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A Study on Earth System Science

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Executive Summary

In order to address the pressing environmental and sociopolitical issues related to climate and the Earth System that are facing Brazil now, and that will be even more serious in the future, the Instituto Nacional de Pesquisas Espaciais (INPE) should take a series of bold steps.

1. *Develop an Earth System Information System*. In order to take maximal advantage of its unique geography, location and distribution of natural resources, Brazil needs an independent capability to make accurate and complete weather forecasts, seasonal predictions and long-term outlooks for the next one to two decades. Based on all available evidence, the best way to achieve this capability is for INPE to develop an Earth System Information System (ESIS). The Brazilian society, and the larger community of South America, will greatly benefit from an ESIS that includes all components of the ES (atmosphere, ocean, land surface, cryosphere, and marine and terrestrial ecosystems) in terms of education, research, disaster preparedness, resiliency, and capacity building. INPE should take leadership in encouraging the other countries in South America that have capability in various aspects of Earth System Science to form partnerships that can contribute toward building the ESIS.) The ESIS should be comprised of four components: an Earth System modeling capability, an observing system component, an Earth System analysis and understanding program, and solutions support.
    - **a.** *Earth System Modeling*. INPE should exert leadership in developing a model that can be used to predict the evolution of the Earth system from days to decades and that can quantitatively project the impact on Brazil, its society, its neighbors in South America, and its trading partners and allies. The capability for Earth System modeling includes (i) a major computing center that will grow toward petascale capability and beyond; (ii) a dedicated cadre of 200 scientists with domain expertise in all areas of relevance to Earth System Science and growth of the scientific core into areas that include interactions among Earth System components; and (iii) a strong interaction with stakeholders and the applications research community. Building this capability will also require strong interactions with the academic sector in Brazil to ensure a steady stream of new scientists trained in multi-disciplinary aspects of Earth System Science.
    - b. *Maintain and enhance its observational network*. Expand observing systems for routine monitoring and assessment and in order to provide global observational coverage of change in the atmosphere, oceans, and on land, especially as needed to underpin the research and applications efforts. Assure that the data collected are of the highest quality possible and suitable for both research and forecasting, and that these data are exchanged and archived on a timely and effective basis among all interested scientists and end-users, both within Brazil and among its collaborators.
    - c. *Earth System analysis and understanding*. There is a rich record of the past and current climate that can provide deep insight into the evolution of the Earth system in the future. A detailed analysis of the climate anomalies of the past, e.g., droughts and floods that have occurred in the Amazon basin and Nordeste Brazil over the 20th century, can enhance our understanding of the dynamics of the Earth system for the betterment of Earth system models and for the more rational management of observing system resources.

   - **d.** *Solution support*. The ultimate Earth system science goal is to expand and accelerate the realization of societal and economic benefits from Earth science, information and technology. This end-goal is part of an end-to-end Earth system science challenge that will use recent Earth system science progress to build a solutions support infrastructure that will assist the decision and policy makers in meeting the environmental challenges of society. The challenge proposed here is to develop the observations and predictions that may be used to impact policies for managing the Earth's natural resources by the global society, and provide the decision support tools for Earth resources stewardship for this and future generations.

2. *Establish collaborations with international partners*. There are several organizations that specifically address the issues that are of great interest and relevance to INPE and Brazil. These include the International Research Institute for Climate and Society (IRI), the Inter-Americas Institute (IAI), and the Third World Academy of Sciences (TWAS). The IRI is focused on how best to use climate information and predictions to address pressing issues such as disease, flood, drought, and other extremes, with particular attention to countries in the developing world. The IAI focuses on the impact of environmental change on countries in North and South America. The TWAS promotes scientific capacity and excellence for sustainable development in the South. All three of these organizations have valuable resources and contacts that could be of great benefit to INPE if meaningful partnerships were formed.

3. *Nurture collaborations within Brazil and South America*. There are several groups in the Brazilian government, in the universities and in the private sector with similar goals and complementary capabilities. For example, within the government there are two large organizations – the Instituto Nacional de Meteorologia (INMET) and the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC), which is a part of INPE – both of which are committed to studying and routinely predicting weather and climate. Similarly, there are government laboratories in various regions of the country, research groups within the federal and state universities, and private companies with research and development activities, all of which have some interest in Earth System Science. The first step would be to gather information about all the programs that are currently operating, and make it available to all (e.g. via a web page), so that individual groups can identify potential partners. The second step would be to make modest seed resources available for groups to form trial collaborations.

4. *Develop mechanisms for interacting with the Earth System Science research community*. As described above, there are many international programs (e.g., Diversitas, IGBP, IHDP, WCRP and many other international programs) with research agendas that are relevant to INPE's needs. INPE scientists should be encouraged to engage with these programs in a more systematic way.

1. Introduction

Brazil is unique in several aspects of its geography, natural resources and demographics. The largest country in Latin America, occupying almost half the land area of South America, Brazil spans nearly the breadth (74°W to 34°W) and length (33°S to 5°N) of the continent, with portions of its 8.5 million km^2 land area in the foothills of the Andes cordillera, a vast area of the Amazon River basin, and coasts on both the northern and southern Atlantic Ocean.

Brazil's Amazon rain forest is among the most biodiverse of Earth's environments, as it is home to half the worlds' rain forests and known species. Through complex evapotranspiration, recycling, and global teleconnection processes, Brazil's forests generate tremendous cloud cover that plays a central role in distributing the Sun's heat, and therefore regulating global climate.

The principal natural resources in Brazil are associated with the Amazon River and the rain forest that the river drains. Many of its products are harvested from the forests, including wild rubber, hardwoods for construction and furniture, and raw materials for pharmaceutical formulation. Over one-tenth of the population is engaged in agriculture, growing primarily coffee (Brazil is the world's leading exporter), cacao, cotton, sugarcane, oranges, bananas, beans, and soybeans. The most common livestock raised includes cattle, pigs, and sheep. Mineral extraction and manufacturing also contribute greatly to the national economy. The state of Rio de Janeiro is heavily industrialized with its steel center of Volta Redonda, and the state of Minas Gerais has some of the finest iron reserves in the world, as well as other mineral wealth. Leading industries produce cotton textiles, paper, fertilizer, asphalt, cement, and iron and steel products; mineral extraction includes quartz and chrome ore, manganese, diamonds, iron, and aluminum. Motor vehicle production is increasing. Brazil also exports iron, cotton, beef, sugar, soybeans, and oranges (juice concentrate). Most trade is with the United States, the European Union, and Argentina. Importantly, Brazil also possesses one of the world's largest hydroelectric potentials.

Brazil has been inhabited by human populations from before recorded history. At the time of the arrival of the Europeans in the 16th century, it is estimated that several million indigenous people lived in the region. The modern occupation of Amazonia started around 1540, but, until the end of World War II, the human presence in the Amazonian environment brought almost no changes to its natural vegetation cover. The new period of development started with the new policies to develop agriculture and to settle immigrants, mostly landless peasants, coming from densely populated areas such as the poverty-stricken northeast and the southern states. Brazil's 180 million inhabitants, concentrated in large cities of Sao Paulo, Rio de Janeiro, Manaus, Salvador (Bahia), Fortaleza, Recife, Belo Horizonte and Brasilia (the capital), are now a diverse mix of European and African immigrants along with indigenous peoples. The government is a democratic, constitutional federation of 26 states (plus one federal district). Portuguese is the official language, and over 75% of the residents are Roman Catholic. Brazil shares international borders with Uruguay, Argentina, Paraguay, Bolivia, Peru, Colombia, Venezuela, Guyana, Suriname, and French Guiana.

During the last two decades of the 20th century, major portions of the Amazon rain forest were cleared for agriculture, ranching and habitation. That anthropogenic activities such as deforestation, pollution, and hunting have drastically altered Brazil's ecologic and hydrologic systems is readily apparent. The potentially irreversible effects of deforestation on the local climate and ecology of the Brazilian natural environment, as well as possible global consequences, were brought to light in the 1990s. Due to the efforts of several international movements and far-sighted leadership in the Brazilian government, the rate of Amazon deforestation has been reduced and is under better control but, because market forces determine how much forest clearing takes place, deforestation and biomass burning remain serious issues for the regional ecology and the global climate. Because of the very delicate and unpredictable nature of the intricate ecosystem relationships, it is not clear what long-term impacts human activities will cause in this globally-important region. Altered cycles of water, energy, carbon and nutrients, resulting from the changes in Brazil's vegetation cover, are expected to have climatic and environmental consequences at local, regional and global scales. To understand these consequences and to mitigate their negative effects, enhanced knowledge is needed of the functioning of both the existing natural environmental systems as well as systems which have already been converted to various other forms of land use.

The many unique aspects of Brazil's geography and natural resources have a larger role to play in the regional, continental and global climate and ecosystem that is planet Earth. The main landform – the Amazon River and the rain forest that it drains – has an impact on the Earth system through several mechanisms. First, the surface hydrology of the entire South American continent depends on the Amazon, which is the largest river by volume on Earth, larger than the next six rivers combined, and the second longest river overall, after the Nile. The area drained by the Amazon (6.9 million km^2 or 40% of the surface of South America) is the largest in the world, and the discharge is up to 0.3 million m^3/s in the rainy season, which is 20% of the total fresh water transport by all rivers worldwide. The water transported by the Amazon River enters the Atlantic Ocean near the equator, providing an enormous source of fresh water to the ocean, thereby influencing its salinity for hundreds of kilometers from the river mouth and affecting the strong ocean currents found along the coast of South America.

A second important feature of the Amazon River basin is the evapotranspiration from the surface. The global water cycle includes five major components: precipitation, evaporation from the ocean surface, evapotranspiration from the land surface, atmospheric transport and transport by surface and groundwater movement. The Amazon River basin accounts for a large fraction of the total evapotranspiration on an annual basis. Furthermore, since the basin is nearly entirely occupied by a dense rain forest due to the plentiful rainfall, the canopy of trees participates actively in the water cycle by intercepting rainfall on its leaves, thereby permitting water to evaporate back into the atmosphere, and by storing water within its biomass. The dense vegetation on the ground also participates by reducing erosion of soil and reducing the surface water transport. The vegetation has a major effect on the surface radiation budget of the Earth, which controls the planet's temperature, because the canopy has a relatively low albedo, compared to bare soil or other less substantial vegetation types, so that solar radiation is absorbed rather than scattered back to space. Finally, the rain forest presents a resistance to the wind, having a higher roughness than bare soil or open water. This affects the momentum budget of the planet, which has consequences for the large-scale flow of the atmosphere. All these ways in which the Amazon River basin and its rain forest participate in the water cycle, the radiation budget and the momentum budget, are typically referred to as land-atmosphere interaction.

Third, the Amazon River basin and rain forest is a self-sustaining, self-regulating ecosystem, which is among the richest and most diverse on Earth. This is something of a paradox, since the tremendous amount of rain over many thousands of years has depleted the soil of its nutrients, so that the Amazon River basin soil is one of the poorest soils on the planet. Nevertheless, the Amazon is home to more species of plants, invertebrates, birds and mammals than any other region on Earth. The biomass of the Amazon rain forest is estimated to be over 100 million kg/km^2 with an estimated 75,000 different types of trees and over 150,000 types of higher plants in each km^2. One estimate places 20% of all birds on Earth in the Amazon rain forest.

Biomass burning and alterations in the basin wide carbon balance, resulting from changes in net ecosystem productivity associated with the establishment of new, different vegetation covers following deforestation, may have further significant effects. Amazonia contains almost half of the world's undisturbed tropical evergreen forest and a large area of tropical savanna. The basin is important in the metabolism of the Earth system accounting for approximately 10 percent of the terrestrial net primary production. The tropical atmosphere is responsible for 70% of the global oxidizing potential and Amazonia is an important natural source for methane and nitrogen oxides.

Fourth, the Amazon rain forest may be a major source of isoprene and other volatile organic compounds, which can react with other atmospheric constituents to form aerosols. Quantifying the complex chemistry, involving ozone and hydroxyl radicals, remains an open question, but it is clear that the biogeochemistry necessary to understand the Amazon’s changing role in planetary pollution, radiation budget, and the water cycle is of great importance.

We currently have little understanding of how Amazonia behaves as an integrated environmental system and how its many ecosystems respond to human intervention. Although there have been some quantitative studies of the large-scale environmental effects of Brazilian deforestation, these have simply extrapolated the results of single site studies to the whole of Brazil, with little regard to the different ecological, hydrological and climatic zones which exist. The Instituto Nacional de Pesquisas Espaciais (INPE) of Brazil must continue to increase the scientific understanding, through field and modeling studies, of how these environmental systems function as a regional environmental entity, and of how this function is affected by land use change and climate and how it will function in the future. The physical, biogeochemical, ecological, and socioeconomic issues associated with understanding prediction and the future management of the Amazon system should be a major undertaking for INPE.

Brazil’s unique geography contributes to its regional climate as well as the global climate variability in other ways besides the participation of the rain forest. In particular, South America is located between the two largest oceans, Pacific and Atlantic, on Earth. Each of these oceans has its own effects on the mean climate and its variability.

Perhaps the best known phenomenon and the one having the largest impact on interannual time scales is a variation of the sea surface temperature (SST) in the equatorial Pacific and the associated large-scale atmospheric pressure patterns throughout the tropics referred to as El Niño and the Southern Oscillation (ENSO). El Niño is a Spanish term for the Christ child. Historically, the term was used by the fisherman along the coast Ecuador and Peru to refer to a warm, nutrient-poor, ocean current that typically appears around Christmas-time and last several months. The suppression of upwelling nutrients affects the local economy in Ecuador and Peru, which suffers from the loss of fish and guano birds. The opposite phase (cold SST near the coast of South America) is usually referred to as La Niña.

ENSO is a global coupled ocean-atmosphere phenomenon with an irregular period of about 4 to 7 years.. In the tropical Pacific, a large-scale pattern of surface pressure called the Southern Oscillation, with high (low) pressure near Darwin, Australia and low (high) pressure near Tahiti typically accompanies El Niño (La Niña). These effects were first described in 1923 by Sir Gilbert Walker. The Walker circulation, named for Sir Gilbert, is a global tropical variation in the zonal overturning flow of the troposphere in which the upward branches of motion, usually associated with atmospheric convection and rainfall, are displaced from their normal locations.

The impact of ENSO on Brazil and the rest of South America's climate is profound. In late boreal spring, especially May, there is a strong relationship among precipitation anomalies over equatorial South America and the Atlantic intertropical convergence zone (ITCZ), and eastern equatorial Pacific and central equatorial Atlantic SST anomalies. The zonal Walker circulation shifts that occur together with tropical Pacific SST anomalies affect the wind stress on the western equatorial Atlantic. That in turn affects the equatorial Atlantic SST and precipitation, which in turn affect Atlantic equatorial ocean dynamics. The whole sequence affects the northeastern Amazon and the Guiana highlands.

Independent of the ENSO and related chain of events in the equatorial Atlantic and equatorial Amazon, there are also variations of the northern tropical Atlantic SST which can likewise affect rainfall in Brazil's Nordeste region. In particular, there is north-south SST gradient that straddles the equator in the central Atlantic (sometimes referred to as the Atlantic SST dipole) whose strength waxes and wanes, producing variations in the ITCZ between South America and Africa. The variations in rainfall at the western end of the ITCZ produce drought and flood conditions in Nordeste, which have a major impact on the economy of the region.

Finally, the Andes cordillera to the west of Brazil presents a formidable barrier to the normal westerly flow that carries moisture from the Pacific Ocean onto the continent. The Andes force upward motion of air, which cools and condenses the moisture producing rain on the windward side of the mountain chain. In the lee of the ridge is a rain shadow. On the larger scale, the South Atlantic subtropical high transports moisture westward from the tropical Atlantic Ocean to the Amazon basin, and then southward toward the extratropics. The flow grows stronger to the east of the Andes Mountains becoming the South American low level jet, with the strongest winds in Bolivia near Santa Cruz de la Sierra. The low level jet transports moisture out of the Amazon basin and into the La Plata basin to the south[1].

The vast size of Brazil and its position in the humid equatorial tropics, give the region a potential for influencing global energy, water, carbon and trace gas budgets which we cannot afford to neglect in the search for understanding of how climate may change in the future. The exchanges

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[1] Vera, C., J. Baez, M. Douglas, C. B. Emmanuel, J. Marengo, J. Meitin, M. Nicolini, J. Nogues-Paegle, J. Paegle, O. Penalba, P. Salio, C. Saulo, M. A. Silva Dias, P. Silva Dias, and E. Zipser, 2006: The South American Low-Level Jet Experiment. *Bull. Amer. Meteor. Soc.*, **87**, 63-77.

of energy, water, carbon, trace gases and nutrients through the atmospheric, terrestrial and riverine systems need to be quantified and understood, at scales from the small plot up to that of the entire basin. How the conversion of tropical forest will alter those exchanges also needs to be understood. INPE should develop the ability to predict what impact this deforestation will have on the ecological, climatological and hydrological functioning and how it may affect the region's long-term sustainability, and to predict what impact these changes will have on the global Earth system. INPE should also develop the ability to quantify, understand and predict the physical, chemical and biological processes controlling the energy, water, carbon, trace gas, and nutrient cycles in Amazonia and to determine how these link to the global atmosphere, and the ability to quantify, understand and predict how the energy, water, carbon, trace gas and nutrient cycles respond to human activities, how these responses are influenced by climate, and predict the impacts of these responses both within and beyond Amazonia. This is necessary to provide quantitative and qualitative information to support sustainable development and ecosystem protection policies in Brazil, in the context of both its regional and global functioning.

The fact that all these complex physical, biological and chemical processes are inter-related and interactive, and the fact that these processes are so diverse and far-reaching, some with global consequences, suggest that, in order to understand, and eventually predict, Brazil’s and South America’s climate, INPE should develop a full Earth system framework.

2. Definitions of Earth System Science and Earth System Model

Earth System Science

The Earth is a complex, dynamic system in which the lithosphere, the oceans, the atmosphere, and life (both human and non-human) interact. While these components of the planet are often represented by interacting "spheres" (atmosphere, hydrosphere, cryosphere, biosphere, etc.), the Earth functions as a single whole entity. Another convenient way to divide the problem is along disciplinary boundaries: physics, chemistry, biology, ecology, etc., but this is likewise problematic since the various interacting processes often require understanding across disciplines. It is necessary to treat the Earth system as a whole since no part can be truly isolated from any other, and deconstructing the conceptual model of the Earth to try to establish cause and effect typically leads to misunderstanding.

Earth is the only planet we know of that sustains life. Life on Earth is critically dependent on the abundance of water in all three phases – liquid, vapor and ice. Carbon, existing in a variety of forms, is the very basis of life on Earth, and its greatest reservoir. In the atmosphere, carbon fully oxidized as carbon dioxide, fully reduced as methane, and in particulate form as black carbon soot produces the greenhouse effect making Earth habitable. Earth's atmosphere and electromagnetic field protect the planet from harmful radiation while allowing useful radiation to reach the surface and sustain life. Earth exists within the Sun's zone of habitation, and with the moon, maintains the precise orbital inclination needed to produce our seasons. [2]

One of the most compelling and challenging intellectual frontiers facing humankind, then, is the comprehensive and predictive understanding of Earth's structure, dynamics, and metabolism. Recent progress in understanding the atmosphere, ocean, and solid Earth, and the rapid expansion in our ability to observe our planet, present the geosciences community with new and expanded opportunities to advance understanding of the Earth as a coupled system. This improved understanding will provide a basis for meeting urgent needs to reduce the uncertainty in predictions of Earth system processes, provide more accurate and comprehensive tools to decision-makers, and foster technological development in the geosciences-related spheres of the public and private sectors.

Understanding global environmental issues such as global warming, and particularly their regional manifestations, requires the cooperation of scientists across many disciplines, which is the essence of *Earth System Science*. It includes chemistry, physics, biology, geology, meteorology, oceanography, and ecology, as well as societal dimensions such as economics and politics, and focuses on the interactions among the various components of the Earth system. Earth System Science seeks a rational basis for understanding the world in which humans live and upon which humankind seeks to achieve sustainability. Earth System Science works toward a synthesis of disciplinary knowledge into a holistic model of Earth with broader interdisciplinary relevance.

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[2] Ward, P. and D. Brownlee, 2000: *Rare Earth: Why Complex Life Is Uncommon in the Universe.* (Springer, 368 pp).

In addition to requiring attention to several dynamic, interacting components of the Earth system and to several traditional scientific disciplines, the problem of Earth System Science is increasingly a multi-scale problem. For example, it is recognized that the variations typically identified as “weather” – day-to-day fluctuations in local temperature, pressure and other atmospheric variables – have a rectified effect on longer time scale aspects of the climate system. Similarly, the particular regime in which the climate may be at a given moment has a profound effect on the development, intensity and propagation of weather systems. Similar scale interactions with much smaller spatial scales and much shorter time scales as well as planetary spatial scales and climate change time scales are now viewed as essential aspects of the Earth system.

Within the concept of the Earth as a complex and dynamic entity involving the disciplinary spheres for land, air, water and life, there is no process or phenomenon that occurs in complete isolation from other elements of the system. While this system view is elegant and satisfying philosophically, the challenge to researchers and educators attempting to quantify the breadth of the system’s elements, states and processes within the classroom is enormous. No individual, academic department or university is capable of developing and offering the enormous depth and breadth of knowledge such a paradigm demands. Only by joining faculty from different disciplines within and among universities and scientists from different research centers can the diversity and complexity of Earth system science be fully appreciated.[3]

Earth System Model

Given the complex, dynamic and interactive nature of the scientific problem of the Earth system, it is natural to attempt to encapsulate the components and their interactions in a model that can be used to simulate the behavior and evolution of the Earth system. Computer simulation models are the primary tools by which knowledge of the workings of the Earth System can be integrated. Only through Earth system models can we, for example, predict future climate variability and change, including the possible effects of human activities on the global climate system. The long-term objective of Earth system modeling and simulation is to create and apply models that provide credible predictions (including levels of certainty and uncertainty) of changes and variations in climate on regional-to-global scales, along with useful projections of potential environmental and societal consequences. Gaining scientific understanding and predictive capability for variability and change in our planet’s environment requires the study of the dynamic interactions among the major components of the Earth system, including the oceans, atmosphere, land surface, and sea ice. Typically, the range of time scales is selected, and the model is designed to suit the scientific problem on that time scale.

For example, if one wanted to simulate apparently simultaneous variations in surface air temperature and carbon dioxide concentration that have been observed in ice cores taken in

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[3] Johnson, D., M. Ruzek, M. Kalb, 1997: "What is Earth System Science", proceedings of the 1997 International Geoscience and Remote Sensing Symposium, Singapore, August 4 - 8, 1997, pp 688 – 691.

Antarctica, simulations of Earth's climate for the past 600,000 years would be needed. Realistic simulations of multi-millennial length require a complete Earth system model that includes, at a minimum, components representing the atmosphere, oceans, sea ice, marine sediments, land surface, vegetation, soil, and ice sheets and the energy, water and biogeochemical cycles (obviously carbon, but also nitrogen and sulfur, among others) within and between components. Figure 1 [4] provides one schematic representation of an Earth System Model.

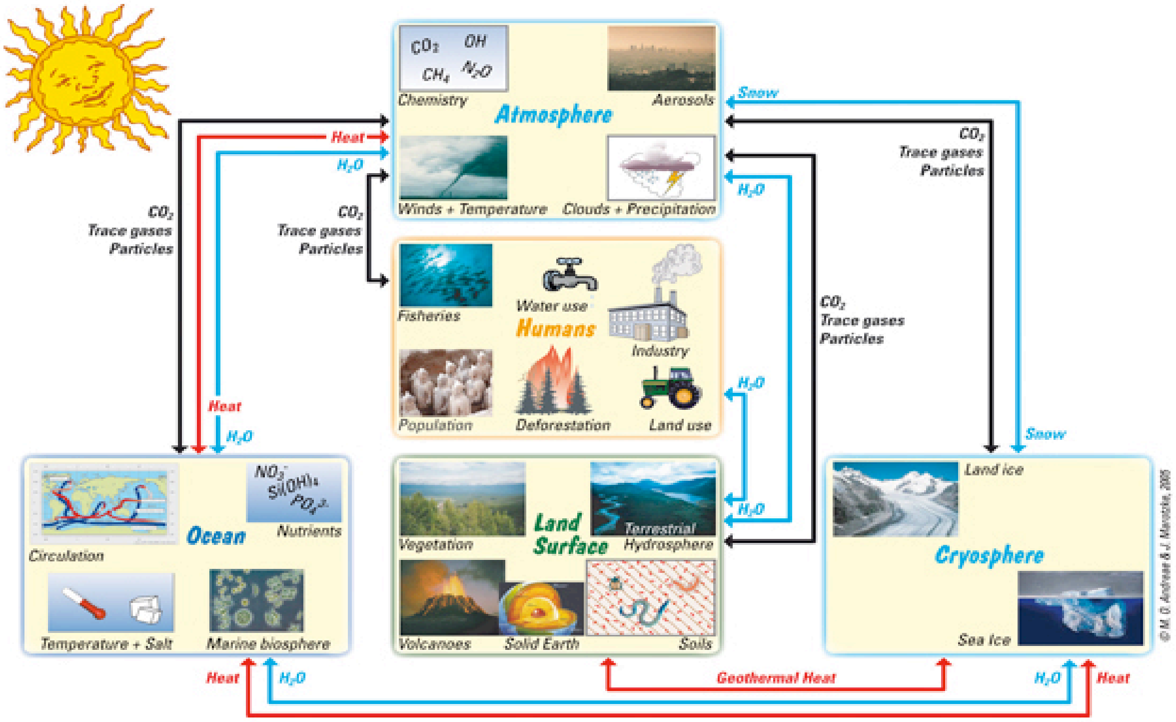

Figure 1 - The Earth system. A modified "Bretherton Diagram" highlighting linkages between social, biogechemical, and physical climate systems. (Guy P. Brasseur, NCAR)

Models of these components of the Earth system have been developed and have reached various stages of maturity and fidelity; however, they have typically been developed and are used separately. In contrast, the detailed physical prediction models of the coupled atmosphere, ocean and land developed and used within the World Climate Research Program, for example in the recent Intergovernmental Panel on Climate Change Assessment Report 4, are increasingly being extended to include atmospheric chemistry, the carbon cycle, including dynamic vegetation, and interactive marine eco-systems. Such models are too demanding computationally for multi-millenial simulations. The probabilistic nature of climate also requires that model simulations be done in ensembles to provide estimates of uncertainty, which places an even greater computational burden on these simulations. In contrast, existing efficient models of the Earth system, e.g. CLIMBER-2 [5] employ highly idealized models of the individual components, with

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[4] http://www.csar.cfs.ac.uk/about/csarfocus/focus10/vis_earth.pdf

[5] Petoukhov, V., et al., 2000: CLIMBER-2: A climate system model of intermediate complexity. Part I: Model description and performance for present climate, *Clim. Dyn.*, **16**, 1 – 17.

reduced dimensionality and low spatial resolution. A summary of current Earth System Models is given below.

Another aspect of Earth System Models is that they are being used to answer questions that are not only of academic interest, but may have consequences for economies, ecosystems and societies. For example, it is now recognized that the usefulness of the predictions that are becoming possible depends on the details of the proposed application, and that for some purposes it is necessary to quantify the use that is made of the prediction. For example, models of specific applications such as crop-growth and malaria incidence are having model data fed directly to them or are even being added to the prediction models. For this reason, Earth System Models are being developed with some of these applications in mind, so that the spatial and temporal scales and variables of interest for a particular application are properly represented in a given model.

It is envisioned that a comprehensive Earth System Model (ESM) will explicitly resolve weather and climate relevant physical, chemical and biological processes, in order to improve dramatically the use of space-based observations, and the application of these observations to the understanding and prediction of weather and climate. This will require (a) non-hydrostatic atmospheric dynamics on quasi-uniform grids defined by observed process scales, (b) explicit microphysics of clouds that represent observed cloud processes and their interactions with radiation, (c) observationally complete and interactive chemistry for the atmosphere, ocean and land, (d) ultra-high-resolution observation-driven land surface model with process-scale hydrology and biogeochemistry dynamics, (e) an observation-driven eddy-resolving ocean model with lead-pattern-simulating sea-ice and ocean biogeochemistry models, (f) coupled model evaluation and refinement based on high-resolution satellite observations, and (g) a common software environment to enable component model coupling, inclusion of observational constraints, and research community interaction. This model will be invaluable for a wide range of applications, including satellite data assimilation, observation system design, weather forecasting and climate simulation.

3. Human Resources Requirements

In order to address the problems of Earth System Science over the next one to two decades, considerable development of human resources will be required that fall into several categories:

- basic research scientists who can develop the component and integrative Earth System Models that are needed
- applied research scientists who can help design Earth System Models based on specific knowledge of the applications
- numerical modelers who can develop the algorithms necessary to accurately represent the process and scale interactions that are critical to Earth System simulation
- computer scientists who can help adapt the algorithms to the evolving high performance computing architectures that are necessary for the very large computational problems associated with Earth System Models

This is challenging primarily because it requires education and training across traditional boundaries of physical sciences, biological sciences, engineering and computer science. It amounts to no less than training the next generation of students who will be capable of performing original research at the seams of the traditional disciplinary sciences.[6] This is referred to as inter-disciplinary or multi-disciplinary science education, or, more colloquially, teaching in the "white space" between disciplines. *Multi-disciplinary science is not fully mature and is evolving rapidly*.

Several agencies and universities are already building interdisciplinary science programs. For example, in the United States, the following universities have programs in Earth System Science: University of Alabama at Huntsville, University of California at Irvine and at Los Angeles and Santa Barbara, California State University at Monterey Bay, Clark University, University of Florida, George Mason University, University of Illinois, University of Maryland, University of New Hampshire, University of North Dakota, University of Oklahoma, Penn State University, University of Washington, and University of Wyoming. Many other schools offer courses embedded in a traditional disciplinary degree program. There are also several national programs that are facilitating the building of interdisciplinary science programs, including the Digital Libraries for Earth Science Education, the National Aeronautics and Space Administration, the University Space Research Association, the World Resources Institute. There are several international programs aimed at advancing Earth System Science including Diversitas, the International Geosphere-Biosphere Program (IGBP), the International Human Dimensions Program on Global Environmental Change (IHDP) and the World Climate Research Program (WCRP). The Earth System Science Partnership (ESSP), which is a collaboration among Diversitas, IGBP, IHDP, and WCRP, aims to bring together at the highest level the disciplinary scientists and science programs that are needed for true Earth System Science. A list of web sites for the above departments and programs is given at the end of this document.

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[6] for example see http://www.geotimes.org/sept02/feature_educators.html

4. Computing Requirements and Earth System Modeling

a. Computing Requirements

The essence of Earth System Science is the dynamic interaction among components of the Earth system and the dynamic interaction among spatial and temporal scales. Because this system approach represents an exceeding complex problem, the prevailing view is that it can only be adequately addressed with a hierarchy of models designed to represent and simulate the relevant processes on the appropriate spatial and temporal scales. Models of the components of the Earth system (atmosphere, world oceans, cryosphere, land surface, and biosphere) have been developed almost exclusively in isolation from one another. Taken as a whole, these models include the processes that determine the evolution of Earth system components (large-scale fluid dynamics, turbulence and mixing, convection, radiation, land surface hydrology, ground water flow, atmospheric chemistry, biogeochemistry, marine and terrestrial ecosystems dynamics, weathering, etc.); however, no single model exists that incorporates all the relevant processes.

Each of the component models and the presumed Earth System Model that incorporates all relevant components is based on a set of physical, chemical or biological/ecological laws representing the current state of understanding based on past laboratory experiments and observations of nature. For example, the large-scale motions of the atmosphere and oceans are determined by Newton's laws of motion and conservation laws for mass, energy, and momentum. When these laws are expressed mathematically, the equations describing the evolution of the system are typically nonlinear, coupled partial differential equations for which closed analytic solutions are not available. Therefore, the equations are solved by representing them with numerical approximations integrating the approximate equations using high-speed computers.

Along with theory and observation, computational simulation has become established as a cornerstone of this progress in Earth system science. Increasingly, numerical simulations are not only tested by observations, but provide the first glimpses of new phenomena and quantitative characterization of complex processes. In turn, these simulations inspire new theoretical investigations and observational strategies. Because the equations are complicated, and because the numerical solution methodology typically involves decomposing the spatial domains into small parts (grids of spatial locations within the Earth system) and solving the equations on each part separately, very sophisticated codes executed on high-performance computers are required. The available capability of the current generation of supercomputers therefore limits the complexity, resolution and integration duration of Earth System Models.

There is considerable evidence that very high resolution models are needed in all components of Earth System Models. This stems from the fact that, in resolution-limited models, the approximations necessary to make it possible to integrate the models with existing supercomputing technology are overly crude and omit essential aspects of the relevant physical, chemical or biological/ecological processes. For example, in models of the physical climate system, the relevant processes are parameterized – represented as functions of variables on scales that are far from the scales on which those processes typically function. There is evidence that parameterizations of physical processes, those associated with convective clouds in particular, are the main source of error in current climate models. This is a special case of the general notion that processes relevant to a given phenomenon should be fully resolved in a numerical model of that phenomenon. Recent work[7] at the European Centre for Medium-Range Weather Forecasts suggests that models with a global grid spacing of 150 km is necessary to properly represent the baroclinic instability process, and global grid spacing of 50 km is needed to adequately resolve the extratropical cyclones that transport the heat, moisture and momentum between the tropics and the poles. Accurate simulation of the track and intensity of tropical storms has recently been demonstrated with models whose horizontal grid spacing is 4 km.

The accurate representation of biogeochemical cycles and biogeophysical processes is an area where there has been less investigation to date on resolution requirements. However, there is a clear indication that ecosystem models and models of atmospheric chemistry are very sensitive to sharp gradients in quantities in the physical climate system, such as the thermocline in the upper ocean or the elevation and orientation of the land surface. This suggests that accurate simulation of the marine and terrestrial ecosystems requires that the physical climate system be resolved and accurately represented at very fine scales.

Recognizing these issues, the World Climate Research Program (WCRP) has recently adopted a new strategy for unifying research activities across its diverse programs, called Coordinated Observation and Prediction of the Earth System (COPES). The COPES framework calls for global models to be run with “resolution of a few kilometers (as required for many practical applications), very large model ensembles to assess uncertainty, simulations of paleoclimates with fully coupled global climate models, and highly-resolved regional models in response to the demand to develop adaptation policies and measures at the regional level.” It also calls for high-resolution models that include detailed parameterizations, cloud-system-resolving capability, and other detailed representation of relevant climate processes. The increasing resolution, complexity, ensemble size and run duration of these climate prediction systems represent a fundamental challenge to the evolving capability of high-end computing.

The modeling systems likely to be used to realize the COPES vision of weather-to-climate, days-to-decades prediction will be highly sophisticated computer programs that represent the coupled ocean-atmosphere-land-cryosphere system and all the dynamical, physical and biogeochemical processes that are relevant on those time scales. Such models will be substantially more complex and sophisticated in many aspects than the weather and climate models in use today.

To accelerate progress, weather-to-climate, days-to-decades modeling will require a science plan that clearly articulates the case for an international investment in breakthrough, high-end computing capability. Significantly increased model resolution, complexity, integration duration and ensemble size are necessary to advance our understanding of the Earth system and to better quantify the uncertainty in predictions of its behavior. Scientific challenges include but are not limited to the inclusion of important additional physical, chemical, and biological processes, improvement of existing unresolved parameterized processes and understanding the increased complexity in behavior permitted by such models of greater fidelity and sophistication.

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[7] Jung, T., S.K. Gulev, I. Rudeva, and V. Soloviov, 2006: Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model. *ECMWF Tech. Memo*., **485**, 17 pp.

Incremental refinements in weather and climate models yield incremental improvements. But the dramatic increases in model fidelity proposed in the COPES vision will make possible fundamental breakthroughs in model design. Perhaps most importantly, it will be possible to resolve phenomena that are currently parameterized. For instance, cumulus convective and large-scale cloud processes are usually separately parameterized. At the 1 km scale, cloud microphysical models can unify these phenomena into a prognostic cloud system submodel[8]. In the middle atmosphere, there is a requirement to resolve the relatively fine structure of potential vorticity and the radiatively active species that are found there. In the upper troposphere, there is a need to explicitly resolve cloud system processes, which occur on O(1 km) spatial scales. Near the surface, the turbulent atmospheric boundary layer must continue to be parameterized, but with much more defensible schemes that depend on large-eddy simulation closure results with O(10 m) scale resolution. The details of orography, vegetation and land cover are important and must be resolved. Near the surface of the ocean, turbulence in seawater, currently only represented in terms of thermally-stratified flows must also include the effects of salinity. Access to these scales will afford more realistic representation of atmospheric features (e.g. tropical cyclones), oceanic features (e.g. warm- and cold-core eddies), and land-surface characteristics (e.g., landscape-scale features and gradients) and the potential to improve prediction of severe weather, extreme weather and climate events, and large, long-lasting climate anomalies, all of which have major impacts on global society.

Trends in Numerical Weather Prediction and Climate Simulation

There have been no revolutionary changes in numerical models of weather and climate since their advent 30 years ago. The models make use of the same dynamical equations, with improved numerical methods, and have comparable resolution and similar parameterizations with a modest extension of the processes included. These incremental changes have yielded steady improvement in prediction of weather and climate phenomena. Over these same 30 years, computing power has increased by a factor of 10^6. Of the million-fold increase in computing throughput over the past 30 years, a factor of about 1,000 was used to increase the sophistication of the model. Model resolution, the inclusion of more physical and biogeochemical processes and more elaborate parameterizations of unresolved phenomena have all been modestly improved. In the atmospheric component models, the horizontal resolution has quadrupled, and the number of layers has tripled. At the same time, models have increased in complexity through the addition of processes other than the basic dynamics and thermodynamics of the atmosphere and ocean. For example, the inclusion of models of chemical reactions to simulate the creation and destruction of species in the atmosphere that may be radiatively active or that may interact with water vapor in the formation of cloud droplets, ice crystals or raindrops, is a relatively recent model development. The models used to simulate climate variability now include modules for atmospheric chemistry, atmospheric aerosols, land surface vegetation and terrestrial ecosystems, the carbon cycle, and marine ecosystems. Processes such as the formation of liquid and solid clouds have been added. Parameterizations like the long-wave radiation in the atmosphere have been enhanced by increasing the spectral resolution of the absorption bands of radiatively active species. Arguably, computing power was not the only limiting factor in this stage of the development of weather and climate models as our ability to understand these and many other aspects of the system has been dependent on ever more sophisticated observational technologies which has followed a similar evolutionary path as did computing.

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[8] D.A. Randall, "Counting the Clouds", SciDAC 2005, *J. Physics: Conf. Series* **16**, 339. jpconf.iop.org.

The other factor of 1,000 was used for longer and more numerous runs of the numerical models. In the early 1970s, numerical weather predictions were extended to two weeks[9] (e.g. 1975 establishment of ECMWF, chartered to make 10-day weather forecasts). In the early 1980s, 30-day[10] [11] and in the early to mid-1980s, 90-day [12] [13] climate simulations were attempted. In the mid-1980s, simulations of El Niño and the Southern Oscillation (ENSO) were made [14] [15] and fully coupled general circulation models were used to predict interannual climate variations in the 1990s [16]. Similar increases in model integration length have been made in paleoclimate and global change simulations. More numerous runs are primarily made to increase the ensemble size to provide a measure of the uncertainty in a given weather or climate forecast.

These trends indicate that the problem of weather and climate modeling can be organized in terms of four dimensions:

- resolution
- complexity
- integration length
- ensemble size

Each of these competes for computational resources. The current capability in high-end computing at any given time places a bounding surface on what can be achieved in these four dimensions. It should be noted that the four dimensions are not strictly orthogonal as there are some dependencies among them. For example, some advances in complexity cannot be attempted until a certain threshold of resolution is achieved. One example is the full simulation of oceanic biogeochemical cycles, for which the accurate simulation of oceanic eddies is a necessary condition.

Trends in High-End Computing

As mentioned above, over the past 30 years, computing power has increased by a factor of a million. This has resulted mainly from the increase in large scale integration, often referred to as Moore's Law[17]. More of an observation than a law, the transistor density on a processor chip has doubled roughly every two years. The increase in floating point performance in high-end computational platforms has resulted from the exploitation of this density trend and the increase in the number of processors available for simultaneous use by a single computation. The latter

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[9] Miyakoda, K., G. D. Hembree, R. F. Strickler, and I. Schulmann, 1972: Cumulative results of extended forecast experiments. I: Model performance for winter cases. *Mon. Wea. Rev.*, **100**, 836-855.

[10] Shukla, J., 1981: Dynamical predictability of monthly means. *J. Atmos. Sci.*, **38**, 2547-2572.

[11] Miyakoda, K., C. T. Gordon, R. Caverly, W. F. Stern, J. Sirutis, and W. Bourke, 1983: Simulation of a blocking event in 1977. *Mon. Wea. Rev.*, **111**, 846-869.

[12] Shukla J., D. M. Straus, D. Randall, Y. Sud, and L. Marx, 1981: Winter and summer simulations with the GLAS climate model. *NASA Tech. Memo.* Winter and summer simulations with the GLAS climate model. (Goddard Space Flight Center, Greenbelt, MD), pp. 1-282.

[13] Kinter III, J. L., J. Shukla, L. Marx, E. Schneider, 1988: A simulation of the winter and summer circulation with the NMC global spectral model. *J. Atmos. Sci.*, **45**, 2486-2522.

[14] Philander, S. G. H. and A. D. Seigel, 1985: Simulation of El Niño of 1982-1983. In *Coupled Atmosphere-Ocean Models* (J. C. Nihoul, editor; Elsevier, Amsterdam), pp. 517-541.

[15] Cane M. A., S. E. Zebiak, and S. C. Dolan, 1986: Experimental forecasts of El Niño. *Nature*, **321**, 827-832.

[16] Ji, M., A. Kumar and A. Leetmaa, 1994: A multi-season climate forecast system at the National Meteorological Center. *Bull. Amer. Meteor. Soc.*, **75**, 569-577.

[17] *Electronics*, v. 38, 1965 - ftp://download.intel.com/research/silicon/moorespaper.pdf

was first exploited in mainframes and supercomputers in the 1960s and 1970s, and has, since the advent of relatively cheap microprocessors in the early 1990s, grown to include several hundreds to thousands of processors in a single computing platform.

The current capability available in high-end computing systems may be characterized in terms of peak processor speed, size of system integration, and the degree to which the peak theoretical speed is realized in execution of application codes. The current peak speed of individual processors is about 2-3 GF[18]. System integration now reaches a maximum of about 100,000 processors in a single system. There are a variety of architectural (e.g. shared memory vs. distributed memory, vector vs. scalar, and various topologies of interconnect among processors) and engineering (e.g. liquid-cooled vs. air-cooled) choices in the marketplace today with the capability to provide integration across a large number of processors, with varying levels of capability and achieved performance. Typical "on chip" floating point performance for fluid dynamical codes on scalar processors is about 5-15% of peak theoretical speed and about 35-50% of peak theoretical speed on vector processors. Overall code performance also depends highly on network interconnect speeds and the ability of the code to exploit it.

Currently, some example "high water marks" in high-end computing are:

- The Earth Simulator[19] in Japan (NEC, 5,120 processors, installed in 2002) with a capability of about 35 TF peak and 12 TF sustained. (Number 10 on the June 2006 Top 500 list[20])
- Project Columbia[21] at NASA Ames (SGI, 10,160 Altix processors, installed in 2005) with a capability of about 52 TF peak and 5-10 TF sustained. (Number 4 on the June 2006 Top 500 list)
- Blue Gene/L at Lawrence Livermore National Laboratory (IBM, 65536 Power PC 440 processors, installed in 2005) with a capability of 183 TF peak. (Number 1 on the June 2006 Top 500 list)

Systems in addition to the Earth Simulator Center that are specifically intended for weather and climate research and prediction include:

- Each of the two systems at European Centre for Medium-range Weather Forecasts[22] (ECMWF; IBM, two identical systems of 2176 Power 4+ 1.9 GHz processors, installed in 2004) has a capability of 16.5 TF peak and ~2 TF sustained. Numbers 42 and 42 on the June 2006 Top 500 list. (Note that the combined capacity of these two machines would be Number 15 on the June 2005 Top 500 list)
- Japan Meteorological Agency. (JMA; Hitachi, two identical systems of SR110000, based on IBM Power5+ chips, installed 2005) with a combined capability of 21.5 TF. (Numbers 45 and 46 on the June 2006 Top 500 list; combined system would be Number 20)

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[18] Computer performance in modeling applications is typically measured in floating point results per second (flops); a megaflops (MF) is 10^6 flops, a gigaflops (GF) is 10^9 flops, a teraflops (TF) is 10^{12} flops and a petaflops (PF) is 10^{15} flops.

[19] http://www.es.jamstec.go.jp/esc/eng/

[20] http://www.top500.org/ ; The Top 500 list is a measure of the speed achieved on LINPACK, a highly idealized metric with little relation to real application codes; while flawed, it provides a relative measure of the investment in computing resources applied to weather and climate research.

[21] http://www.nas.nasa.gov/

[22] http://www.ecmwf.int/

- National Centers for Environmental Prediction (IBM, two identical systems. 1216 Power 5+ processors, to be installed in 2006, too recent to be included on Top500 list)
- The NCAR Scientific Computing Division[23] capacity at about 2 TF sustained (as of January 2007).

Some examples of current (or soon to be implemented) state of the art production global weather and climate models include:

- ECMWF IFS T799L91 – used twice per day for medium-range (10-day) weather prediction
- ECMWF IFS T399L62 – used twice per day to produce a 51-member ensemble medium-range weather prediction
- NCEP GFS T382L64 – used four times per day for 7.5-days weather prediction (T190L64 is used to continue from 7.5 to 16 days)
- NCEP GEFS T62L64 - used four times per day to produce a 45-members/day ensemble 16-day weather prediction
- NCEP CFS T62L64 AGCM with ~1°(1/3 in deep tropics)X40L OGCM – used twice per day to produce 9-month climate prediction
- NCAR CCSM T85L26 AGCM with ~1°X40L OGCM. A coupled climate model used for simulation of climate variability and change.
- UK MetOffice HadCEM3 3.75°X2.5°X19L AGCM and 1/3°X1/3°x40L OGCM. An ocean eddy permitting coupled climate model.

Some examples of very high resolution simulations that push the envelope of current generation computing resources are

- An "aqua-planet" (ocean-covered Earth) simulation performed on the Earth Simulator using a geodesic grid with 3.5 km cell size (~10 million columns), 54 layers, and a 15-second time step. The simulation was executed 7 times faster than real time on 640 processors of the Earth Simulator [24].
- AMIP integrations of the Finite Volume dynamics version of NCAR CAM at 0.25^{o} X 0.375^{o} X 26L achieved 1,200 simulated years per wallclock-year on 880 processors of the Earth Simulator and will likely scale well past 2000 processors with reasonable efficiency.

High-end computing performance is expected to improve at a substantial rate. The peak speed of individual processors is expected to increase to ~30-50 GF, as Moore's Law is expected to continue to hold up for about another decade using conventional chip development and fabrication technologies and taking into account trends in multicore chip design (dual-core chips are currently common and quad-core chips are expected in 2007). Beyond that, the size limitations of individual molecules will prevent further speedup, and radical new technologies will be required to advance processor performance. High-end systems can be expected to integrate well over 100,000 processors in a single system. This level of system concurrency will likely require three-dimensional domain decomposition (as opposed to the currently used one- or two-dimensional domain decomposition) within each Earth system process submodel and a

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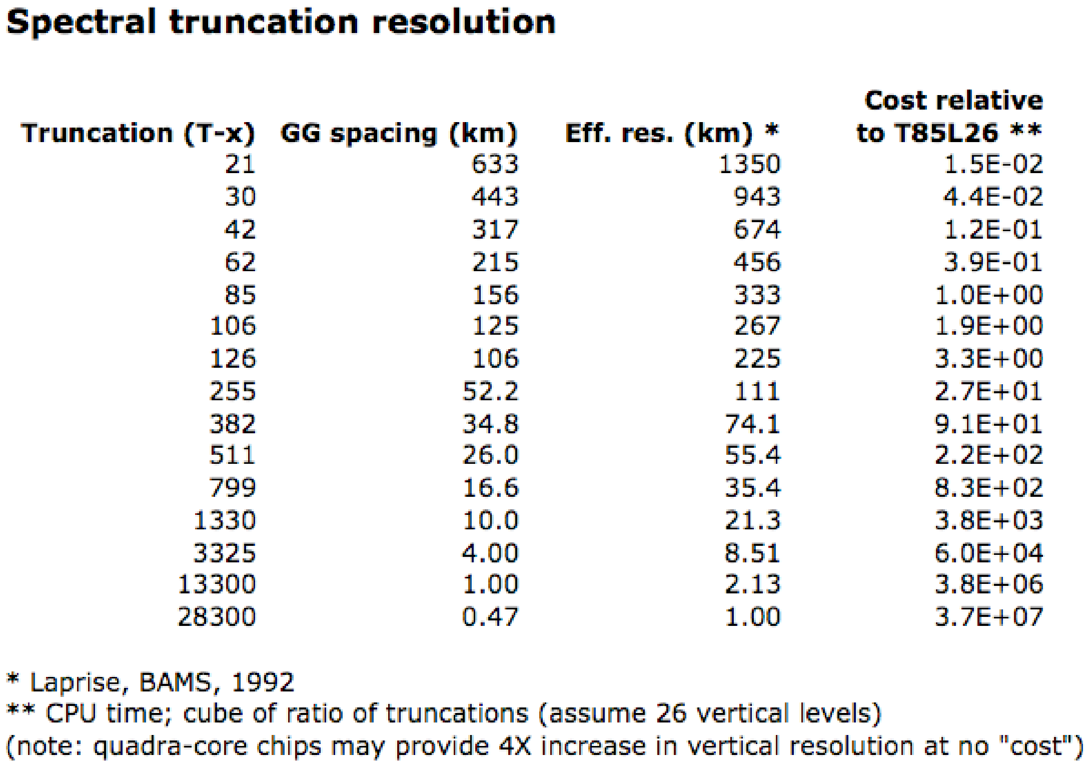
[23] http://www.scd.ucar.edu/

[24] Satoh M., H. Tomita, H. Miura, S. Iga and T. Nasuno, 2005; **"**Development of a global cloud resolving model – a multi-scale structure of tropical convection" *J. Earth Sim.,* **3**, 1-9

higher degree of process parallelism in order to realize the potential speedup. It should be noted that weather and climate models, like other fluid dynamics applications can be constructed to favorably scale to these numbers of processors at the very high resolutions envisioned in the COPES strategy [25]. However, the processors must be substantially faster than current technologies to overcome the superlinear scaling of operation count dictated by the Courant-Friedrichs-Levy (CFL) stability condition.



Spectral truncation resolution

Truncation (T-x)	GG spacing (km)	Eff. res. (km) *	Cost relative to T85L26 **
21	633	1350	1.5E-02
30	443	943	4.4E-02
42	317	674	1.2E-01
62	215	456	3.9E-01
85	156	333	1.0E+00
106	125	267	1.9E+00
126	106	225	3.3E+00
255	52.2	111	2.7E+01
382	34.8	74.1	9.1E+01
511	26.0	55.4	2.2E+02
799	16.6	35.4	8.3E+02
1330	10.0	21.3	3.8E+03
3325	4.00	8.51	6.0E+04
13300	1.00	2.13	3.8E+06
28300	0.47	1.00	3.7E+07

* Laprise, BAMS, 1992
** CPU time; cube of ratio of truncations (assume 26 vertical levels)
(note: quadra-core chips may provide 4X increase in vertical resolution at no "cost")

Table 4.1 Global atmospheric models are typically classified by the spectral truncation (column 1) wave number in a triangular, two-dimensional Galerkin decomposition), which can be associated with a Gaussian grid spacing (column 2), an effective resolution (column 3), and a computational cost that scales with the cube of the grid spacing (column 4).

Highly complex, high-resolution models can be expected to require O(10^{16}) operations per simulated day, which means that to achieve a 1,000-fold ratio of simulated time to wallclock time, ~100-150 TF sustained capability (i.e., O(1) PF peak performance) will be required. Assuming that 150 TF sustained can be achieved by 2010, then an ensemble of 30-40 members of a 17-km global hydrostatic atmospheric general circulation model (AGCM) coupled to an ocean general circulation model (OGCM), each with ~100 levels, or an ensemble of 25 members

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[25] Oliker, L., J. Carter, M. Wehner, A. Canning, S. Ethier, B. Govindasamy, A. Mirin , D. Parks, P. Worley, S. Kitawaki, Y. Tsuda: Leading Computational Methods on Scalar and Vector HEC Platforms. *IEEE/ACM Conference on High Performance Computing and Communications ("Supercomputing")*, SC05, Seattle, WA, Nov 12-18, 2005.

of a 5-km global non-hydrostatic NWP model coupled to an OGCM, each with ~100 levels, can be completed within a typical 3-wallclock-hour supercomputing window. Table 4.1 illustrates the progression toward process-resolving models of the future.

If such advances can be made in the next five years, the progress in the 2010-2015 period can be even more exciting. One can envision that the weather and seasonal climate prediction model of 2015 will be a coupled global ocean-land-atmosphere-cryosphere model with 1-km (cloud-system resolving) resolution in the atmosphere, 10-km (eddy-resolving) resolution in the ocean, both on unstructured, adaptive grids, and a 100-m (landscape-resolving) land surface model, fully initialized with the satellite-based, high-resolution observations of the global Earth system.

In order to have in place the necessary computational capability for seamless weather-to-climate, days-to-decades modeling in support of COPES objectives, it has been suggested that the WCRP encourage the development of an international strategy to address the gap between the scientific requirements for, and the availability of, high-end computational resources. Such a strategy must include a science plan that articulates the case for a international investment in breakthrough, high-end computing capability that will make it possible to address the issues of resolution, complexity, integration duration and ensemble size, advance our predictive understanding of the components of the Earth system and their interaction with one another, and make it possible to address science challenges such as dramatically expanding the scale content and mechanism content of complex systems, providing access to previously unexplored parameter regimes, and permitting the inclusion and coupling of additional physical, chemical, and biological processes. The plan should acknowledge that major advances depend on dramatic increases in model resolution, which is a necessary condition for addressing some of the model complexity issues.

To achieve a seamless weather-to-climate prediction capability will require substantial effort across all components of simulation-based research. Resources will have to be devoted to developing, porting, and optimizing weather and climate model application codes to achieve the necessary execution rate of simulation for the target computing architectures. Resources will have to be balanced with respect to computation, mass storage access and post-processing support for exabyte-volume datasets as well as visualization. Realizing the vision will also require attention to many aspects of high-end computing, including computing hardware - architecture, data storage and archival, networking etc.; software – operating systems, compilers, data management systems and visualization tools; and power, cooling and infrastructure. Success will depend on development of new codes expressly intended for these high resolutions rather than re-engineering of existing models. In addition, there is a significant requirement for highly-skilled human resources to support multiple models and modeling groups at remote locations.

Because the modeling systems likely to be used to realize the COPES vision will be highly sophisticated computer programs that represent at high resolution the coupled ocean-atmosphere-land-cryosphere system and all the dynamical, physical and biogeochemical processes that are relevant on a broad spectrum of time scales, the potentially useful data produced by a single model for a single type of application will occupy O(10^{17} – 10^{19}) bytes of storage. Since the order of magnitude of modeling centers that will engage in this level of computing is O(10), the expected data volumes will be of order $10^0 – 10^2$ exabytes,[26] distributed across multiple data centers worldwide. Every research group engaged in Earth system model development and analysis cannot copy such a huge volume of data, so technologies will have to be employed to enable distributed data management, analysis and visualization.

Relevant Distributed Data Management Technology Trends

The growth in data density in magnetic storage systems has accelerated in the past decade. Prior to the 1990s, disk density doubled every three years or so. With the introduction of magnetoresistive read heads in 1991, the doubling time was reduced to two years, and, since the giant magnetoresistive head (GMR) reached the market in 1997, density has been doubling every year. As an example of data volume growth, including archives on less volatile media, the Mass Storage System (MSS) at the U.S. National Center for Atmospheric Research acquired its first petabyte (10^{15} bytes) over about 18 years of data accumulation. The MSS reached its second petabyte 18 months later. The measured rate of growth of the MSS at NCAR is about 50 bytes per sustained kiloflop (KF)[27].

The capacity (bandwidth) of wide area networks (WAN) that link computing centers worldwide has likewise experienced exponential growth over the past decade or more. In the 1990s, the typical highest speed within a data center was 100 Mb/s[28] (using fiber distributed data interface, FDDI, technology) and the WAN speed was typically up to 45 Mb/s. Today, the fastest data center network is about 1-10 Gb/s, and, while 10 Gb/s is possible in WAN, the practical limit is currently 1 Gb/s. Therefore, WAN bandwidth has barely kept pace with disk storage volumes, and, given the fact that large data transfers over long haul networks were unwieldy or impossible in the past, this situation has not improved.

With petaflop-class computing throughput and accelerating exponential online storage growth, exabyte (10^{18} bytes) data volumes will be the norm by 2015. With relatively similar or slower WAN bandwidth growth, the networks will not be able to keep pace with the volume of weather and climate model output. Inevitably, such data will of necessity be widely distributed worldwide, and sophisticated subsetting and on-demand processing and visualization will be absolutely required. Similarly, the trend in data management systems and software has been away from the centrally designed, implemented and maintained systems that characterized data centers in the 1990s and earlier. The new generation of data management systems and software are integrated systems of independently designed, implemented and maintained system elements. One example of this is the Open-source Project for a Network Data Access Protocol (OPeNDAP)[29], which has been conceived as an access/delivery element in this environment of distributed data system elements. OPeNDAP is a software framework used for data networking that makes local data accessible to remote locations.

Of critical importance for future data management systems will be the capabilities to extract

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[26] An exabyte is 10^{18} bytes or one million terabytes.

[27] Computer performance in modeling applications is typically measured in floating point results per second (flops); a kiloflop (KF) is 10^3 flops. Sustained supercomputer performance is expected to reach 100 teraflops (TF; 10^{12} flops) in 2010 and 1-10 petaflops (PF; 10^{15} flops) by 2015.

[28] Mb/s - megabits or 10^6 bits per second; Gb/s - gigabits or 10^9 bits per second

[29] http://www.opendap.org/

subsets of the very large data sets, stored in different formats, and to create derived data sets that represent the results of on-demand processing on the server side, delivered over the network. These capabilities significantly reduce or eliminate the bottleneck, expected to worsen over the next decade, caused by the growing group of scientists seeking data from large repositories of model output. The subsetting capability allows users to retrieve a specified temporal and/or spatial subdomain from a large data set, meeting a user's needs while minimizing the amount of data transferred. Generating derived data sets in response to user requests by processing data on the server side can further reduce the volume of data that must be transported over the WAN, and makes it possible for experts to share intermediate results and analysis methods with each other.

Model and observational data sets can currently be accessed through various web and internet-based interfaces (e.g., ftp, GDS[30], ESG[31], LAS[32]), each with different evolving capabilities. All can transfer complete files from a single site over the internet. Some provide a level of security, e.g., denying access except to approved users. Some can extract subsets of data and perform simple server-side calculations (e.g., obtain a single pressure level, a climatological mean, a zonal mean), and some can perform more complex server-side calculations. There is a rudimentary capability among some tools to transfer data from disperse sites, but make it look like a single aggregated site.
Another important aspect of distributed data management is the fact that data are served in a variety of formats (e.g., GRIB[33], binary, netCDF[34], HDF[35], BUFR[36], and GrADS station format), while the programs scientists use to analyze those data are often format-specific. Software can be written that unifies the variety of data formats into a single framework to simplify data analysis. One example of such software is the GrADS Data Server[37] (GDS), which provides subsetting and analysis services across a wide range of commonly used meteorological and oceanographic data formats.

The capability to analyze ensembles of predictions or simulations from multiple models, station observations, objective analyses and remote sensing data in a single analytic framework is becoming essential. This capability can facilitate the assimilation of observational data and model output, and it can make it possible to perform analyses in a variety of ways, across models, across ensemble members, across real time and across forecast/simulation time.

b. Earth System Modeling

As described in *The World Climate Research Programme Strategic Framework 2005-2015: Coordinated Observation and Prediction of the Earth System (COPES)*[38], the WCRP is

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[30] Grads Data Server - http://www.iges.org/grads/gds/gds.html

[31] Earth System Grid - https://www.earthsystemgrid.org/

[32] Live Access Server - http://ferret.pmel.noaa.gov/Ferret/LAS/ferret_LAS.html

[33] WMO gridded data format standard - http://www.wmo.ch/web/www/WDM/Guides/Guide-binary-2.html

[34] http://www.unidata.ucar.edu/software/netcdf/

[35] http://hdf.ncsa.uiuc.edu/

[36] WMO station report format standard - http://www.wmo.ch/web/www/WDM/Guides/Guide-binary-1A.html

[37] http://www.iges.org/grads/gds/gds.html

[38] WCRP-123, WMO/TD-No. 1291, August 2005; available from WCRP, World Meteorological Organization, 7 bis, avenue de la Paix, P.O. Box 2300, 1211 Geneva 2, Switzerland

embarking on an ambitious, decade-long observing and modeling activity that is intended to improve understanding of the mechanisms that determine the mean climate and its variability, with the ultimate objective of providing the soundest possible scientific basis for a predictive capability for the total climate system. The framework calls for an integrated approach in which the roles of the atmosphere, ocean, land and cryosphere are considered in comprehensive models of the climate system, which are also capable of assimilating weather and climate observations. The continuum of prediction problems, from weather-to-climate and days-to-decades, will be addressed by a hierarchy of models that should become increasingly similar to one another, merging eventually into "unified models" with common infrastructure and interchangeable parameterizations, and variously configured to address a wide range of problems. This fact, when considered with the anticipated increasing international coordination of model development, integration and analysis, implies that the modeling and model output data management challenges will be very large.

Increasingly, century-long climate projection will become an initial-value problem requiring the current observed state of all components of the Earth system: the global atmosphere, the world oceans, cryosphere, and land surface (including physical quantities such as temperature and soil moisture as well as biophysical quantities such as leaf area index etc.) to produce the best projections of the Earth system and also giving state-of-the-art decadal and interannual predictions. The shorter time-scales and weather are known to be important in their feedback on the longer-time-scale behavior. In addition, the regional manifestations of longer-time-scale changes will be felt by society mainly through the changes in the character of the shorter time-scales, including extremes. For example, the well-known features of the climate that operate on interannual time scales, such as ENSO, are likely to be the agents of change in a greenhouse-warmed climate. Also, distributions in space and time of weather extremes such as floods and tropical cyclones are likely to be the most obvious (and costly) manifestations of global climate change. In the process of addressing this challenge, it will be necessary to build more accurate models of the climate system that replicate more faithfully the behavior of the observed climate.

In the meantime, while the WCRP COPES strategy is being developed and implemented, there are many research groups around the world that are developing Earth System models of various degrees of complexity and sophistication. Many groups are working with highly developed models of the components of the Earth system, while others have chosen to emphasize completeness and feedbacks at the expense of resolution and accuracy. In the latter category, Earth System Models of Intermediate Complexity (EMICs) attempt to overcome the gap between simple and comprehensive models [39]. Such models describe a considerable number of processes and feedbacks in the climate system, generally including more components than most coupled atmosphere-ocean general circulation models. Because EMICs are implemented at very low spatial resolution with simplified governing equations, they are significantly less computationally expensive and can therefore be integrated for much longer simulated time, up to and including multi-millenial scale calculations. Recently, large model comparison experiments have shown that EMIC results can be comparable to observational data and fully coupled ocean-

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[39] Claussen, M., Mysak, L.A., Weaver, A.J., Crucifix, M.,Fichefet, T., Loutre, M.-F., Weber, S.L., Alcamo, J., Alexeev, V.A., Berger, A., Calov, R., Ganopolski, A., Goosse, H., Lohman, G., Lunkeit, F., Mokhov, I.I., Petoukhov, V., Stone, P., Wang, Z., 2002: Earth system models of intermediate complexity: Closing the gap in the spectrum of climate system models. *Climate Dynamics*, **18**, 579-586.

atmosphere models. This suggests that EMICS can be used to improve understanding of processes and feedbacks within the climate system that occur on time-scales longer than are generally possible with more complex models. In Table 4.2 below (labeled Table III [40]) indicates a possible progression of models for the next two decades with increases in complexity, realism, and computational demand.

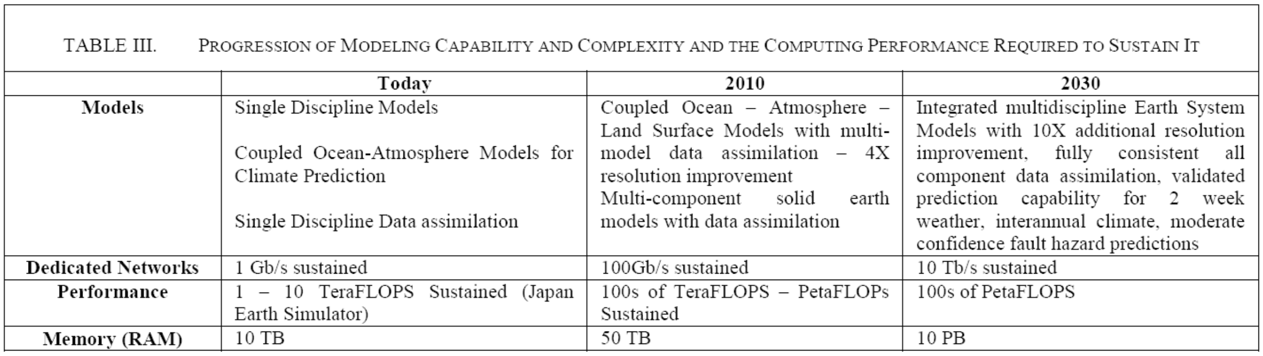

TABLE III. PROGRESSION OF MODELING CAPABILITY AND COMPLEXITY AND THE COMPUTING PERFORMANCE REQUIRED TO SUSTAIN IT

	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 multidiscipline 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	1 Gb/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)	10 TB	50 TB	10 PB

Table 4.2. Progression of modeling capability and complexity and the computing performance required to sustain it.

Table 4.3 (below) provides a sample list of Earth System Models that are currently in use. It is intended to be illustrative and not comprehensive.

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[40] http://esto.nasa.gov/conferences/igarss03/files/TU09_1700%20Ferraro.pdf

Institution (country) **web site**	**Modules** [41]
UCLA (USA)	AGCM, OGCM, ACM, OCM
http://www.atmos.ucla.edu/~mechoso/esm/	
GFDL (USA)	AGCM, OGCM
http://www.gfdl.noaa.gov/	
NCAR (USA)	AGCM, LSM, OGCM, SIM
http://www.ccsm.ucar.edu/	
GENIE (U.K.)	AGCM, OGCM, SIM, LSM, LIM, ACM, OCM, MEM, TEM, MSM
http://www.genie.ac.uk/	
DFGI (Germany)	AGCM, OGCM, HYD
http://www.dgfi.badw.de/index.php?id=71	
UEA (U.K.)	(using parts of GENIE)
http://tracer.env.uea.ac.uk/esmg/ESMResearch.html	
JAMSTEC (Japan)	AGCM, OGCM, SIM, LSM, ACM
http://www.jamstec.go.jp/frsgc/eng/program/imrp/group02.html	
AWI (Germany)	AGCM, OGCM, LSM, EMIC
http://www.awi-bremerhaven.de/Modelling/Paleo/ESM.html	
INGV (Italy)	AGCM, OGCM, SIM, LSM, MEM
http://www.bo.ingv.it/eng/LIVELLO3/esm.htm	
Potsdam Institute	EMIC
http://www.pik-potsdam.de/research/research-domains/earth-system-analysis/climber3	
NASA GMAO (USA)	AGCM, OGCM, LSM, HYD, ACM
http://gmao.gsfc.nasa.gov/overview.php	
Penn State University (USA) - GENESIS	AGCM, OGCM, LSM, SIM
http://www.essc.psu.edu/genesis/	

Table 4.3. Some of the institutions with Earth System modeling activities and the modules included in each of their models.

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[41] AGCM = global atmosphere; OGCM = world oceans; SIM = sea ice model; LSM = land surface processes; HYD = surface hydrology model; LIM = land ice model; ACM = atmospheric chemistry; OCM = ocean chemistry; MEM = marine ecosystem; TEM = terrestrial ecosystem; MSM marine sediments model; EMIC = Earth System Model of Intermediate Complexity

5. Observing Systems and Sensor Networks

The observation systems needed for the advancement of Earth System Science over the next few decades will involve systematic in-situ, focused experiments, and satellite system observations. However, because of their global view, observations from space will be essential for addressing broad range of Earth science problems and issues, expanding our understanding of Earth system dynamics and processes while informing environmental, natural resource, and societal planning and decisions. Satellite remote sensing is the only practical means of obtaining systematic measurements over the entire Earth surface for long time periods, and many applications have come to rely on this unique resource. Satellite remote sensing is critical for extending in-situ terrestrial, oceanic, and atmospheric measurements through time and over large regions. Through the continuing development of new sensors, platforms, and data products for Earth observation from space as well as the calibration, validation, and interpretation of satellite observations and their assimilation into Earth system models, various space agencies make essential contributions to Earth science, observation, and monitoring.

Satellite Missions

Satellite platforms must be fully exploited to observe the Earth and provide a critical resource for Earth science research. As a result of growing research efforts, many measurements from space are now routine and essential. For example, satellite remote sensing has become indispensable for accurate weather forecasts and severe storm warnings. But other important measurements require new concepts that take advantage of advancing technology—many observations remain difficult to interpret.

From the 1960's through the 1980's, capabilities to observe the Earth were steadily advanced, launching a new eras of scientific discovery by remote sensing from space. Key early results include discovery of the processes behind Antarctic ozone depletion; the Earth's response to incoming solar radiation; and the extent, causes, and impacts of land use and land cover change. The emerging view of the whole Earth enabled by satellite perspectives stimulated the development of an interdisciplinary Earth system science motivated to observe a sufficient suite of characteristics and variables to identify and track change over long time periods at scales from local to global.

Satellite observations are now enabling increasingly interdisciplinary Earth science research leading to better understanding of the Earth as a system that responds as a whole to forces acting on its major components. Earth system models are incorporating data from multiple sensors as constraints on model parameters and solutions.

Suborbital and Surface Observations

Measurements on land and within the Earth's atmosphere and oceans are required to calibrate and validate measurements are an integral part of a complete Earth observing system. Suborbital measurements and sensors on the Earth's surface augment observations from space with higher spatial and temporal resolutions that can be targeted at specific regions or focused on specific processes. Additionally, major experiments and field campaigns provide detailed information about and understanding of systems and processes observed from space. A comprehensive Earth observing system requires a global, integrated approach combining observations from spacecraft, suborbital vehicles such as aircraft and balloons, surface instruments such as carbon flux towers and ocean buoys, as well as major experiments and field campaigns engaging multiple surface and suborbital measurements carefully coordinated with satellite observations and modeling, prediction, and application needs.

Aircraft and other suborbital platforms provide laboratories for testing new approaches and sensors. Experience with suborbital observations is important for determining the value of sensors for space missions. Data collected by prototype sensors or simulators for sensors intended for satellite deployment are crucial for algorithm development and testing. In addition to their critical role in calibration, validation, and sensor development, suborbital remote sensing data compliment satellite observations with higher resolutions and less interference that are often critical for characterizing heterogeneity in space or time or for understanding complex processes.

Systematic Earth Observing Systems and Data Records

There is a need to develop and deploy a global, integrated, and sustained observing system to address science requirements and decision support needs at appropriate accuracies and spatial and temporal resolutions. The overarching question is: How can we provide active stewardship for an observation system that will document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society? Current sensors are providing unprecedented measurements of Earth system properties and variables with global coverage. The challenge for the next decade is to maintain current capabilities, implement new elements, make operational the elements that need to be sustained, and integrate observations into a comprehensive global system. The vision requires an observing system that addresses research and decision support needs in climate, the global biogeochemical cycles of carbon and other elements, water, energy, atmospheric composition, and changes in land cover and land use.

As measurements become reliable and well understood, they must be incorporated into a growing suite of systematic observations obtained operationally. Sustained measurements are meant to identify and monitor long-term changes in the Earth system. Such Earth system data records must meet standards that allow comparison of measurements over extended periods, frequently through the lifetimes of multiple platforms and sensors, while maintaining sufficient and well-understood accuracy. These are “climate quality” data records, meaning that the records are suitable for investigating change over time periods corresponding to climatic variations and change. Achieving the necessary consistency and accuracy requires observations that conform uniformly to underlying principles. As summarized in Table 5.1, the Global Climate Observing System (GCOS) specifies a core set of principles for Earth system data records. The GCOS principles highlight the importance of radiance calibration, calibration monitoring, and satellite-to-satellite cross-calibration. [42]

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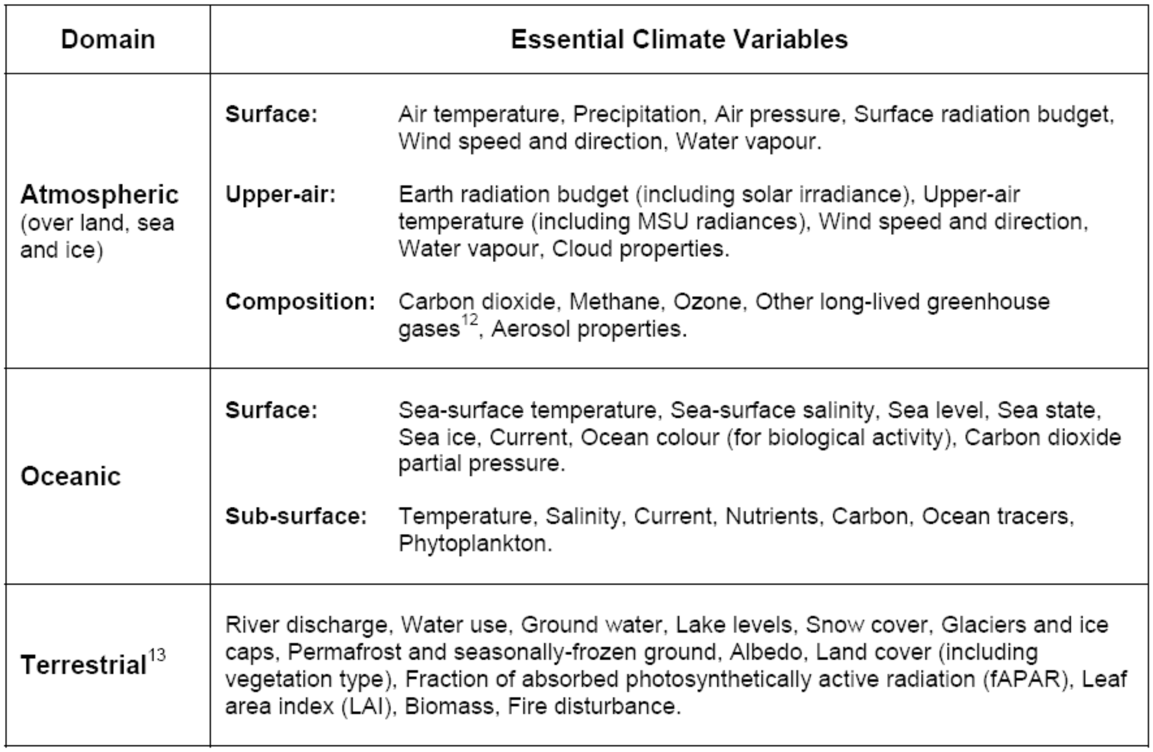
[42] http://science.hq.nasa.gov/strategy/researchPlan.pdf

Table 5.1. Essential Earth System variables that are currently feasible.



Domain	Essential Climate Variables	
Atmospheric (over land, sea and ice)	**Surface:**	Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour.
	Upper-air:	Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties.
	Composition:	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases[12], Aerosol properties.
Oceanic	**Surface:**	Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.
	Sub-surface:	Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.
Terrestrial[13]		River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI), Biomass, Fire disturbance.

There is substantial promise for the advancement of Earth System Science using Networks of Environmental Sensors and Observing Systems. Recent technological developments in the miniaturization of electronics and wireless communication technology have led to the emergence of Environmental Sensor Networks (ESN). These will greatly enhance monitoring of the natural environment and in some cases open up new techniques for taking measurements or allow previously impossible deployments of sensors. ESNs are typically arrays of devices containing sensors and interconnected using a communication network. These systems allow the study of fundamental processes in the environment, as well as providing vital hazard warnings. This is particularly important in remote area where many essential processes have rarely been studied due to their inaccessibly.

Environmental Sensor Networks have evolved from automated loggers that record data at specific intervals and require manual downloading by a maintenance team. Some of the earliest examples of automated environmental monitoring include analogue loggers such as early paper plotters measuring barometric pressure. An Environmental Sensor Network comprises an array of sensor nodes and a communications system, which allows their data to reach a server. The sensor nodes gather data autonomously and a data network is usually used to pass data to one or more base stations, which forward it to a Sensor Network Server (SNS). Some systems send commands to the nodes in order to fetch the data, while others allow the nodes to send data out autonomously. At the SNS level the data can be visualized and analyzed within a Geographic Information System (GIS), combined with a satellite images, and put on the Web to give users seamless access. Development of sensor networks in general requires technologies from three different research areas: sensing, communication and computing.

In the future there will likely be an evolution from large static sensor nodes (such as weather stations and seismic sensors) to ‘smart dust’. Smart dust is a futuristic concept to build tiny wireless nodes which often use microelectromechanical sensors (MEMS) on a cubic millimeter scale. The idea is that thousands of these micro sensors will be scattered around the environment to sense different variables. Sensor nodes do not necessarily need to be static. Not only can they be moved by the environment but can be actively moved by aerial tramways, robotic vehicles, airplanes, submarines and satellites.

Particular challenges for the development of ESN include:

- Power management — For an ESN to work unattended, the systems must use sophisticated power management techniques which are coupled to their communications design.
- Management and usability—There is a need to evolve sensors from research platforms to user-driven commodity deployments.
- Standardization—Compatible hardware and operating software will need to be developed to enable seamless interoperability, to make it possible to deploy nodes from a variety of vendors and visualize the data in a unified way
- Data quality—Sensor calibration and defining the exact source of sensor data, without placing too much burden on the users is essential for producing useful, high quality data.
- Data mining and harvesting — Standardization and semantic markup will lead to a high data availability, and thuse, a need to make data mining simple for users.
- Development of new sensors — Miniaturization, cost reduction and low-power design are still needed to enable the ESN vision.

In the future, ESNs will be a standard part of earth system and environmental science, and a scientist will be able to observe the environment from their office. The ability to be in daily contact with the data source allows a researcher to have a better connection with the environment they study. ESNs are a new approach to study the environment, new field methods to be conceptualized, and new solutions to scientific problems advanced.[43]

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[43] Hart, J. K. and Martinez, K. (2006) Environmental Sensor Networks:A revolution in the earth system science?. Earth-Science Reviews 78 pp. 177-191 http://eprints.ecs.soton.ac.uk/13093/01/esn.pdf

6. Strategies for Contributing to Advancement of Earth System Science

Brazil's Amazon rainforest is among the most biodiverse of Earth's environments, as it is home to half the worlds' rainforests and known species. Through complex evapotranspiration, recycling, and global teleconnection processes, Brazil's forests generate tremendous cloud cover that play a central role in distributing the sun's heat, and therefore regulating global climate. Brazil is also economically important, producing significant lumber, fiber, food, and medicine. However, due to anthropogenic activities such as deforestation, pollution, and hunting, drastic alterations of Brazil's ecologic and hydrologic systems are apparent. Because of the very delicate and unpredictable nature of the intricate ecosystem relationships, it is not clear what long-term impacts human activities will cause in this globally-important region. Altered cycles of water, energy, carbon and nutrients, resulting from the changes in Brazil's vegetation cover, are expected to have climatic and environmental consequences at local, regional and global scales. To understand these consequences and to mitigate their negative effects, enhanced knowledge is needed of the functioning of both the existing natural environmental systems as well as systems which have already been converted to various other forms of land use.

Despite widespread concern and increased international efforts at conservation, Brazil's tropical forests continue to disappear at an unprecedented rate. Of vital importance in developing sustainable management and exploitation systems for tropical forests are the questions as to how far human intervention affects the forests' basic capacities to renew themselves and how to safeguard the basic ecological processes such as biological productivity and nutrient and water cycling. Altered cycles of water, energy, carbon and nutrients, resulting from the changes in Amazonian vegetation cover, are expected to have climatic and environmental consequences at local, regional and global scales. To understand these consequences and to mitigate their negative effects, enhanced knowledge is needed of the functioning of both the existing natural forest systems as well as systems which have already been converted to various other forms of land use or secondary regrowth. These issues are at the heart of how INPE can contribute to the advancement of Earth System Science in Brazil.

In order to take maximal advantage of its unique geography, location and distribution of natural resources, INPE needs an independent capability to make accurate and complete weather forecasts, seasonal predictions and long-term outlooks for the next one to two decades. Based on all available evidence, the best way to achieve this capability is for INPE to develop an Earth System Information System (ESIS). The Brazilian society, and the larger community of South America, will greatly benefit from an ESIS that includes all components of the ES (atmosphere, ocean, land surface, cryosphere, and marine and terrestrial ecosystems) and serves all relevant sectors of society, including education, research, disaster preparedness, resiliency, and capacity building. Brazil should take leadership in encouraging the other countries in South America that have capability in various aspects of Earth System Science to form partnerships that can contribute toward building the ESIS.

An ESIS includes four components: an Earth System modeling capability, an observing system component, a database and analysis capability, and the development of solutions support capability that can bridge the gap between Earth System Science and stakeholders to create an end-to-end system. The first two components were described in sections 4 and 5 above. The database and analysis capability amounts to assembling and probing the rich record of past and current climate that has been gathered to date. For example, all the atmospheric observations that have been collected in Brazil and provided to the world meteorological centers for weather prediction purposes should be gathered, quality controlled and catalogued. Similarly, all the measurements of the Earth System taken in various field programs in the vicinity of South America (over both the continental region and the adjacent oceans) should be assembled and merged with the operational meteorological observations.

Once these databases are assembled and documented, a program of analysis should be undertaken that can provide a detailed level of understanding and attribution of the variations in the Earth System that have taken place in the recent past. Such a detailed analysis of the climate anomalies of the past, e.g., droughts and floods that have occurred in the Amazon basin and Nordeste Brazil over the 20th century, can enhance our understanding of the dynamics of the Earth system for the betterment of Earth system models and for the more rational management of observing system resources.

The solutions support uniqueness of ESIS is described in section 10.

Looking beyond the resources available in INPE and Brazil, partnerships with the international research community should be developed that can advance earth system science, including climate change science research and assessments. INPE should participate in the planning for development of a new global Earth observing system. Recent elevated international attention on these issues has been brought by the Earth Observation Summit (EOS), and through establishment of the Group on Earth Observations (GEO).

It has long been recognized that it is essential to study climate change and variability on both global and regional scales. To do so effectively – in terms of both scientific and financial resources – requires international cooperation – among scientists, among research institutions, among governmental agencies, and among governments themselves. Brazilian scientists, institutions, and agencies are at the forefront of such international cooperation. INPE should help develop and maintain an intergovernmental framework within which Earth System Science, including research and observational programs, can be planned and implemented. The overarching goals of this effort should be to:

- Develop an internationally-recognized, comprehensive Earth System Model that will explicitly resolve weather and climate relevant physical, chemical and biological processes, in order to improve dramatically the use of space-based observations, and the application of these observations to the understanding and prediction of Brazilian weather and climate.
- Actively promote and encourage cooperation between INPE scientists and scientific institutions and agencies and their counterparts in Brazil and around the globe so that they can aggregate the scientific and financial resources necessary to undertake research on change at all relevant scales, including both the regional and global.
- Expand observing systems in order to provide global observational coverage of change in the atmosphere, oceans, and on land, especially as needed to underpin the research effort.

- Assure that the data collected are of the highest quality possible and suitable for both research and forecasting, and that these data are exchanged and archived on a timely and effective basis among all interested scientists and end-users.
- Support development of scientific capabilities and the application of results in developing countries in order to promote the fullest possible participation by scientists and scientific institutions in these countries in research, observational, and data management efforts.
- Develop multi-national (South American) Earth System Science research collaborations (a.k.a. ECMWF) to support river basin, trade, pollution, and migration studies and management.

As a leader in climate change and earth system science, INPE and other Brazilian institutions play an important role in international assessments such as ozone, biodiversity, and ecosystems, as well as those concerned with regional climate.

Group on Earth Observations

The Group on Earth Observations (GEO) has established a political commitment to move toward development of a comprehensive system that will enable researchers and decision makers to monitor continuously the state of the Earth, increase understanding of dynamic Earth processes, enhance prediction of the Earth system, and further implement international environmental treaty obligations. Ministers from developed and developing countries seek through their agreement to increase timely, high-quality, long-term, global information, which can serve as a basis for sound decision making for the benefit of society. More than 20 international organizations also participated in the initiative. An Earth Observing System as described in the Declaration will produce a number of benefits, in both the near and long-term. In the near term, all of the countries participating in this system can expect that, through improved observations of weather, climate, the oceans, seismic activity, and fires, among others, loss of life and damage to property can be reduced. Additional benefits will include improved water management, health assessments, agricultural efficiencies, aviation safety, coastal management, and disaster management. In the long term, an Earth observing system will offer greater understanding of the Earth system that will underpin decision making in many areas, including the reduction of disaster loss and supporting sustainable global development.

Inter-Americas Institute for Global Change Research (IAI)

The IAI brings together the over 200 research universities and government institutions in the Western Hemisphere that make up its research network. Research programs sponsored by the IAI have aided in development of new decision and management tools in diverse areas, ranging from the incorporation of long range forecasts into dam management for hydropower and irrigation, to the establishment of a tri-national sardine fishery forum that regularly brings together regulatory agencies, resource managers, fishermen, and researchers from Canada, Mexico, and the United States. In addition, IAI research enabled the first rigorous scientific ranking of drivers of global change, based on scenarios of changes in global biodiversity.

Engaging the International Climate Change Research Community

International cooperation plays an important role in focusing the world's scientific resources on the -priority climate and global change research issues, in helping to reduce scientific redundancy in a world of limited financial resources, and in improving exchange of data and information internationally. By developing both conceptual and research frameworks, international research programs provide models that aid in planning and coordinating their efforts. Much of the research conducted benefits from and contributes to projects sponsored by the four major international research programs: the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), the Diversitas program, and the newly launched interdisciplinary collaboration among all of the programs, the Earth System Science Partnership (ESSP).

The IGBP is transitioning into its second phase with new emphases in biogeochemical sciences with relevance to issues of societal concern, interdisciplinarity, Earth system science, and regional-scale integrated research. Many of the IGBP phase-one projects are coming to a close or, as in the case of International Global Atmospheric Chemistry (IGAC), being reoriented. New projects such as Land-Atmosphere, Land, Land-Ocean, and Ocean are in the development stage or beginning work.

The WCRP is focusing its efforts on its major projects, including Climate and Cryosphere (CliC), Climate Variability and Predictability (CLIVAR), Global Energy and Water Cycle Experiment (GEWEX), Stratospheric Processes And their Role in Climate (SPARC), and the World Ocean Circulation Experiment (WOCE), which continues to provide satellite, *in situ* observations, and models. CLIVAR hosted its international conference in June 2004 in Baltimore, Maryland. Development of the first global integrated data set of the water cycle (GEWEX, CliC, CLIVAR), which is the first element of the Coordinated Enhanced Observing Period (CEOP), is currently underway.

IHDP is focusing on a number of core project efforts, including the Global Environmental Change and Human Security (GECHS) project, the Institutional Dimensions of Global Environmental Change (IDGEC) project, the Industrial Transformation (IT) project, and Land-Use Land-Cover Change (LUCC) project. In addition to the core projects, the IHDP is also addressing cross-cutting questions, such as thresholds/transitions, vulnerability/resilience, adaptation/learning, and governance in the face of global environmental change. Additional questions include study of human drivers of change, as well as its relevance for sustainable development. Through investigation of these issues, IHDP will develop perspectives on key questions in global environmental change research.

Diversitas, the newest of the international programs, is focusing on development of three core projects- bioDISCOVERY, ecoSERVICES, and bioSUSTAINABILITY, as well as cross-cutting networks and projects. The Biodiscovery project is focused on discovery and understanding of changes in global biodiversity. The Ecoservices project will assess the impacts of biodiversity changes, while the Biosustainability project will develop the science of conservation and sustainable use of biodiversity. The three core projects are completing their planning and beginning implementation.

The ESSP, a partnership for the integrated study of the Earth system, changes, and the implications of those changes, is currently developing its core projects: the Global Carbon Project (GCP), Global Environmental Change and Food Systems (GECAFS), the Global Water

System Project (GWSP), and Global Environmental Change and Human Health (GECHH). These projects are designed to address issues critical to the understanding of global change and to build upon the existing core programs and, to the greatest extent possible, their existing infrastructure.

Examples of international institutions and programs that already have substantial interactions with INPE are the IRI, LBA and IGES.

International Research Institute for Climate Prediction (IRI)

The IRI conducts strategic and applied research on climate information and prediction, decision systems, impacts, institutions and policy, with a focus on education and capacity building in developing countries. The IRI works in partnership with experts and institutions in project regions to advance understanding of climate in the context of decision strategies in sectors including agriculture, health, and water resource management. In northeastern Brazil, this IRI collaboration has resulted in the demonstration of decision opportunities to maximize water usage in a drought-prone region by introducing climate-informed strategies to minimize annual spill of reservoirs. Many of the inhabitants of the vast, semi-arid region of the state of Ceará in Northeast Brazil live by small-scale, rain-fed agriculture and ranching. They face hunger, unemployment, and dislocation during recurrent water shortages in the region. Two million rural people were affected by the last severe drought in 1998. INPE's ability to predict and provide drought relief and mitigation support will come from advances in forecasting and analyses of climate, water supply and demand, agriculture, and socioeconomics. Those advances will be incorporated into a new decisionmaking framework consisting of existing institutional channels, the people most affected by water and drought management, and a new procedure for them to use in comparing policies.

Large Scale Biosphere-Atmosphere Experiment in Amazonia

The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) is intended to improve understanding of the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia; the impact of land-use change on these functions; and interactions between Amazonia and the Earth system. The LBA is led by Brazil and involves substantial participation by U.S. scientists, institutions, and agencies. Recent results include the release of two LBA data sets for the study area (i.e., longitude 85 o to 30 o W, latitude 25 oS to 10 oN). The first data set consists of LBA regional historical climatology (precipitation, temperature, and pressure data) for the period 1832-1990 and is a subset of the Global Historical Climatology Network (GHCN) Version 1 database for sites in the LBA study area. The second data set on LBA Regional Derived Soil Properties includes measurements for several variables, including soil organic carbon density, soil carbonate carbon density, soil pH, and soil water capacity. Under the aegis of the LBA, substantial progress has been made in training and educating students (73 PhD and 46 Masters Degrees underway or completed. In addition, almost 300 students and 35 Amazonian institutions have been and are involved in U.S.-Brazil collaboration in LBA research. [44]

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[44] http://www.usgcrp.gov/usgcrp/Library/ocp2004-5/ocp2004-5-hi-international.htm

Institute of Global Environmental and Society (IGES)
The Institute of Global Environment and Society was established to improve understanding and prediction of the variations of the Earth's climate through scientific research on climate variability and climate predictability, and to share both the fruits of this research and the tools necessary to carry out this research with society as a whole. The Institute has established two centers of excellence dedicated to basic research on the Earth's current climate (Center for Ocean-Land-Atmosphere Studies - COLA), and the Earth’s water and energy cycle (Center for Research on Environment and Water - CREW). COLA aims to explore, establish and quantify the variability and predictability of the Earth's seasonal to decadal climate variations through the use of state-of-the-art dynamical coupled ocean, land, and atmosphere models, and conducts research on how to transform this predictability into societally beneficial predictions. CREW aims to quantify and predict global water cycle and environmental consequences of Earth system variability and change through focused research investments in observation, modeling, prediction, and solutions.

7. **Vulnerability and Adaptation and Earth System Science**

There is little doubt that the Earth's global mean climate is warming and that human activity is responsible for a significant portion of the warming, particularly over the past several decades. There is likewise little doubt that global warming will continue for the decades to come, regardless of whether or not emissions of greenhouse gases are reduced or even eliminated. This is due to the inertia of the Earth system. Some greenhouse gases have long residence times in the Earth's atmosphere (100 years for carbon dioxide; 120 years for nitrous oxide), and the world oceans respond slowly to warming. The rise in global temperatures taking place now is only a partially response to the accumulation of greenhouse gases in the Earth's atmosphere over the past 100 years.

These statements are all referenced to the Earth's global mean climate – what are the implications for regional climate, particularly in South America? Based on the results of scholarly papers that will be used in the Intergovernmental Panel on Climate Change (IPCC) fourth assessment (AR4), there are several potential consequences of regional manifestations of global warming for South America, in roughly decreasing order of certainty:

- *mean temperature* – warming will likely continue with increasing mean temperatures
- *temperature extremes* – heat waves will likely increase in frequency, duration and intensity, which has the potential to result in increased mortality for the elderly and to impact (mostly negatively) on agricultural production
- *precipitation extremes* – torrential rain events and tropical cyclone intensity will likely increase; tropical cyclone frequency may possibly increase
- *variability* – because the Earth system is more energetic under greenhouse warming conditions, variability will likely increase; also, the signature of increased variability will be more extremes in the natural modes of variability such as ENSO
- *tropical Pacific* – the greenhouse signal in most AR4 models resembles a quasi-permanent modest warm ENSO which could imply more droughts in South America
- *Amazon basin* – there is a fairly confident projection by AR4 models of a small reduction in rainfall over the Amazon basin, which implies that the rain forest itself might suffer, including the possibility of large-scale tree death and changes in the landscape, water availability, water quality, erosion and navigation
- *cryosphere* – greenhouse warming will accelerate the melting of glaciers, which has negative implications for the tourist industry and water availability

In general, the countries of South America will become increasingly vulnerable to negative consequences of climate change. As the population increases and land use changes, climate changes will increase the vulnerability of society to human mortality, property destruction and political instability. Developing countries in particular, and primarily the poor, are expected to be the most adversely affected by climate change. The poor are more dependent on climate-sensitive economic activities (such as subsistence agriculture) and local ecological resources. They also typically have more limited financial, institutional and human capacity. Perhaps 100 million people worldwide are at risk of experiencing direct climate impacts like sea-level rise. Several billion people are at risk of experiencing indirect climate change impacts such as water scarcity caused by reduced precipitation. Reduced water availability in turn will impact that ability of people to grow food for their own consumption and to sell as a source of income.

Perhaps as important as impacts on human populations, the effects of global climate change on the environment, particularly the ecosystems of the rain forest and coastal Brazil, are of significant concern. There are two main ecosystem issues that are pertinent especially in Brazil. These are the health and sustainability of the rain forest with its profusion of plant and animal species, and the water quantity and quality of the estuaries and coastal waters of Brazil's very long coastline.

Rain Forest Ecology and Biodiversity

The rain forest maintains a delicate balance, with a high degree of interdependency among plant and animal species. The very large amount of rain that falls has, over the millennia, flushed away nutrients that might normally be stored in the soil, so the rain forest must conserve nutrients - leaks of vital nutrients, such as are common in temperate ecosystems would spell disaster. The dense root mat system on the rain forest floor, combined with fungal mycorrhiza bridges, literally sucks up any decomposing matter from the forest litter.

Above ground, the system of tall trees, with its great profusion of epiphytes — the ferns, orchids and bromeliads that have attached themselves to the stem and branches of the large trees — take up any nutrients that are flushed down with the heavy rains. Most of the fauna lives in the canopy, and is also perfectly integrated into the nutrient recycling system by providing the sustenance for the lateral extension of the forest.

There is some indication among the climate projections produced for the IPCC AR4 that the increase in temperature and, more importantly, the reduction in rainfall, could be devastating for the relatively fragile rain forest ecology. This would result in a substantial reduction in the diversity of species within the Amazon and, because it is the home of a large fraction of the species on Earth, it would mean a reduction in the planet's biodiversity.

It is beyond the scope of this study to provide an in-depth evaluation of the importance of biodiversity or the threat that global warming presents to biodiversity. There are several sources that may be useful for this topic. The U.S. National Biological Information Infrastructure provides a listing [45] of sources for biodiversity information and projects. The GLOBIO (Global Methodology for Mapping Human Impacts on the Biosphere) [46] consortium aims to develop a global model for exploring the impact of environmental change on biodiversity.

Estuaries and Coastal Waters

The mouth of the Amazon River is a vast estuary in which the mixture of fresh water from the river and salt water from the Atlantic Ocean provide an ideal environment for a profusion of marine species and plant life such as mangrove trees. The sustainability of this environment is dependent on several water properties, including temperature, salinity, and acidity.

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[45] http://www.nbii.gov/issues/biodiversity/general.html

[46] http://www.globio.info/index.cfm

With respect to water acidity, during the past 100 years or so, the ocean surface has become more acidic by 0.1 pH units [47] and has warmed by 0.6 K [48]. In recent decades, the temperature and salinity changes [49] suggest modifications in the ocean circulation and thus in the distribution of surface nutrients. Surface nutrients also are being modified by changes in fluvial supply and by changes in Aeolian transport of nutrient-enriched dust. In addition, overfishing modifies the predation on large zooplankton by small fish and could have top-down effects on the lower food web. These changes affect marine ecosystems in ways that are neither well understood nor quantified.

All these issues having to do with vulnerability and adaptation are characterized by relatively fragile balances among competing factors, interdependency among components of the ecosystem, and resiliency to change. Therefore, unlike predicting the weather, predicting the future changes in vulnerability of human systems and ecosystems requires a more complete model of the interacting components and especially a quantitative understanding of the feedbacks. There is a high degree of uncertainty about several of these processes and components, so it is necessary for INPE to develop a sophistical Earth System Model to evaluate scenarios and adaptation opportunities.

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[47] Orr, J. C. et al., 2005: Anthropogenic ocean acidification over the twenty-first century and its impacts on calcifying organisms. *Nature*, **437**, 681-686.

[48] Folland, C. K. et al., 2001: Observed climate variability and change. In Climate Change 2001: The Scientific Basis – Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (J. T. Houghton et al., ed.; Cambridge Univ. Press, New York), 183-237.

[49] Curry, R., B. Dickson and I. Yashayaev, 2003: A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, **426**, 826-829.

8. Linkage between Earth System Science and Land Use and Cover Change

Terrestrial vegetation cover and land use state and change are central to many biophysical processes and Earth system processes. Changes in land cover include changes in biotic diversity, primary productivity, soil quality, runoff and sedimentation rates. Land cover changes are sources and sinks for most of the material and energy flows that sustain the biosphere and geosphere. Contemporary land cover is changed mostly by human activity. Forestry, parks, livestock herding, urbanization and farmlands are, for example, classes denoting intent or purpose. Biophysical manipulation, by contrast, refers to the specific way in which human uses treat vegetation, soil, and water for the purpose in question: for example, the cut-burn-hoe-weed sequence in many slash-and-burn agricultural systems; the use of fertilizers, pesticides and irrigation for mechanized cultivation on arid lands; or the use of an introduced grass species for pasture and the sequence of movement of livestock in a ranching system.

Land-use and land-cover change are part of a complex and interactive system linking human use and land cover change to Earth system feedbacks, at different spatial and temporal scales. The outflow of soil nutrients, for example, has immediate impacts on land productivity, vegetation changes and soil erosion, mid-term impacts on landscape fragmentation and land productivity, and possible long-term impacts on climate change.

Environmental Impact of Land-Cover Conversion

Humankind has altered terrestrial ecosystems since, at least, the use of fire to hunt and the advent of plant and animal domestication. These changes increased dramatically throughout history, but in spatial scale, magnitude and pace they pale in comparison to those produced by modern industrial society. Today, land-cover changes are global and rapid, being large enough to contribute significantly to changes in global biogeochemical flows.

Over the last 200 years, cropland has increased by approximately 400%, with irrigated cropland increasing by 2,400%. Over the same period, global forest cover has diminished by about 15%. These land cover changes have been centered primarily in the mid-latitudes of the Northern Hemisphere. During this century, the major land-cover changes have occurred in the tropics. In this realm, cropland and grassland/pasture expansion, deforestation, and urbanisation, among other changes, are increasing rapidly. Land-cover change has led to, or is leading to, significant losses in species numbers and varieties worldwide. It is estimated that the loss in tropical forests leads to the loss of 27,000 species annually. Ecosystem structure and function, long-term ecological processes, and genetic diversity are also at risk in biodiversity loss.

Impacts of Land Cover on Biogeochemical Cycles

The conversion of natural systems to agriculture and other human uses of the land has resulted in a net release of carbon dioxide to the atmosphere that is roughly equivalent to the release from fossil fuel burning over the last 150 years, and the current release of carbon dioxide from land-cover conversion is approximately 30 percent of fossil fuel combustion. Thus, land-cover conversion may have an important influence on regional climatology and hydrology[50] [51].

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[50] Shukla, J., C. A. Nobre, and P. J. Sellers, 1990: Amazonian deforestation and climate change. *Science*, **247**, 1322-1325.

Both land cover and land-cover change data are important for determining the biogeochemical cycling of carbon, nitrogen, and other elements at regional to global scales. The estimates of carbon released from land clearing and biomass burning combined with the estimates of oceanic uptake of carbon cannot now be reconciled in a balanced global budget. The atmospheric concentrations of CO_2 and other trace gases are closely linked to each other through their involvement with and interactions in chemical processes in the atmosphere. When compiling a list of the sources and sinks of these gases, it is apparent that both the land cover and land-cover change play major roles in determining their actual emissions and thus final atmospheric trace gas concentrations. Land cover also determines surface roughness, albedo, and latent and sensible heat flux, and changes in the distribution of land cover alter the regional, and possibly global, balance of these fluxes. Such changes are important parameters for general circulation models.

Part of the hydrological cycle involves the movement of water over continents. Plants act like waterpumps in this part of the cycle, extracting water from soils and returning it to the atmosphere through evaporation and transpiration. Water recycling in the Amazon rain forest is exemplary; the present precipitation patterns observed there are partly a function of the vegetation cover. Changes in land cover, therefore, may trigger changes in the hydrological cycle which, in turn, would have significant implications for land uses. The impacts of the hydrological cycle caused by land-use/cover changes in the Amazon are not yet adequately assessed. One of the few such assessments indicates that a significant regional decrease in evaporation and precipitation would follow massive removal of forest there. At the global scale, land-use/cover change has been shown to have an impact on atmospheric circulation[52].

Land-Use/Cover Impacts on Sustainability

Changes in land use and land cover have significant environmental implications, such as the direct use-cover impacts from soil degradation, surface runoff alterations, or the draw down in ground water. These kinds of changes - those confronting the land manager on a daily basis - as well as their impacts on, and sensitivity to, global environmental change are issues of sustainability. We need not reiterate the magnitude, spatial scale, and pace of changes in sustainability inasmuch as they are intimately linked to, indeed often the same as, those detailed above for land-cover changes (impacts on states/faces and biogeochemical cycles). At least three points are important here. (i) Increasingly, the global environmental change community appears to realize the centrality of land-use/cover change in its own right to sustainability. (ii) Many of the projected problems associated with land-use/cover sustainability, such as ground water depletion, may well trigger large-scale environmental problems in the near term that will have impacts on land-use/cover dynamics. (iii) The sustainability of any land-use is not only tied to the environmental attributes of the land and the techno-managerial strategies employed on it, but to the socio-economic condition of the land manager. Land-use/cover sustainability, therefore, is largely captured in the kinds of integrated modeling efforts that are central to understanding land-use/cover change.

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[51] Nobre, C. A., P. J. Sellers, and J. Shukla, 1991: Amazonian deforestation and regional climate change. *J. Climate*, **4**, 957-988.

[52] Foley, J.A., J.E. Kutzbach, M.T. Coe, and S. Levis. 1994. Feedbacks Between Climate and Boreal Forests During the Holocene Epoch. *Nature,* **371**, 52-54.

Modeling and Projecting Land-Use/Cover Changes

Modeling land-use/cover change has been approached through field-based case studies of land use, thematic assessments of the patterns of land-cover change, and prognostic, regional and global models of land-use/cover. However, these models often lack generalities prevent the derivation of macro-models, and current prognostic macro-models are often criticized for their unrealistic assumptions and simplifications that preclude real-world usefulness, let alone accuracy. These stereotypes are not only unwarranted but miss the critical point that each approach complements, and, if integrated properly, improves the others.

Our current understanding of cause-use-cover dynamics must be used to improve regional and global models and projections of these dynamics. Model systems must be developed that are geographically sufficiently disaggregated but can be aggregated to the global, are multi-sectoral and sensitive to the non-linear and interrelated driving forces of land-use and land-cover change, account for major biophysical feedbacks, and are capable of coupling to biophysical models, such as global circulation models. It is difficult to conceive of any other mechanism than models for projecting the impact of such a complex matrix of driving forces and biophysical feedbacks. Such models, if constructed properly, are not limited to land-use and land-cover change, but can provide the quantitative framework for scenario analysis relating to climate change, hydrological cycles, biodiversity, sustainability, and food security as well as general changes in tastes, values, and norms of society. Future LUCC model systems will include several important components: a demographic component and modules for representing changes in social expectations/ values and policy settings, an economic model, a land-use allocation component, models of resulting land cover and environmental impacts, and a land productivity module, feeding the simulated impacts back into the economic and other social components, thereby closing the feedback loops.

Lastly, the questions of sensitivity analysis and model verification and validation are of importance. The validation methods to be applied will have to vary with the type of model being used. In many cases formal validation methods will not be available. In such situations, the necessary validation needs to stress: (i) rigorous testing of specification and methodological foundation of the models; (ii) thorough testing of model sensitivity with respect to parameterization including backcasting; (iii) sensitivity of model results with respect to quality of used data sources; and (iv) econometric estimation of parameters as warranted by quality and amount of available data. [53]

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[53] http://lcluc.umd.edu/products/pdfs/strategy-igbp-report35.pdf

9. Linkages among Earth System Science, Intergovernmental Panel on Climate Change (IPCC), Millennium Ecosystem Assessment (MEA) and the United Nations Environmental Conventions on Climate Change, Biodiversity and Land Degradation

The international science community has recognized the value of enhanced partnerships among international programs like WCRP, IGBP, IHDP, and Diversitas. There is discussion going on about developing an international Earth System Science Program, which will combine the expertise of WCRP, IGBP, IHDP, and Diversitas. For implementing scientific and technological solutions towards adaptation and mitigation of impending climate change, it is essential that all the programs work together to provide the best information to policy-makers and stakeholders.

IPCC background

Human activities now occur on a scale that is starting to interfere with natural systems such as the global climate. Because climate change is such a complex and challenging issue, policymakers need an objective source of information about the causes of climate change, its potential environmental and socio-economic impacts, and possible response options. Recognizing this, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The Panel's role is to assess on a comprehensive, objective, open and transparent basis the best available scientific, technical and socio-economic information on climate change from around the world. The assessments are based on information contained in peer-reviewed literature and, where appropriately documented, in industry literature and traditional practices. They draw on the work of hundreds of experts from all regions of the world. IPCC reports seek to ensure a balanced reporting of existing viewpoints and to be policy-relevant but not policy-prescriptive. Since its establishment the IPCC has produced a series of publications, which have become standard works of reference, widely used by policymakers, scientists, other experts and students.

MEA background

The Millennium Ecosystem Assessment (MEA) is an international work program designed to meet the needs of decision makers and the public for scientific information concerning the consequences of ecosystem change for human well-being and options for responding to those changes. The MEA was launched by U.N. Secretary- General Kofi Annan in June 2001 and was completed in March 2005. It will help to meet assessment needs of the Convention on Biological Diversity, Convention to Combat Desertification, the Ramsar Convention on Wetlands, and the Convention on Migratory Species, as well as needs of other users in the private sector and civil society. If the MEA proves to be useful to its stakeholders, it is anticipated that such integrated assessments will be repeated every 5– 10 years and that ecosystem assessments will be regularly conducted at national or sub-national scales.

The MEA focuses on ecosystem services (the benefits people obtain from ecosystems), how changes in ecosystem services have affected human wellbeing, how ecosystem changes may affect people in future decades, and response options that might be adopted at local, national, or global scales to improve ecosystem management and thereby contribute to human well-being and poverty alleviation. The specific issues being addressed by the assessment have been defined through consultation with the MEA users.

The MEA synthesizes information from the scientific literature, datasets, and scientific models, and includes knowledge held by the private sector, practitioners, local communities and indigenous peoples. All of the MEA findings undergo rigorous peer review. More than 1,300 authors from 95 countries have been involved in four expert working groups preparing the global assessment, and hundreds more continue to undertake more than 20 sub-global assessments. The findings are contained in the fifteen reports listed in the box above.

The MEA is an instrument to identify priorities for action. It provides tools for planning and management and foresight concerning the consequences of decisions affecting ecosystems. It helps identify response options to achieve human development and sustainability goals, and has helped build individual and institutional capacity to undertake integrated ecosystem assessments and to act on their findings.

The MEA reveals that 15 of the planet's 24 life systems are threatened with collapse. This most massive study of global ecosystems to date includes action proposals to avoid the collapse of civilization within our lifetime. The MEA reveals that approximately 60 percent of the ecosystem services that support life on Earth such as fresh water, capture fisheries, air and water regulation, and the regulation of regional climate, natural hazards and pests are being degraded or used unsustainably. Fresh water supplies, in fact, the Millennium Ecosystem Assessment reported in April, "are now so degraded that they are well beyond levels that can sustain existing demands, let alone provide for future needs." This landmark study displays enough evidence for the experts to warn that the ongoing degradation of 15 of the 24 ecosystem services examined is increasing the likelihood of potentially abrupt changes that will seriously affect human well-being. This includes the emergence of new diseases, sudden changes in water quality, creation of dead zones along the coasts, the collapse of fisheries, and shifts in regional climate.

United Nations Environmental Conventions on Climate Change, Biodiversity and Land Degradation

The United Nations Framework Convention on Climate Change (UNFCCC or FCCC) is an international environmental treaty produced at the United Nations Conference on Environment and Development (UNCED), informally known as the Earth Summit, held in Rio de Janeiro in 1992. The treaty aimed at reducing emissions of greenhouse gas in order to combat global warming. The treaty as originally framed set no mandatory limits on greenhouse gas emissions for individual nations and contained no enforcement provisions; it is therefore considered legally non-binding. Rather, the treaty included provisions for updates (called "protocols") that would set mandatory emission limits. The principal update is the Kyoto Protocol, which has become much better known than the UNFCCC itself. Its stated objective is "to achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system."

COP-1, The Berlin Mandate: The "Berlin Mandate", established a 2-year Analytical and Assessment Phase (AAP), to negotiate a "comprehensive menu of actions" for countries to pick from and choose future options to address climate change which for them, individually, made the best economic and environmental sense.

COP-2, Geneva, Switzerland: Acceptance of the scientific findings on climate change proffered by the Intergovernmental Panel on Climate Change (IPCC) in its second assessment (1995); Rejected uniform "harmonized policies" in favor of flexibility; Called for "legally binding mid-term targets."

COP-3, The Kyoto Protocol on Climate Change: Most industrialized nations and some central European economies in transition agreed to legally binding reductions in greenhouse gas emissions of an average of 6 to 8% below 1990 levels between the years 2008-2012.

COP-4, Buenos Aires: Adopted a 2-year "Plan of Action" to advance efforts and to devise mechanisms for implementing the Kyoto Protocol, to be completed by 2000.

COP-5, Bonn, Germany: Primarily a technical meeting, and did not reach major conclusions.

COP-6, The Hague, Netherlands: Developed the following agreements: (a) Flexible Mechanisms: allows industrialized countries to fund emissions reduction activities in developing countries as an alternative to domestic emission reductions. (b) Carbon sinks: Credit was agreed to for broad activities that absorb carbon from the atmosphere or store it, including forest and cropland management, and revegetation. (c) Compliance: broad outlines of consequences for failing to meet emissions targets. (d) Financing: Three new funds were agreed upon to provide assistance for needs associated with climate change.

COP-7, Marrakech, Morocco: Operational rules for international emissions trading among parties to the Protocol and for the CDM and joint implementation; _A compliance regime that outlines consequences for failure to meet emissions targets but defers to the parties to the Protocol after it is in force to decide whether these consequences are legally binding; Accounting procedures for the flexibility mechanisms;

COP-11, Montreal, Canada: Marked the entry into force of the Kyoto Protocol.

10. **Earth System Models Integration with Social Systems**

There is a growing recognition within the research community that Earth system science must be studied in a more holistic and integrated way. Crucial to the emergence of this perspective is the increasing awareness of two aspects of Earth System functioning. First, that the Earth itself is a single system within which the biosphere is an active, essential component. Secondly, that human activities are now so pervasive and profound in their consequences that they affect the Earth at a global scale in complex, interactive and apparently accelerating ways. Furthermore, this recognition suggests that it is no longer appropriate to consider humans as an outside force perturbing an otherwise natural system but rather to consider a coupled, interactive human-environment system as a whole. This emerging perception is challenging the way in which research on the analysis and modeling of the Earth System is organized. The research community is just beginning to develop complex Earth System models, using GCMs as the base and systematically building in further components of the Earth System (e.g., interactive carbon cycle, atmospheric chemistry, interactive terrestrial and marine biospheres). A few Earth system models are being developed with integrated social and biophysical processes that include physical climate, element cycles, globalization/urbanization, biological diversity, impacts and responses.

Today’s modeling systems are specific to the discipline product they produce. Weather forecast models do not use the same resolution scales, model components, parameterizations, or observations as climate models. Land surface and water cycle models are still largely disconnected from state of the art atmosphere models. The terrestrial biosphere is only grossly represented in any of the climate prediction models. A complete understanding of the planetary water and carbon cycles will ultimately require the coalescence of these individual modeling disciplines into an Earth System Model (Fig. 1) that can trace and reproduce these global cycles. This presents a major computing challenge in the volume of data ingested, the capability of computing systems, and the construction of the modeling systems that combine these disciplines together.

Projections of climate change over the next century have been hampered by limits to our understanding of, and ability to model, the complex interdependencies of the human-climate system. Further complicating the analysis task is the century-scale nature of the issue, including the difficulty of projecting anthropogenic emissions of greenhouse gases and aerosols, and possible land-use change, over such a long horizon. Efforts to project population, economic development and technological evolution over many decades necessarily involve great uncertainties. Moreover, these human systems are subject to feedbacks from any future climate change itself, through climatic effects on agriculture and fisheries, effects of sea level rise on coastal regions, and other impacts.

An example of the philosophical framework for a fully-coupled probabilistic approach to the climate problem is given by the MIT Integrated Global System Model (IGSM) (Prinn et al., 1999). The climate system component of the IGSM was designed to provide the flexibility and computational speed required to handle multiple policy studies and uncertainty analysis while representing to the best degree possible the physics, chemistry and biology of the Earth system. Also, within the IGSM the earth system components are linked to a model of human interactions. The nature of the analysis that such a facility can provide is illustrated by its use to analyze key aspects of the climate issue. As depicted in Fig. 2, the IGSM includes sub-models of the relevant aspects of the natural earth system coupled to a model of the human component as it interacts with climate processes.

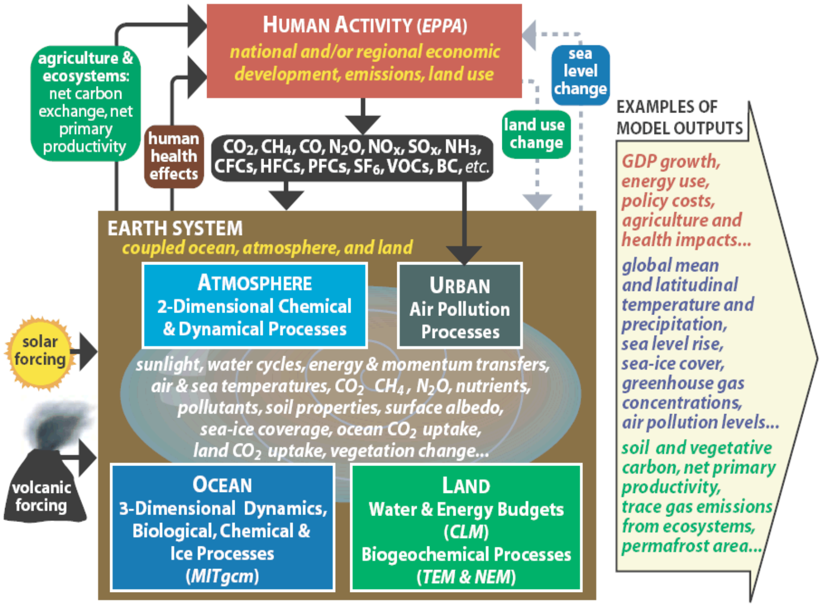

Figure 2. Schematic of the MIT Integrated Global System Model

The major model components of the IGSM are:

- A model of human activity and emissions,
- An atmospheric dynamics, physics and chemistry model, which includes a sub-model of urban chemistry,
- An ocean model with carbon cycle and sea-ice sub-models,
- A linked set of coupled land models, the Terrestrial Ecosystem Model (TEM), a now more fully integrated Natural Emissions Model (NEM), and the Community Land Model (CLM), that encompass the global, terrestrial water and energy budgets and terrestrial ecosystem processes.

This earth system model represents a fully coupled system that allows simulation of critical feedbacks among its components. Time-steps used in the various sub-models range from 10 minutes for atmospheric dynamics, to 1 month for TEM, to 5 years for the EPPA model, reflecting differences in the characteristic time-scales of different processes simulated by the IGSM.

Adaptive Capacity

The vulnerability of communities, regions and countries to climate change is determined by a combination of their exposure to the impacts of climate change and by their adaptive capacity—their capacity to effectively prepare for and respond to changes such as those that will occur as a result of climate change. In trying to understand how communities and countries may adapt to the long-term impacts of climate change, researchers and policy-makers are increasingly looking at their adaptive capacity. This focus has emerged from the fact that while there is general agreement on the expected impacts of climate change at the global and continental level, uncertainty remains regarding the specific effects it may have on a regional or local scale. As we currently cannot predict exactly how a community will be impacted by climate change, emphasis is put on increasing the capacity a community has to respond to a range of possible impacts.

The adaptive capacity of poor communities in developing countries is typically low as local people lack the income; access to basic social services and natural resources; and empowerment needed to rebuild their lives in response to (for example) the loss of food crops due to an increase in the number of drought years. Increasing the adaptive capacity of these communities requires ensuring access to resources; income generation activities; greater equity between genders and social groups, and an increase in the capacity of the poor to participate in local politics and actions. In other words, increasing adaptive capacity requires promoting many activities associated with sustainable development. As stated by the IPCC (2001), climate adaptation, sustainable development and improved equity can all be mutually reinforcing if policies are advanced that lessen resource pressure, improve environmental risk management and increase welfare for the poorest members of society.

It is possible to promote poverty eradication in developing countries while at the same time reducing current or future greenhouse gas emissions. Some of the ways in which the potential synergies between sustainable development, climate change mitigation and climate change adaptation can be achieved include:

- Promoting ecosystem practices such as reforestation and grassland management. These practices can improve watershed function through reduced runoff and increased deep percolation, thereby increasing the land's resilience to key climate stresses such as floods and droughts. These practices also enhance the formation of carbon sinks and can contribute to efforts to combat desertification and maintain biodiversity.
- Expanding the use of renewable energy sources. These technologies not only reduce greenhouse gas emissions, the energy provided through wind, solar, bioenergy and micro-hydro systems can (for example) reduce the need to collect fuelwood from natural forests. Not only would this change result in greater protection of forests, women and children could benefit from no longer having to spend hours each day travelling to collect wood for cooking and heating. Renewable energy can also free up money currently being used by national governments to purchase imported oil, making it available to spend on other activities, such as education and health care.

Switching to less polluting fossil fuels. Along with encouraging greater fuel efficiency, switching from the use of coal to natural gas in energy production will reduce emissions not just of greenhouse gases but also pollutants such as nitrous oxide and sulphur dioxide. Fuel switching helps reduce urban air pollution, which in turn contributes to the health and well-being of millions of people.

Solutions Support

The ultimate Earth system science goal is to expand and accelerate the realization of societal and economic benefits from Earth science, information and technology. With increasing population, demands on natural resources are being stretched to their limits. Fresh water is becoming an increasingly critical natural resource to manage due to the multiple, and often conflicting, societal demands for water use. Water withdrawal for irrigation, industry, and municipal use are placing significant burdens on this finite resource. The water demands for agriculture, industrial and municipal water will continue to increase due to urbanization, and increases in income and population. In fact, by the year 2025 the Earth's water cycle is projected to be stressed more from population growth and development than from climate change[54]. Since water is required to sustain the world food supply to serve the projected populations, there is a need for water management policies that optimize the use of water amongst its various end uses.

Can the Earth system keep up with such great demands on water management and food production to accommodate future generations? The challenge is to establish an approach based on the capacity of Earth science information to support decision makers in establishing policies and management solutions to better utilize Earth's resources (food, water, energy, etc.) for the good of the global society. A component of the challenge is to develop an Earth resources management infrastructure. The Earth science and engineering communities have the opportunity to build the infrastructure to use the observations, the computational models, and the knowledge about Earth system science to enable decision support to be used globally, nationally, regionally, and locally.

In an effort to address challenges of managing the Earth's resources to meet the basic needs of increasing populations while preserving the environment, a series of international meetings have taken place over the last decade. These include the Rio Earth Summit in 1992, the Johannesburg World Summit on Sustainable Development in 2002, and the annual UN Framework Climate Convention (UNFCCC) Conference of the Parties (COP).

This represents an end-to-end challenge that will use recent Earth system science progress to build a solutions support infrastructure that will assist the decision and policy makers in meeting the environmental challenges of society. Decision support tools that are based on scientific knowledge of Earth system processes benefit policy makers in evaluating scenarios to optimize the balance of Earth resources and economic stewardship in developing and evolving global and regional policies and resolutions. We now have the ability to embark on the scientific grand challenge of understanding the earth system to sufficient capacity for answering questions of whether expanding our knowledge and increasing access to that knowledge may alleviate the pressures impacting the habitability of the planet Earth.

Earth system science, the study of how the Earth works as a system of continents, oceans, atmosphere, ice, and life, is based on our ability to measure key parameters and integrate the knowledge into Earth system models. This research helps envision the impact of global change on food and fiber production and can serve as a component of the Earth resources management infrastructure.

Implementing the Earth resources management infrastructure to realize societal and economic benefits requires a focus on solutions that are citizen-centered, results-oriented, and market-

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[54] Vörösmarty, C.J., P. Green, J. Salisbury, and R. Lammers. 2000. Global water resources: Vulnerability from climate change and population growth. *Science*, **289**, 284-288.

driven. To accomplish this objective it is necessary to provide a bridge between Earth system science research and the operational solutions manifested in the Earth resources management infrastructure. These operational solutions and applications that benefit society are enabled by systematically relating appropriate results from measurements and applied research in weather, global climate change, and natural hazards. Applied research, in turn, is enabled by basic research and technology developments in Earth system science. The relationship among basic research and development, applied research, and operational solutions is dynamic and iterative and a systematic approach to bridge the gaps between the research and operational domains is required.

One method for realizing these connections is to take a systems engineering approach to benchmarking practical uses of recently developed Earth system science developments. This approach would enable the assimilation of Earth science model predictions and measurements to serve as inputs to decision support systems. The challenge proposed here is to develop the observations and predictions that may be used to impact policies for managing the Earth's natural resources by the global society, and provide the decision support tools for Earth resources stewardship for this and future generations[55].

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[55] King, R. L., R.J. Birk, 2003: Science for Society: Delivering Earth System Science Knowledge for Decision Support in the Year 2025. *Proc. IEEE Int. Geosci. Rem. Sens. Sym.*, Toulouse, France. CDRom.

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http://www.dlese.org/library/index.jsp
DLESE – digital library on Earth Science Education
http://www.essic.umd.edu/
ESSIC – UMCP
http://www.essp.org/
ESSP = Diversitas + IGBP + WCRP + IHDP
http://www.scs.gmu.edu/Academics/MSESS_new.html
George Mason University
http://www.juneauicefield.org/
Glaciological and Arctic Sciences Institute
http://www.globio.info/index.cfm
GLOBIO
http://www.igbp.net/
International Geosphere-Biosphere Program
http://www.ihdp.uni-bonn.de/
International Human Dimensions Program on Global Environmental Change
http://meted.ucar.edu/climate/climchange/index.htm
Kevin Trenberth webcast on climate change
http://pubs.wri.org/pubs_content_text.cfm?ContentID=1412
nitrogen cycle
http://www.esse.ou.edu/
OOU ESS department
http://www.essc.psu.edu/
PSU ESS department
http://www.nsstc.uah.edu/essc/
UAH ESS department
http://www.ess.uci.edu/dept/welcome.html
UCI ESS department
http://www.eses.uiuc.edu/about/main.php
UIUC ESS department
http://essp.und.edu/
UND ESS department
http://www.icess.ucsb.edu/esrg/ess_sum97/announcement_1999.html
University of California at Santa Barbara
http://www.unh.edu/nressphd/index.html
University of New Hampshire
http://ess.geology.ufl.edu/ess/Introduction/00-Introduction.html
University of Florida
http://www.uwyo.edu/ess/
U. Wyoming ESS department
http://www.usra.edu/esse/essonline/home.html
USRA

http://www.cses.washington.edu/cig/
UW Climate Impacts Group
http://www.geotimes.org/sept02/feature_educators.html
why we need a corps of Earth Science educators
http://wcrp.wmo.int/
World Climate Research Program

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