in the future. On the other hand, it is clear the such model code optimization places a significant burden on the groups developing such models, and a balance needs to be struck between optimization of codes for specific machines and developing the software tools and hardware that will allow for the relatively easy use of existing and newly developed codes in a variety of computational environments.

In other areas, significant challenges associated with data availability limit model advancement. In particular, ecological models, coupled surface-atmosphere models, and biogeochemical cycling models are most limited currently by the availability of quantitative, accurate measures of the entire global land and ocean surface for their initialization and testing. Satellite data provide the only feasible alternative when consistent complete global measures of surface properties are required. In some cases, these models are also severely limited by current understanding of key ecological processes (e.g., carbon allocation, root function, ecological disturbance). Thus, research to advance total Earth system modeling must proceed along a number of fronts simultaneously: increasing computational capability and software optimization, developing and improving observational data sets, and improving our understanding of controlling processes and how to effectively portray them in models.

NASA is interacting closely with modeling efforts in other federal agencies, notably the Department of Energy and the National Science Foundation to help promote the development of computer hardware and software, as well as the specific modeling frameworks and algorithms, that will together enable the enhancement of modeling capability. Close involvement of ESE in NASA's High Performance Computing and Communications (HPCC) initiative is an important element of NASA's strategy for advancing the state of Earth system modeling.

7.3.1 Process Models

Process models are designed to provide detailed representations of physical, chemical, or biological processes that occur within the Earth's system. These models are typically developed with full knowledge of the findings of process-oriented observational campaigns, especially studies based on comprehensive analyses of frequent, high resolution measurements of a large number of parameters. The existence of a comprehensive set of observations together with the development of a model based on well-defined physical, chemical, or biological processes provides a strict test of one's understanding of these processes. A model that accurately represents a large number of related quantities is more effectively constrained by observations, can be more thoroughly tested, and is more likely to be correct than "simple models" which simulate only a limited set of observables.
Realistic process models, carefully evaluated through comparison with independent observations, provide critical tests of our understanding of specific environmental processes and can be used for a range of environmental conditions. Applied in this way, they can predict observational parameters that can then be quantitatively tested through additional observations. Such models can thus provide guidance for the conduct of observational programs and help in identifying spatial or temporal regions of disagreement between theory and observations. When disagreement is found, consideration of the observed discrepancies helps focus further research efforts on related conceptual issues and observable parameters.

Process models, because they attempt to account for as much detail of a process as possible, are frequently very complex and computationally demanding, and thus are not usually well suited for direct use in global models of the Earth system or its components. In such cases, parameterizations of process behavior are developed so that the important biological, chemical, and physical processes can be represented in the global models with the computationally daunting details omitted. The parameterizations are typically tested through comparison with process models and then applied in larger-scale models. Process models applied to limited regions can also be nested within larger-scale parameterized models.

Examples of process models and associated simpler parameterizations abound in Earth science.; Several such process models are referred to in the relevant sections of the preceding chapters. e. g. with reference to the heterogeneous chemistry that takes place on aerosol and cloud particles in the stratosphere, the formation of cloud particles in convective systems in the atmosphere, etc. In all cases, detailed process models are developed on the basis of chemical, biological, and physical principles and tested by comparison with comprehensive observations made in airborne campaigns. The development of corresponding parameterizations that can be quantitatively evaluated through comparison with large-scale and global observations is an essential complement to process modeling.

7.3.2 Component Models

Model development is frequently initiated by focusing on the dynamics of one component of the Earth system, while the roles of the other components are held fixed or otherwise specified as a time-dependent external boundary conditions or "forcings". These component models frequently correspond to the subjects of traditional Earth science disciplines: meteorology, atmospheric chemistry, oceanography, ecology, solid earth, etc. Models in this category may be used to simulate the present, past, and future evolution of an Earth system component, although assumptions must be made about the effect of changes in other interacting components of the total system. By focusing on a single component, such models necessarily ignore or overly simplify the interactions and feedback processes that may exist with other components. On the other hand, single component models provide a means to very carefully describe that component and to focus computational resources for higher spatial and temporal resolution, or for more detailed representation of operative processes, than would be possible in a more comprehensive model.

Numerous examples of component model applications are given in the previous chapters. For example, atmospheric general circulation models that use specified sea surface temperature fields provide important information on atmospheric evolution over a wide range of time scales, including response to seasonal, interannual and longer-term ocean temperature anomalies. However, such atmospheric models clearly cannot represent the critical feedback loop between the atmospheric and oceanic circulations. Similarly, models of ocean biology may include an assumed flux of nutrient substances from the atmosphere but cannot represent the actual variations in this flux caused by changes in meteorological or conditions; therefore they might miss an important source of biogeochemical variability. It is important that the limits inherent in the use of single-component models that are not coupled with the other components of the Earth system be fully recognized in drawing conclusions from the results of such model simulations.

7.3.3 Model Integration Strategy

The development of interactively coupled models that realistically link different components of the Earth system is one of the most important goals of NASA's Earth Science Enterprise. Given the current limitations of computing power as well as limitations in our understanding of many relevant biological, chemical, and physical processes, it makes the most sense to use an incremental approach in linking together different Earth system components in coupled models. In this way, the effect of including the most critical interactions and feedback processes can be investigated through a series of numerical experiments, and the resulting coupled model simulations can be critically evaluated through comparison with observations.

Several successful examples exist of coupled models that represent some of the most critical interactions that link Earth system components. For example, the NASA Seasonal to Interannual Prediction Project (NSIPP) includes a realistic representation of physical and dynamical coupling between the atmosphere and ocean and of hydrological coupling between the atmosphere and the vegetated land surface. The resulting model is thus capable of simulating seasonal and interannual variability in the atmospheric circulation, temperature and moisture structure, and precipitation, as well as relationships with ocean surface temperature and land surface hydrology (soil moisture, snow accumulation, etc.). An important part of the NSIPP effort is maximizing the use of remotely sensed data by employing the most advanced data assimilation and initialization schemes for the moderately slow components of the coupled system: the upper ocean and the land surface. NSIPP is using a three-step approach to develop an experimental capability to predict significant climate variations on seasonal-to-interannual time scales. The first step consists in coupling component oceanic and atmospheric general circulation models (GCM's) and testing the coupled model for its ability to predict the interaction between the two media, especially as manifested in the tropical Pacific as El Niño and La Niña occurrences. The second step consists of coupling a land surface model with hydrology to an atmospheric GCM and testing the result for its ability to predict land surface hydrology and its evapotranpirative feedback to the atmosphere. Evapotranspiration feedback is especially important during the warm season over large continental areas. Predictions with both of these two-component coupled models are executed with prescribed forcing from the uncoupled component. The third step consists of coupling the atmospheric GCM to both the ocean model and the land surface model for three-way coupling. The resulting coupled system is then to be tested for its ability to predict both the simultaneous and lagged effects of El Niño and La Niña occurrences on the seasonal climate of North America and other regions of the world. The immediate goal is to make predictions with a useful level of skill up to a year in advance. Longer-term goals include extending predictive capability to interannual time scales and relating El Niño and other seasonal-to-interannual climate variations to decadal and longer climate system variability and trends.

NSIPP activities are connected both to the needs of other agencies, especially NOAA, and to other research efforts in the seasonal-to-interannual climate community. NSIPP coordinates with NOAA's Climate Prediction Center and will make its advances in seasonal-to-interannual prediction capability available to the Center for possible operational implementation. NSIPP has established a working science team of collaborating researchers from the broader community to help in achieving its goal. Some of the important tasks that the science team will assist with include assimilation of ocean data, improved representation of ocean/atmosphere coupling processes, inclusion of the effects of sea ice, testing of alternative component models in the coupled predictive system, and diagnostic evaluation of model simulations.

Similarly, the climate models developed at NASA's Goddard Institute for Space Studies (GISS) include realistic representation of individual and combined effects of different forcing factors on the Earth's climate, especially the role of aerosols on atmospheric climate, and the effects of variations in solar radiation, land surface properties, and atmospheric ozone distribution. Calculating the response of the model atmosphere to these combined forcing factors and comparing the simulated response to global observation records are essential aspects of this work. The focus of the GISS modeling effort is directed mainly (though not exclusively) toward the causes of climate variability and change on decadal and longer time scales.

GISS is engaged in making major improvements to its component models in order to represent the total climate system with greater fidelity. A series of workshops is being held in order to bring in community expertise and to develop collaborative modeling activities with outside researchers. So far, workshops on ocean, land surface, and sea-ice modeling and coupling with atmospheric models have been held, along with workshops on atmospheric aerosol modeling and on the observational data base needed for model evaluation. Workshops on other aspects of model development, testing, and application will be held as warranted. Among the applications of GISS models are the role of aerosols in radiative forcing of the climate (both directly and indirectly through cloud modification), the role of solar variability and deeper ocean overturning on climate variations, and feedbacks to climate by land surface vegetation and sea-ice extent. GISS participates in the five-year assessments of the Intergovernmental Program on Climate Change (IPCC) as well as in national climate assessment activities. Increased coordination of GISS modeling activities with those of NSIPP and with other major modeling activities is being developed.

Modeling research at the University of Wisconsin and other institutions that is focused on linking our understanding of the terrestrial biosphere with that of the physical climate system has yielded two important advances. First is the recent development of "Dynamic Global Vegetation Models" (DGVM), which can be used to simulate transient changes in ecosystem processes and vegetation cover in response to climate change or land use. Second is the coupling of terrestrial ecosystem models with atmospheric General Circulation Models. Fully interactive, coupled climate-vegetation models will be able to evaluate vegetation feedbacks on the Earth's climate system, including those resulting from changes in land cover and land use.

Likewise, there has been appreciable interest in linking together atmospheric chemistry and climate models in order to simulate feedbacks between atmospheric chemistry and climate changes, as well as assess the relative impacts of slow climate variations and chemical changes on ozone distribution. Although the ultimate aim is to fully integrate complete atmospheric chemistry and climate models, much of the work to date involves either simplified representation of chemistry in climate models or simplified representation of climate dynamics in atmospheric chemical models. However, the nature of the dynamical, radiative, and chemical feedbacks associated with ozone and water vapor changes in the upper troposphere and lower stratosphere require that fully interactive and balanced coupling be developed to address these problems.

Models that simulate the effect of aerosols on clouds constitute another area of linkage. It has long been recognized that the presence of aerosols can affect the distributions and properties of clouds, but models that represented this interaction did not exist. Now, modeling efforts have begun to represent the formation of aerosols from precursors, their microphysical evolution and interactions with clouds. At this time, such models typically must simplify the simulation of aerosol microphysical processes, but it is increasingly clear that the complexity of aerosol composition and interactions with clouds can only be simulated by models designed to provide reasonably complete treatment of aerosol and cloud microphysics. Progress in this area is rapid and will be facilitated by a significant increase in space-based observations of global aerosol distribution and properties. Finally, simulations of the role of aerosols in providing nutrients for oceanic organisms are just beginning. Such models need to couple ocean dynamics, ocean biogeochemistry, and atmospheric processes that are responsible for nutrient deposition into the surface layers of the ocean. Again, the availability of global aerosol data and observations of biological activity in the ocean is driving the development and evaluation of such models.

A major challenge to the ESE modeling program is, therefore, to facilitate linking models for different components of the Earth system. Achieving this linkage requires the availability of well studied component models as well as sufficient understanding of the processes that link the components, particularly boundary layer processes that control the exchanges of momentum, energy, water, and trace chemicals between these components. For instance, models attempting to link the exchange of trace gases between the ocean and atmosphere must include a realistic representation of air-sea exchange mechanisms and their effects on trace gas distributions in both the surface layer of the ocean and the boundary layer of the atmosphere. The detailed knowledge necessary to develop rigorous (or sufficiently well parameterized) coupled models typically comes from the process models described in section 7.2.1.

The incremental strategy used by the Earth Science Enterprise in linking component models should help assure a smooth progression in state-of-the-art models despite the limitations in computing power and associated software systems that now exist. The strategy allows for different component model versions to be used in differing linkage studies. The specific structure of a coupled model is determined by the application for which it is intended. For example, fairly high-resolution atmospheric general circulation models will be needed to simulate processes that couple the atmosphere to land surface hydrology, for prediction of the evolution of the chemical composition of the atmosphere in a changing climate, or for diagnostic studies of atmospheric transport of carbon dioxide from various terrestrial and oceanic sources.

7.3.4 Earth System Models

In the longer term, the ultimate objective is the construction of fully interactive coupled models that include the full range of physical, chemical, and biological processes occurring in the Earth system. Such comprehensive models are conceivably needed to identify and assess the non-linear impacts of the combined interactions and feedback processes that operate in the Earth system. In particular, coupling the three classes of processes (physical, chemical, and biological) noted above would represent a significant advance over most existing coupled models, which tend to include at most two among these three classes, as described in the previous section. Future fully coupled models should also be capable of simulating multiple spatial and temporal scales, given the great interest in both the scientific and policy communities for information across a wide range of scales. Such coupled models would be especially useful for regional and global assessments of future environmental trends and would help document the full diversity of expected changes in the total Earth system. Variable grid and nested models may play an important role in allowing for high spatial resolution where needed without sacrificing computational efficiency.

The development of this class of models will require a careful analysis of the quality of the component models, the knowledge of interactions and feedback processes being considered, and the availability of adequate computational resources. Clearly, it makes little sense to couple two or more inadequate component models into an even more unreliable linked model to represent complex interactive phenomena when the underlying processes are not well known. On the other hand, much can be learned even from imperfect models. One cannot wait for perfection in each component model to begin learning about emergent phenomena resulting from first-order interactions between various components of the Earth system. For this reason, a detailed ESE research strategy for the development of fully interactive Earth system models has not yet been formulated, although it seems clear that the greatest challenges in this area will be integrating biological models into the physical modeling framework. This task will become particularly difficult for longer-term simulations, as our knowledge of the biosphere responses to changes in climate, atmospheric trace gas composition, etc. over long periods of time is much more limited than our knowledge of shorter-term responses. The Earth Science Enterprise expects to make significant investments to include chemical and biological processes in coupled earth system models over the coming few years.

7.3.5 Assessment Models

The atmospheric chemistry community has a long history of supporting assessments of the impacts of various disturbances on the atmospheric environment. The most widely known among those are the periodic Scientific Assessments of Ozone Depletion, carried out on behalf of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) as well as the assessment of climate forcing factors on behalf of the Intergovernmental Panel on Climate Change (IPCC, 1995). Comparable studies have been organized in cooperation with NASA's Office of Aero-Space Technology to assess the impact of projected aircraft traffic on the composition of the atmosphere and climate. Model simulations, incorporating given scenarios for changes in relevant forcing factors, constitute the most compelling means to estimate the potential impacts of anticipated changes on all aspects of the global environment. For these assessments, both retrospective diagnostic model studies simulating the past evolution of the global environment using known or assumed changes in forcing, and prognostic studies aiming to simulate the potential future evolution in response to anticipated changes in forcing, are effective means to provide the scientific information required by responsible authorities. The international assessments of global climate change sponsored by the IPCC and participating nations make extensive use of nested (fine-mesh) climate assessment models to explore the full range of potential environmental impacts on the appropriate regional scales. The application of such models as they become available will form an important part of NASA’s contributions to the national assessment of climate change carried out in the US as well as to IPCC assessments. Similarly, ecological models will be applied to explore scenarios of ecosystem change within national environmental assessments as is being done now using the VEMAP models for the U.S. in the National Assessment of Potential Consequences of Climate Variability and Change.

7.4 LINKAGE OF OBSERVATIONS AND MODELS

Although observations and models have been discussed separately in the preceding sections, it is important to emphasize that the maximum benefit of each can only be achieved by combining both resources. NASA’s strategy is designed to assure very close linkage between the observational and modeling efforts. Some reasons for this linkage are obvious: initial conditions of models used for prediction should be as accurate as possible, and global observations provide an accurate means to initialize many model parameters. Similarly, the evaluation of global model performance depends on the availability of sufficient observed data, and the global observations made by NASA are among the primary data sets that can be used for this purpose.

Other connections between models and observations are perhaps less obvious. Two of these are inverse modeling and data assimilation. In the former, a global model is used to help assess some elements of the earth system (for example, the sources and sinks of long-lived trace gases) given observations of the distribution of a parameter of interest and knowledge of the other environmental processes that affect it. Data assimilation assures the optimal combination of observations and short-term predictions of a global model to provide accurate, physically consistent, and globally distributed data sets. Details of NASA's activities in these areas are given in the following sections.

7.4.1 Inverse Models

Most Earth system modeling is done in the direct mode by calculating the likely environmental response to a known or assumed evolution of forcing factors. However, in many cases, the forcing factors and especially their geographic distribution are not completely known. In such cases, models may be used together with observations of the response of the Earth system to infer the values of the forcing factors. This approach is known as inverse modeling, as the intent is to "go backwards" and infer what forcing factors gave rise to the observed response.

The application of inverse modeling is critically dependent upon the availability of accurate and complete observational data to characterize the response of the environmental parameters of interest and their spatial and temporal changes. The global data sets provided by the Earth Science Enterprise, as well as the data provided by its partner agencies, are critical elements of any strategy using inverse modeling. For instance, the sources and sinks of chlorofluorocarbons (CFC's) have been estimated, using atmospheric tracer transport models, on the basis of surface concentration data obtained by the AGAGE ground-based observation network described in Chapter 3. Annual emission inventories of CFC's have been estimated and compared with known production figures and their corresponding geographical distributions using similar inverse modeling techniques. More recently, there has been significant interest in using inverse modeling to better constrain our knowledge of emission and uptake of carbon dioxide. Ground-based measurements of CO_2 concentration made by the flask sampling network of NOAA's Climate Monitoring and Diagnostics Laboratory provide the crucial information for this purpose. A continued emphasis on inverse modeling studies of CO_2 is expected as new information on the terrestrial and marine biosphere become available from the Terra satellite. In the near future, inverse modeling is expected to be used for a variety of other trace gases, including carbon monoxide and methane observed by the MOPITT sensor aboard Terra.
In order for the inverse modeling approach to give useful results, it is necessary that either only one relevant forcing factor is inadequately known or that one forcing factor is dominant over all others. Otherwise, it is difficult to determine the spatial and temporal arrangement of forcings that results in the observed environmental variables. For example, inverse modeling has been used at NASA/GISS and elsewhere in an attempt to determine the role of solar variability (imperfectly known earlier than the last few decades) in past climate variations. In order for the results to be meaningful, one has to either know the other forcing factors such as greenhouse gases quite accurately or assume that, at least in some eras, solar variability was the dominant forcing.

7.4.2 Data Assimilation and Model Evaluation

Data assimilation is the process by which observations and model simulations are optimally combined to provide environmental variable fields that are accurate, internally consistent, and geographically homogeneous. The "direct models" that are used in this process are not perfect and may have a number of systematic errors or limitations. Indeed, the added value of data assimilation methods strongly depends upon the predictive skill of the model which is used to bring forward in time the "memory" of past observations. Furthermore, the internal consistency of data assimilation products reflects, to a considerable degree, the specific process-level assumptions made in the model, resulting in a "model climate" that may differ significantly from the real climate. Since the forward model prediction used in most assimilation systems is short (typically 6 hours in atmospheric assimilation systems), most relevant parameters are usually quite accurately carried forward, though there are exceptions (e.g. winds in the atmospheric jet streams). However, if predicted variables are not updated by observations in nearly every cycle, and in some regions and times they may not be, the

predicted fields will indeed show drift toward those of the model climate. Thus, considerable care must be given to the quantitative interpretation of findings based on data assimilation products.
Nevertheless, the need for internally consistent and globally homogeneous data sets is so pressing that Earth system scientists will continue to make use of data assimilation products, even if the models do not provide perfectly accurate descriptions of the relevant parameters when run in a predictive mode. For this reason, NASA will continue to devote significant effort to improving scientific capabilities in this domain and reducing the residual errors in analysis products. The role of data assimilation is discussed in Chapter 4 in the context of meteorological and climatological applications and Chapter 5 in the context of oceanic applications. Applications of data assimilation to chemical and biological problems are still in their relative infancy, although there is increasing interest in such applications.

The scientific value of much of the new observational data produced by the ESE would be enhanced by being merged into consistent global data sets incorporating multiple related variables such as provided by "multivariate" data assimilation systems. Existing data assimilation systems, principally applicable to meteorological and oceanographic data, will need to be expanded to allow for the incorporation of different classes of measurements when new observing systems come on line. The ESE will vigorously encourage efforts to assimilate these new environmental observations, especially measurements not previously available on a global basis. Much of the effort in this area to date has focused on preparations for the assimilation of new data coming from the EOS Terra and Aqua missions. NASA's advances in assimilation systems and products will be shared with its operational partners, especially when improvement in the resulting products has been demonstrated with the assimilation of new types of observations.

As the range of assimilated variables expands, it is important that progress continues toward more capable and accurate assimilation systems. Continued research in data assimilation algorithms, especially as they relate to new types of measurements, will be an important element of NASA's research program. Similarly, the accuracy of the global models that are used in the assimilation process must be assured. It is desirable that the direct models used in the assimilation process have close heritage to those used in Earth system simulation activities. Thus, the assimilation and modeling activities must be closely linked. In fact, data assimilation provides an objective tool for evaluating the adequacy of global models and can highlight inconsistencies between observed and analyzed fields. In this way, specific model deficiencies can be identified, suggesting further model improvements.
A significant focus of NASA's current research in data assimilation is improvement of the core assimilating model used by the GSFC Data Assimilation Office (DAO). The short-term objective is to implement a higher resolution version (with a one degree by one degree grid) of the current assimilation system in order to realistically resolve meteorological fronts and other dynamically significant small-scale features of the atmospheric circulation. The DAO is also experimenting with use of a variable-grid version of the assimilating model that will have the capability of producing very high resolution in limited regions while retaining continuity with global atmospheric circulation and avoiding the numerical problems of nested grids. A major collaborative activity has been initiated with the National Center for Atmospheric Research (NCAR) in the development of a new assimilating model. This model uses a modern semi-Lagrangian advection algorithm to conserve flux quantities and to provide an order-of-magnitude increase in computer power over its predecessor. This model will also facilitate possible replacement of current physical parameterization schemes by others being developed by the climate modeling community. This collaboration is one example of the interagency coordination that is desired in the broad climate modeling and assimilation area.
Longer-term objectives of the DAO include implementing more advanced assimilation methods based on Kalman filter concepts and continuous updating of variable fields. Also, the DAO plans to generate reanalyzed model-assimilated data sets for up to 50 years using a consistent assimilation scheme for the entire time period. Such reanalyzed data sets are of great value for detection of climate variations and trends as well as providing a consistent data base for a wide range of climate diagnostic studies. The DAO is currently assimilating atmospheric observations along with some land

surface ones but will eventually integrate assimilation of ocean, cryospheric, and other land surface data into a more comprehensive assimilation activity. A major challenge for the DAO is developing the capability to do timely assimilation of new kinds of space-based data as they become available.
As was noted in the previous section on models, data assimilation provides a significant burden for the computational systems used. In particular, data assimilation involves significant input and output throughout the assimilation process, and advances in computer hardware and software designed to facilitate data assimilation must pay particular attention to ensuring the availability of both rapid computation speed and movement of data into and out of the assimilation system. Also, it is worth noting that the high spatial resolution desired in the assimilation systems of today and tomorrow will require significant storage capacity as well as the rapid input and output noted earlier. The developers of data assimilation systems will need to pay close attention to evolving computational capability and assure that the appropriate software systems and interfaces are developed to maximize the ability to capitalize on developments in computer hardware.

7.4.3 Model Evaluation and Inter-comparison

In the previous section it was noted that data assimilation provides one of the best ways to evaluate computational models because of the objective way in which model simulations are regularly confronted with observational data, thereby providing a means to quantitatively determine areas of inconsistency between models and observations. By continually comparing model products with measurements, data assimilation quantifies the mismatch between observations and model predictions and provides clues for further model improvements. The interactive optimization of model and data analysis is a systematic, structured, and open-ended learning process and is perhaps the single most important benefit of data assimilation in a research mode. This linkage has been successfully exploited in numerical weather prediction, and the challenge for the broader Earth science community is how to extend the application of assimilation systems to all relevant components of the Earth system. NASA places high emphasis on the evaluation of model performance through direct comparison with the rich sets of observational data collected by its observing projects. At the integrated model level, NASA sees the assimilation of global observational data as the principal means for verification of model results and validation of the representations of component processes. From this perspective, data assimilation is an excellent way to determine the quality of models used for diagnostic and predictive simulations as well as for assimilation.

Observations can also be used in a more traditional way for evaluating models. Several focused inter-comparisons of models with relevant observations have been or will be carried out, either collectively by an informal group of investigators or under the auspices of peer-led international scientific groups, such as the International Global Atmospheric Chemistry project's Global Integration and Modeling activity and the WCRP's Atmospheric and Coupled Model Inter-comparison Projects (AMIP and CMIP). Focused inter-comparisons of models with measurements have also been carried out for atmospheric chemistry models under the auspices of NASA's Office of AeroSpace Technology. These inter-comparisons also compare similar models to one another; this is important for understanding model-to-model variability, especially when there are insufficient data for quantitatively evaluating the processes of particular interest in the models. NASA places a strong emphasis on further quantitative evaluation and intercomparison of these models.

7.5 SUMMARY OF FUTURE RESEARCH DIRECTIONS

This section summarizes the principal directions for NASA observational and research activities envisaged in the next ten years. These prospects are based on a vision of new opportunities for research and technological breakthroughs, continued funding of Earth system science, the availability of the needed operational observing systems and computational resources, all of which are obviously not known in any detail.

7.5.1 Observational Research Directions

The first, and most obvious, direction of future observational activities in support of Earth system science is the proliferation of the observing systems capable of providing the same type of measurements as obtained today, such as multi-spectral imagery of the Earth's surface and clouds, radar imaging of terrain, and a range of atmospheric sensors on both operational and research environmental satellite systems. There are several causes for this proliferation: the increase in the number of space-faring countries that desire to engage in scientific research and/or operational data collection from space, new technologies that allow for miniaturization, integration of spacecraft and optical sensors, and overall cost reduction, and finally the increasing activity of the commercial sector in obtaining its own data. A major challenge to come from this proliferation will be ensuring the consistency of data sets for environmental parameters of scientific and/or operational interest.
The multiplicity of observing systems can leave the user with a complex set of choices: Which data set(s) do I use? On what basis do I choose? Can I put together an integrated data set that covers multiple instrument data sets, especially if they have been calibrated and validated through different procedures and protocols? If I need to "piece together" a long-term data set from several shorter-term data sets, how could I minimize discontinuities, especially if the assembled data set involves instruments from multiple providers? How can I be assured that data sets obtained primarily for operational purposes will be useable for longer-term global change studies? What do I do if I feel a need to create a new historical data set based on reprocessing of those previously obtained, especially if those were from multiple providers? Successfully answering these questions will involve the development of new relationships between research, operational, and commercial organizations, and require enhancements in the degree to which different agencies cooperate with each other.

Another direction for future advances in Earth system science is the exploitation of technological breakthroughs that may enable totally new kinds of observations. In the world of space-based measurements, there are five major areas of advancement that can be expected in the not-too-distant future and would have important implications for earth science research: (1) dramatic advances in the utilization of active optical sensors (lidars) capable of probing the lower reaches of the atmosphere, the land surface (and potentially, the topmost layer of the ocean) with great vertical resolution; (2) progress in active and passive remote sensing techniques operating at relatively low microwave frequencies that can penetrate relatively dense media (e.g., vegetation, snow, upper soil layers); (3) refinement of extremely precise geodetic and gravity field measurements that will give access to hitherto hidden properties such as changes in the distribution of water masses near the surface of the Earth; (4) development and implementation of new distributed observing systems involving multiple spacecraft, especially those that provide good geographical coverage of atmospheric parameters with high vertical resolution (mainly GPS based); and (5) expansion of quantitative measurement to include significantly improved time resolution, as may come from a next generation of geostationary sounding instruments, observations made from the L-1 Lagrange point, or modest constellations of spacecraft in staged low earth orbits.

7.5.2 Modeling Research Directions

The "holy grail" of Earth system modeling is to develop a unified comprehensive model that includes all possible linkages and interactions among the component parts of the system. With this model, interactions could be turned off to test the sensitivity of the Earth's variable environment to various processes or forcings, or replaced with simplified representations (e.g., climatological or similarly specified values) to reduce the computational load. While there is no doubting the inspirational value of this ultimate goal, most interesting and useful scientific applications can and likely will rely on more specialized modeling projects, each focused on a specific subset of relevant interactions and feedbacks. Even though there may not be much practical value in attempting to develop a "model of everything", care needs to be taken that more specialized models do not overlook or trivialize interactions and feedbacks that may in fact be significant for the given application.

The fact is that the on-going, possibly indefinite, progress in computational capabilities will drive the development of Earth system models. Advances in computer technology during the next decade will allow, for the first time, compiling and running models that actually embrace a wide enough range of spatial and temporal scales (Reynolds numbers) to explicitly simulate the dynamical connections between different natural categories of phenomena, for instance in the case of the atmospheric circulation:

- Linking global-scale changes in the atmospheric general circulation to organized weather systems such as tropical cyclones, frontal systems or squall lines.
- Linking organized weather systems to convective-scale phenomena, tornado- and rain-generating storms, and a diversity of terrain and terrestrial ecosystems (e. g. cloud ensemble models; limited-area atmospheric-hydrologic models, etc.).
- Linking cloud-scale dynamics to microphysical and chemical processes.

Another very significant direction of progress is the introduction of progressively more realistic representations of linkages between different types of processes, e. g. climate- transport dynamics-chemistry interactions, climate-biosphere-hydrology interactions, ice-sheet and sea-ice dynamics and forcing by atmospheric and oceanic circulations, climatic impacts on the spreading of disease vectors, etc. In other words, the emphasis of model development efforts will shift from representing large-scale dynamical transport and plane-parallel approximations of radiative and other fluxes, toward the detailed physical, chemical and biological processes that are actually taking place in the system. More attention will need to be given to the integration of modeling efforts and observational field studies, each supporting the other for optimal scientific advances. Recourse to ever more sophisticated explicit or lightly parameterized representations of basic processes will be essential in achieving effective synergy between model and experimental research.

Finally, a hallmark of the ESE modeling strategy is continued or increased emphasis on testing or validating model results against observations of the real Earth system. While observations without the appropriate model-generated theoretical framework may be more confusing than helpful, data-free modeling is not likely to be particularly productive either. NASA will support preferentially modeling developments that clearly can take advantage of the wealth of observational information collected by its global observing systems. In this regard, NASA expects that other Earth system model developments in the future will develop and utilize model-based observational data assimilation systems that are similar in purpose to those used successfully today for numerical weather prediction.

7.6 REFERENCES

NRC, 1998: *The Atmospheric Sciences Entering the Twenty-First Century*; National Research Council; Board on Atmospheric Sciences and Climate; National Academy Press, Washington, DC.