# *Exploring our Planet for the Benefit of Society*

## NASA Earth Science and Applications from Space

## Strategic Roadmap

**Report of the Earth Science and Applications from Space Strategic Roadmap Committee**

**(Strategic Roadmap Committee Number 9)**

**May 2005**

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## Executive Summary

With the successful deployment of the Earth Observing System (EOS), a long-term plan for the future of Earth system science is needed. This Earth Science and Applications from Space roadmap provides a framework for such a plan spanning three decades.

The end goal (2035 and beyond) for this roadmap is a fully instrumented Earth system, networked to predictive models, serving science and decision-makers. This future program will realize the full benefits to society of our research, while opening up new science through discovery. To get there, we must build a foundation for comprehensive observing and modeling in the next decade (2005-2015), and work to expand our view of Earth and reach into society in the decade after (2015-2025). Throughout we must mature our measurement and modeling capabilities, and carefully manage our data - past, present and future.

### Roadmap Objective

*Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems.*

The objective of this roadmap is directly traceable to the nation's objectives for NASA, and to NASA's mission and vision. The Earth Science and Applications from Space Strategic Roadmap is unique within NASA because it responds to multiple presidential directives and initiatives, including Climate Change Research Program, the U.S. Integrated Earth Observation System, the Ocean Action Plan, and the Vision for Space Exploration. Naturally, this roadmap will evolve over time with society's concerns, in response to discoveries about the Earth system, and in response to technology advances for both space and in situ observations.

### Guiding Science Questions

The roadmap Committee developed a set of guiding science questions to frame the discussion on how to achieve the roadmap's objective:

How Does the Earth Support Abundant Life?

- How does the atmosphere protect and sustain us?
- How are our weather and climate evolving?
- What controls the availability of water on the planet?
- How does life influence and respond to changes in environmental processes on Earth?
- What causes changes to the Earth's surface and interior?
- What role do human systems play in driving changes in the Earth system?

Pursuing the answers to these questions will generate fundamental knowledge that enables us to address some of the most intellectually compelling problems humanity faces today. Applying this knowledge to society's practical needs will increase our prosperity and help us protect and enhance Earth's ability to support life.

**Strategic Roadmap Scientific Objectives**

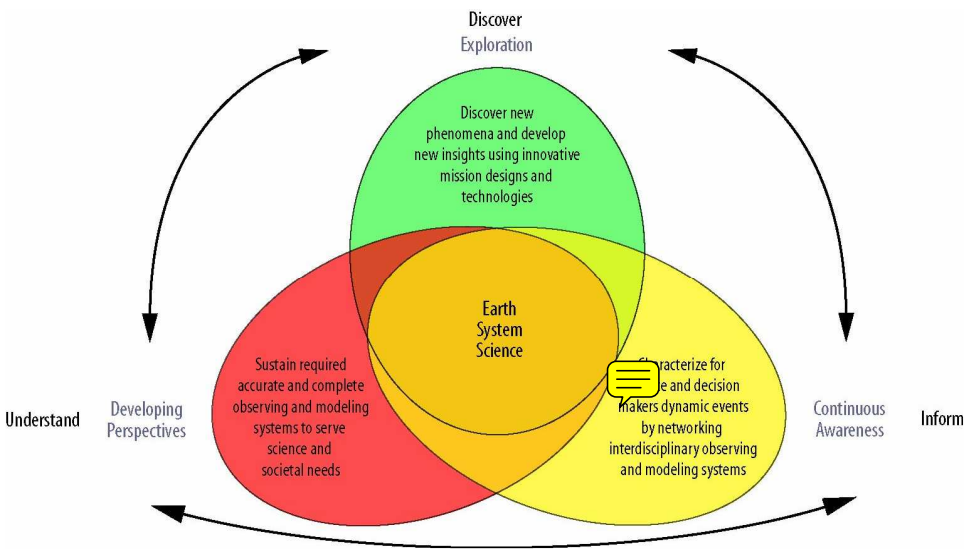
The strategic roadmap scientific objectives map to these questions and are as follows:

Understand the Earth as a system of interacting natural and human systems, including…

- Atmospheric Composition: the sources, sinks, and transformations of aerosols and atmospheric chemical species
- Climate and Weather: the present state and expected evolution
- Water: the storage, distribution, and transport of water in all its forms
- Life: biogeochemical cycles and the distribution and processes of life within the Earth's ecosystems
- Solid Earth: the processes that modify Earth's land surface and interior and contribute to natural hazards

**Strategic Roadmap Integration Objectives**

No individual measurement can answer these guiding questions, but they can be fully addressed through the integration of investigation systems. Because the capacity to answer guiding questions emerges through the combined results of multiple scientific investigations, this document identifies three **strategic roadmap integration objectives** to guide this integration. These are: Exploration and Discovery; Continuous Awareness; and Developing Perspectives. Each integration objective can be roughly mapped to a phase of a measurement's lifecycle, and the philosophy behind each objective helps to determine the best use of research and operational assets.



## Achievements by Decade

Armed with the main roadmap objective for Earth science from space, and an approach based on the integration objectives, the next logical step is to ask what will be known, and by when? The following table maps these integration objectives to some of the important achievements identified for each decade.

| | 2005-2015: Building a foundation for comprehensive observing & modeling | 2015-2025: Expanding our view of Earth & reach into society | 2025-2035 & Beyond: Fully instrumented Earth system networked to predictive models serving science & decisions makers |
|---|---|---|---|
| Exploration & Discovery: Explore unknown aspects of the Earth system by implementing new investigations enabled by new insights, technologies, capabilities, & vantage points | • Global assessment of above-ground carbon biomass<br>• Time-dependent deformation maps of fault zones, volcanoes, slopes & ice sheets<br>• Comprehensive assessment of changes in ice cover | • Characterize water distribution in root zone; improved weather & climate prediction<br>• Upper ocean profiling to understand ocean biosphere | • Pursuing answers to new questions, enabled by: distributed autonomy, bio- & nano technology, very large apertures, etc. |
| Continuous Awareness: Develop new scientific understanding of dynamic processes & demonstrate capabilities useful for decision support by providing prompt recognition & adaptive observation of dynamic events through the networking of distributed observing & modeling systems | • Improved understanding of natural & anthropogenic aerosols & their effects on climate<br>• Ice sheets changes & ocean circulation tied to predictive climate models<br>• Quantified snow deposition & water equivalent<br>• CO2 flux to constrain global sources & sinks | • Quantified dynamics of major ice sheet motion<br>• Tropospheric winds over land & ocean for weather & ocean circulation models<br>• Quantified dynamics of water vapor, clouds, rainfall, surface & subsurface water storage, run-off, & fresh water availability<br>• Vegetation/algal type & land/ ocean carbon sequestration<br>• Surface deformation dynamics & surface beneath ice<br>• Improved understanding of Earth's time-varying magnetic field | • Assessment of plant and algal physiological status and productivity<br>• Improved global topography -- in conjunction with SRTM data first global measurement of topographic change<br>• Detection of volcanic/ tectonic & land-use changes<br>• Fully integrated Earth System model and assimilation system with data distribution portals for simple high speed access to all aspects of the Earth System |
| Developing Perspectives: Enable new scientific understanding of long-term Earth processes & trends by sustaining & integrating comprehensive global observing & modeling systems | • Operational observations calibrated for climate science<br>• Framework to couple Earth system model modules deployed nationally | • Reduced uncertainties in global & regional climate models through accurate models of cloud feedback & aerosol forcing<br>• Models and data assimilation systems integral to the observing system and decision support systems, including future mission design | • Global water cycle, including soil moisture, precipitation, linked to climate & weather models<br>• Networked observations, models, & knowledge systems for science & operational systems |

## Prioritization Criteria

Prioritizing investigations is at the heart of the roadmap, and was done with considerable thought and a defined, logical process. At the core of the roadmap is the time-ordering of activities based on an assessment of scientific and societal relevance, and technical maturity with an emphasis on maximizing efficiency of related measurements. This is the idea of "awareness clusters" that springs from the Continuous Awareness integration objective. *Awareness clusters focus efforts on answering particular science questions in a given line of inquiry by coordinating and connecting information from multiple space and airborne observations, in situ sensors, and modeling systems during the focus time period.*

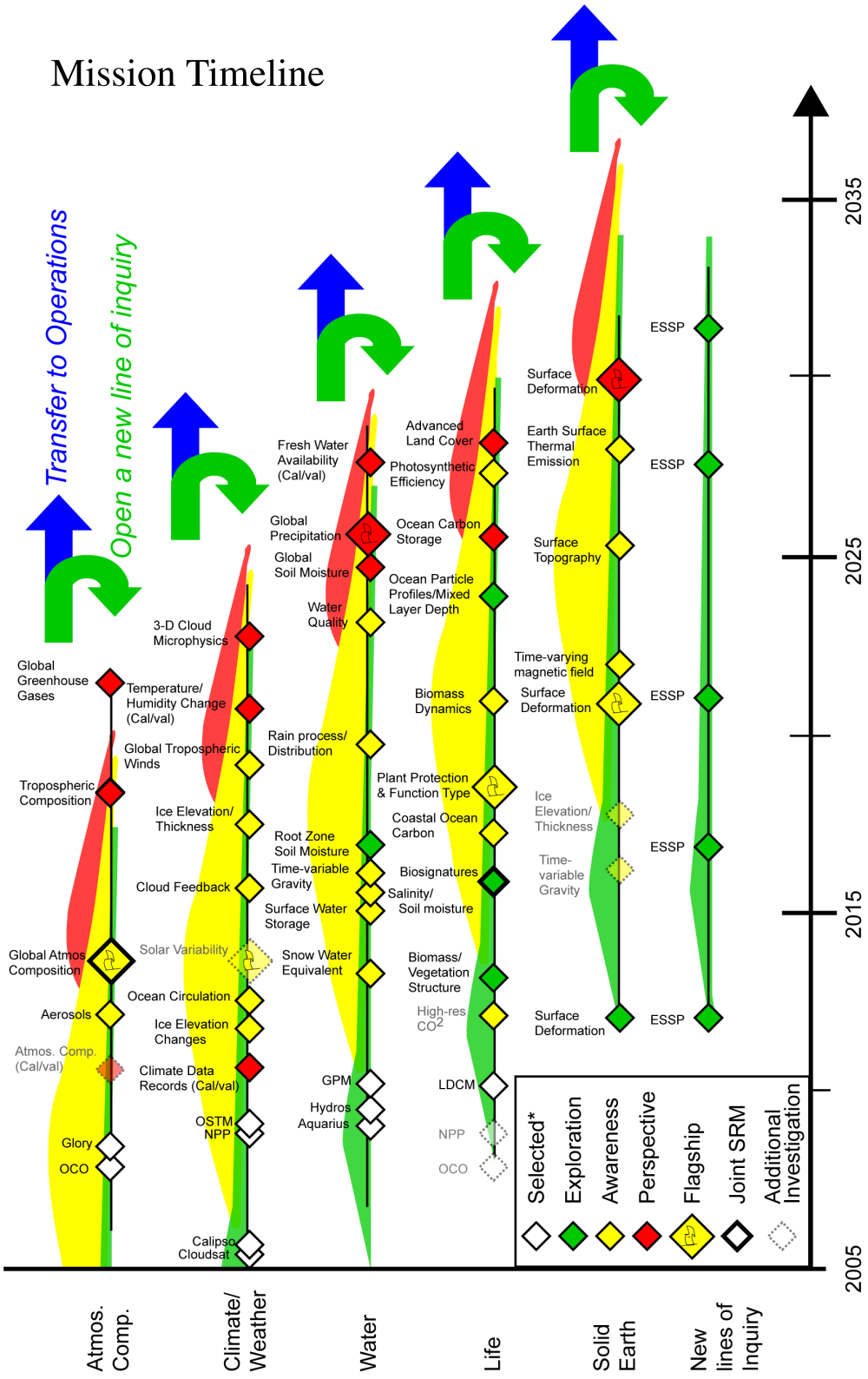
The prioritization criteria are listed below:

- ***Does the investigation advance science?***
- ***Does the investigation support decision-makers?***
- ***Does the investigation benefit society?***
- ***Is the investigation consistent with recommendations of national priorities?***

To determine the current state of each line of inquiry the Committee developed the concept of the measurement maturity index (MMI) for space-based measurements. MMI was also used to help prioritize investigations.

## Mission Timeline

For each line of science inquiry derived from the strategic roadmap scientific objectives, investigations have been prioritized and arranged on a timeline. These missions (shown as diamonds) will realize the achievements laid out for each decade. Blue and green arrows on the timeline indicate planned transitions from research to operations and the opening of new lines of inquiry, respectively.


Mission Timeline
Transfer to Operations
Open a new line of inquiry
Global Greenhouse Gases
Tropospheric Composition
Global Atmos Composition
Aerosols
Atmos. Comp. (Cal/val)
Glory
OCO
Temperature/ Humidity Change (Cal/val)
Global Tropospheric Winds
Ice Elevation/ Thickness
Cloud Feedback
Solar Variability
Ocean Circulation
Ice Elevation Changes
Climate Data Records (Cal/val)
OSTM NPP
Calipso Cloudsat
3-D Cloud Microphysics
Fresh Water Availability (Cal/val)
Global Precipitation
Global Soil Moisture
Water Quality
Rain process/ Distribution
Root Zone Soil Moisture
Time-variable Gravity
Surface Water Storage
Snow Water Equivalent
GPM
Hydros
Aquarius
Advanced Land Cover
Photosynthetic Efficiency
Ocean Carbon Storage
Ocean Particle Profiles/Mixed Layer Depth
Biomass Dynamics
Plant Protection & Function Type
Coastal Ocean Carbon
Biosignatures
Salinity/ Soil moisture
Biomass/ Vegetation Structure
High-res CO2
LDCM
NPP
OCO
Surface Deformation
Earth Surface Thermal Emission
Surface Topography
Time-varying magnetic field
Surface Deformation
Ice Elevation/ Thickness
Time-variable Gravity
Surface Deformation
ESSP
ESSP
ESSP
ESSP
ESSP
2005
2015
2025
2035
Selected*
Exploration
Awareness
Perspective
Flagship
Joint SRM
Additional Investigation
Atmos. Comp.
Climate/ Weather
Water
Life
Solid Earth
New lines of Inquiry

This strategic roadmap includes currently funded NASA investigations for information purposes only. To avoid even the perception of financial conflicts of interest, the Committee did not prioritize or make recommendations concerning any currently funded activities. NASA asked the Committee to assume that NASA will complete currently funded missions in the first decade of the roadmap, including missions in implementation that NASA has committed to complete, as well as missions in formulation that have yet to pass their Mission Confirmation Review. NASA asked the Committee to assume that NASA will find a flight opportunity for the Glory instrumentation.

To determine the recommended order of the awareness clusters linked to each scientific objective, we evaluated the current state of each line of inquiry, based on the current mission set and NASA's near-term plans. In addition, we examined the maturity of all of the measurements addressing each scientific objective using the Measurement Maturity Index.

**Modeling and Data Management**

Modeling is critical to all three roadmap integration objectives. Simulation and prediction are fundamental to improved Earth System understanding, reducing uncertainty and providing societal benefit. The grand challenge is to have an observational system that observes all key Earth system variables and assimilates that information into a system of integrated, interacting models that include each of the major subsystems: oceans, atmosphere, cryosphere, biosphere and solid Earth.

The Committee envisions a future with high bandwidth, universal access to Earth system information that is available via an easily queried Earth system portal. Imagine the usefulness of a map or globe-based query system where scientists, educators, and policy-makers can obtain up-to-the-minute information about specific locations or regions of the planet.

**Links to Other Strategic and Capability Roadmaps**

The Earth science roadmap's primary linkages are with the Sun-Solar System roadmap, and concern a shared desire for joint investigations of the effects of solar variability on the Earth's climate and upper atmospheric chemistry dynamics. The roadmap also shares interests with all three Exploration roadmaps (Lunar, Mars, and Solar System), Earth-like planets, and Aeronautics.

There are several technological advances needed to complete the integration objectives. These needs provide linkages to several capability roadmaps, including Telescopes; Autonomous Systems and Robotics; Instruments and Sensors; Modeling, Simulation, and Analysis; and Nanotechnology.

## Conclusions and Near-term Recommendations

This roadmap outlines a vigorous, robust, yet likely affordable program of investigations for the nation that, if implemented, will give NASA's Earth science program a glorious future that builds upon the successes of the past program. That future is integral to NASA's quest to explore our solar system, yet responsive to society's needs here on Earth.

We recommend four near-term actions that NASA can begin work on immediately, as well as longer-term steps for which NASA should begin planning.

**Near-term recommendations**:

1. ***Complete the approved program*** in a timely fashion, including the next Earth System Science Pathfinder Announcement of Opportunity. This roadmap was built on the assumption that the NASA missions currently in formulation and implementation would be completed as planned, and these missions are the foundation of this roadmap.

2. ***Add advanced planning funding for future Earth Science and Applications missions*** from Space. The following near-term missions and our first flagship mission (listed in order of launch dates) need to be studied immediately to accomplish our recommended timeline:
    - Cal/Val Mission
    - Ice Elevation Changes
    - Surface Deformation
    - Ocean Surface Topography
    - Aerosols and high resolution CO2
    - First Flagship Mission – L1 Atmospheric Composition/Solar influence on Climate

3. ***Fund advanced planning for the first awareness investigation focus:*** atmospheric chemistry, including technology, missions, models, networks, educational opportunities, and international cooperation.

4. ***Fund at least one new start*** for the missions above in FY'07 or FY '08 and the others as soon as possible after that.

# Introduction

*Exploration – The Delicate Balance of Cosmos and Earth*

Our human need to explore is never exhausted. From our home on Earth, we reach ever outward. Each successful exploration is rapidly superseded by the irresistible desire to pursue new vistas.

The compass that today guides this timeless endeavor is scientific inquiry. It is science that gazes outward, providing the grand questions that challenge us to journey farther and farther from home. But it is also science that peers inward, exploring previously inaccessible areas of the Earth, and asking the practical questions that help us to make Earth safer, protect our citizens, and expand our economy.

The NASA scientific program must be carefully constructed to address an underlying reality: knowledge of the Earth drives the economic growth and environmental security that allow us to be an exploring nation. This program must devote equal attention to both *inspirational questions* that underpin our outward desires, and practical questions that support our inward needs. A *sustainable* exploration program depends critically on this delicate balance of Cosmos and Earth.

## 1.1 National Objectives for Space Exploration

NASA's overarching Agency objective is the fundamental goal of the Vision for Space Exploration – "…to advance U.S. scientific, security, and economic interests through a robust space exploration program." NASA will direct its efforts towards five National Objectives. These National Objectives are:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond.
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.
- Study the Earth system from space and develop new space-based and related capabilities for this purpose.

The first four objectives come directly from the *Vision for Space Exploration*. The fifth National Objective affirms NASA's continued commitment to understand and protect our home planet, Earth. This objective was added in *The New Age of Exploration* to address other Presidential initiatives and directives not covered in the Vision for Space Exploration.

## 1.2 NASA Strategic Objective for this Roadmap

The objective for this roadmap is one of 18 NASA strategic objectives for 2005 and beyond derived from the five guiding national objectives for NASA (2005). All of NASA's programs and resources will be tied to these NASA objectives.

*Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems.*

This strategic roadmap is unique within NASA in that it responds to multiple presidential directives/initiatives. NASA has a critical role in implementing several recent major Presidential directives or initiatives, including:

- Climate Change Research;
- The U.S. Integrated Earth Observation System;
- The Ocean Action Plan; and
- The Vision for Space Exploration.

NASA's programs addressing Earth science and applications from space are *essential* to the success of the first three presidential initiatives listed above, and will surely prove to be so to the fourth. NASA's contributions to the Earth sciences are unique, numerous, and critically important to future efforts to protect life and property, facilitate responsible environmental stewardship, and understand and predict the dynamic Earth system. For more information on these initiatives (see Appendix B).

## 1.3 Ties to the NASA Mission and Vision

The NASA vision seeks "To improve life here, to extend life to there, and to find life beyond." The NASA mission is "To understand and protect our home planet, to explore the universe and search for life, and to inspire the next generation of explorers…as only NASA can." The Earth system roadmap addresses several aspects of these important guidelines for NASA's role. It primarily address the aspect of the vision that attempts to "improve life here," but also address the other aspects of the vision and mission. Because humanity is a part of the Earth system, understanding the Earth system scientifically can lead to profound improvements in life on Earth, and can help us protect the Earth. Understanding the way the Earth functions is also a critical foundation for exploring the universe. The Earth, our "home-base," serves as a reference by which we observe and judge the rest of the universe, as well as by which we understand life along with its limitations. Advancements in Earth science can inspire exploration in the next generation in a unique way. Exploration of the Earth is an endeavor that is unique in that we live here, and many more modes of exploration are currently possible than for exploration elsewhere.

## 1.4 NASA's Vital Role: Front-End Research to Enable National Priorities & Societal Benefits

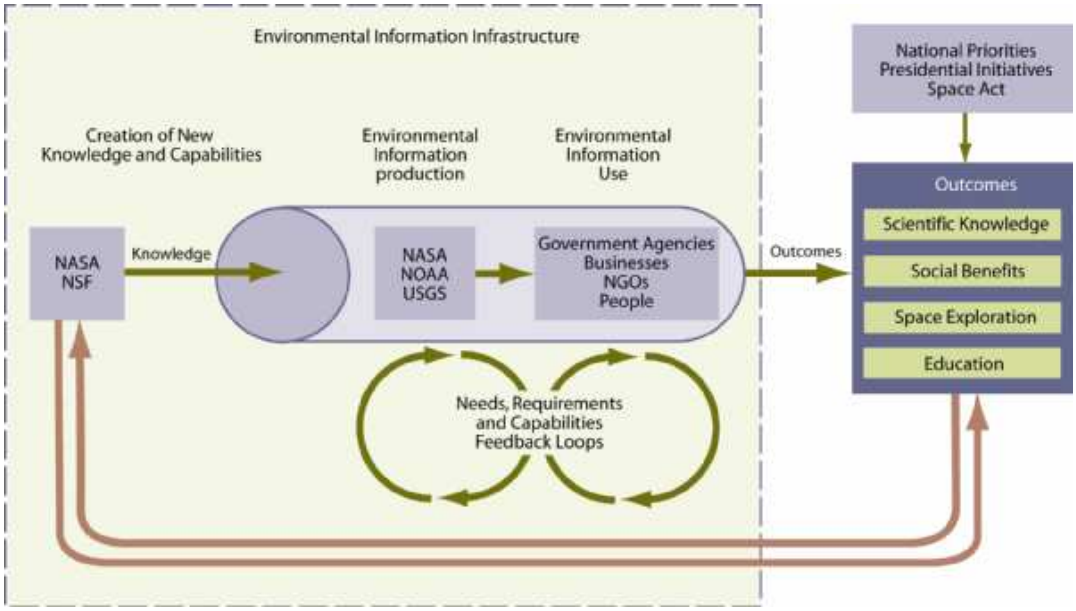
In addition to making fundamental discoveries that lead to societal benefits directly and through spin-offs, an active program that bridges basic and applied science makes it possible for NASA to take leadership in addressing some of the most pressing problems facing humanity in the coming decades, including food security, human health, clean water, and economic development and poverty. Over the next two decades the pressures of human actions on the biosphere will stress its ability to provide natural capital and ecosystem services and this will require a concerted effort by NASA to study the ramifications, indeed to support sound management solutions. Working in partnership with other agencies, NASA Earth science is well positioned to find answers to questions such as "how will future agriculture systems under stress from climate change and land degradation feed a growing population?"

Given NASA's central role in the pursuit of new Earth science knowledge, it is important that NASA also take a leadership role in developing a robust and sustainable mechanism for determining the needs of the nation for Earth science information. This will allow this knowledge to be applied to ensure that we are achieving the greatest benefit of our scientific investments for society, and will help NASA maintain an appropriate balance between curiosity-driven and practical scientific pursuits.

We see the environmental information infrastructure as a pipeline from the creation of new knowledge and capabilities (e.g., through exploration, discovery, and development activities by NASA and NSF), to environmental information production (e.g., by NASA, NOAA, and the USGS), to environmental information use by government agencies, businesses, non-governmental organizations, and individuals. The outcomes of these activities include new scientific knowledge, societal benefits, education, and space exploration, which are national priorities identified through Presidential initiatives and the Space Act. On-going feedback loops of needs, requirements, and capabilities connect the production and use of environmental information. Feedback loops connect national priorities for future outcomes with the research priorities for the creation of new knowledge.

The Committee believes:

1) That it is important to keep the pipeline filled by investing in the creation of new knowledge in order to ensure future outcomes vital to the interests of our nation, and
2) That it is important to formally support feedback mechanisms to ensure that new knowledge is being created that can ultimately satisfy national priorities.
3) That NASA has a unique role in education to excite and inspire the public through its fascinating science results from Earth and space, and better prepare the younger generation for the society of the future.




Societal Benefits of Environmental Information -- Effective Feedback Keeps the Pipeline Filled and Flowing

It is possible to plan and prioritize fundamental (or curiosity-driven) science based almost entirely on needs identified by the science community itself. In contrast, the pursuit of practical science having benefits to society carries the obligation to assess societal needs and determine how best to fulfill them. This is a task that is far more complex and time-consuming than most people realize. The user base for Earth information is large and diverse, ranging from local governments to multinational corporations to individuals. With the rapid spread of information technology, this community and its needs evolve ever more rapidly. How do we know what Earth information will be most needed by governments, businesses, and individuals ten to thirty years from now? Our ability to answer this question accurately is critical if we are to spend NASA budgets wisely. Doing so will require us to explore many new avenues of academic and practical inquiry regarding how people use information and what methods can be used to assess their needs. A dedicated program addressing this issue must be implemented and used to continuously improve our "awareness" of the societal needs that NASA science meets.

The end goal (2035 and beyond) for this roadmap is a fully instrumented Earth system, networked to predictive models, serving science and decision-makers. This future program will realize the full benefits to society of our research, while opening up new science through discovery. To get there, we must build a foundation for comprehensive observing and modeling in the next decade (2005-2015), and work to expand our view of Earth and reach into society in the decade after (2015-2025). Throughout we must mature our measurement and modeling capabilities, and carefully manage our data - past, present and future.

*The objective of this roadmap is directly traceable to the nation's objectives for NASA, and to NASA's mission and vision. It will evolve over time with society's concerns in response to discoveries about the Earth system, and in response to technology advances for both space and in situ observations.*

# 2 Flowdown to Roadmap Objectives

## 2.1 Architecture

A key feature of this roadmap is the flowdown within a pathways and stages framework from presidential initiatives through the roadmap objective to science questions to achievements by decade to investigations and missions (Table 1).

*Direction of flow*

| Hierarchy | Report reference |
|---|---|
| Presidential Initiatives | Appendix B.1.1 |
| NASA Objective for 2005 and Beyond - Earth Science & Applications Roadmap | Section 1 |
| Guiding Science Questions | Section 2.2 |
| Scientific Objectives: | Section 2.3 |
| Integration Objectives | Section 2.4 |
| Pathways/Stages | Section 3.3 |
| Achievements by decade | Section 4.2 |
| Investigations by decade | Section 4.2 |
| Missions by decade | Section 4.5 |

Table 1: Flowdown from Presidential Initiatives to missions within the pathways/stages framework

The roadmap objective contains a key phrase: "*advance scientific knowledge of the Earth system,*" which the Committee took as its primary focus in executing the flowdown to next-level objectives.

## 2.2 Science Questions

**Guiding Questions:** Within the framework of our objectives any line of scientific inquiry will have a gradual progression through phases of Exploration, Continuous Awareness and Developing Perspectives. Our level of knowledge about the Earth system is currently at different stages, depending on what questions we ask. The desired outcome of this roadmap is to advance our scientific knowledge of the Earth system. We will do this through a steady progression of activities that answer guiding questions and provide fundamental scientific knowledge of the Earth. Addressing these questions will lead to results that NASA can pursue with its partners to transform this basic knowledge into the practical science that underlies critical societal benefits. This balance between fundamental and applied knowledge is a hallmark of the Earth sciences, and a key reason for its central importance in NASA.

***Fundamental* Scientific Knowledge:**

How Does the Earth Support Abundant Life?

- How does the atmosphere protect and sustain us?
- How are our weather and climate evolving?
- What controls the availability of water on the planet?
- How does life influence and respond to changes in environmental processes on Earth?
- What causes changes to the Earth's surface and interior?
- What role do human systems play in driving changes in the Earth system?

*We are committed to strengthening the practical* scientific knowledge that follows from addressing these questions. As we do so, we will better able to support decisions that will help to protect and enhance Earth's ability to support life:

- We will better understand how to ensure that the atmosphere continues to protect and sustain us.
- We will better understand how changes in weather and climate impact us, and what can be done to respond.
- We will better understand what we can do to protect and improve the availability of water.
- We will better understand how to positively influence the interaction of life with environmental processes.
- We will better understand how to use our understanding of the solid Earth to mitigate natural hazards.

The guiding questions lead directly to **strategic roadmap scientific objectives** and are linked to the **strategic roadmap integration objectives**.

## 2.3 Strategic Roadmap Scientific Objectives:

Progress towards answering these questions will come from implementing investigations, including observing systems and modeling systems, with requirements directly traceable to the following **strategic roadmap scientific objectives**:

Understand the Earth as a system of interacting natural and human systems, including:

- Atmospheric Composition: the sources, sinks, transport, and transformations of aerosols and atmospheric chemical species
- Climate and Weather: the present state and expected evolution
- Water: the storage, distribution, and transport of water in all its forms

- Life: biogeochemical cycles and the distribution and processes of life within Earth's ecosystems
- Solid Earth: the processes that modify Earth's land surface and interior and contribute to natural hazards.

### *2.3.1 Atmospheric Composition.*

NASA's atmospheric composition program is geared to providing an improved prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation in the context of changing climate, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality.

Atmospheric chemistry and associated composition are a central aspect of Earth system dynamics. Exchanges with the atmosphere link terrestrial and oceanic pools within the carbon cycle and other biogeochemical cycles. Solar radiation affects atmospheric chemistry and thus its composition. The ability of the atmosphere to integrate surface emissions globally on time scales from a week to years couples several environmental issues including global ozone depletion and recovery and its impact on surface ultraviolet radiation, climate forcing by radiatively active gases and aerosols, and global air quality. Aerosols are critical to cloud formation and indirectly to precipitation (Water); cloud feedbacks are among the most critical unknowns in climate models (Climate). CO2 is a greenhouse gas released by both burning of fossil fuel and respiring organisms, and removed from the atmosphere by photosynthesis (Life).

The levels of ozone in the stratosphere and troposphere, respectively, determine the amount of solar ultraviolet radiation reaching the Earth's surface and air quality at the surface. Both can affect human health; increases in the former are helpful, increases in the latter are harmful. NASA currently assesses the state of the stratospheric ozone layer as mandated by the Clean Air Act. According to the Montreal Protocol and it's amendments, as chlorine abundances decline, stratospheric ozone should rise. But will it? Changes in transport and temperature complicate this "expected" recovery. The research program is focused on assessing how the ozone layer recovers in the future.

Greenhouse gases are those that partially trap outgoing infrared radiation. Increases in these gases are widely expected to increase the greenhouse effect, leading to a warming atmosphere and surface; complicating feedbacks are also involved. Carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and chlorofluorocarbons (CFCs) account for most of the forcing, with a small part derived from ozone and water vapor in the stratosphere. NASA's program also measures the detailed distribution and the evolution of these greenhouse gases.

NASA's atmospheric composition research program emphasizes space-borne measurements of tropospheric ozone, aerosols, and gaseous ozone precursors needed to define how emissions in one region affect air quality in other regions. It also looks at possible links between air quality and climate change. Atmospheric winds transport

pollutants (such as aerosols and ozone precursors) over vast distances, even across oceans. Space-borne measurements are essential to define the impact of long-range transport of pollutants on air quality. Production of tropospheric ozone is highly sensitive to temperature and winds; stagnation of warm air promotes ozone formation. Model calculations have shown this process may be sensitive to climate change. The research program should focus on obtaining measurements to test these models.

NASA's atmospheric composition research program also requires essential suborbital and laboratory measurements, as well as a vigorous modeling effort. Suborbital observations, obtained by instruments on board balloons, manned aircraft, and unmanned aerial vehicles (UAVs), provide validation of satellite measurements as well as definition of processes occurring on spatial and temporal scales that are challenging to observe from space. Laboratory measurements of the kinetics of both gaseous and gas–aerosols interactions provide crucial information for models; laboratory observations of spectroscopy provide critical information needed to obtain many of the space-borne measurements. Modeling efforts should span the range from chemical data assimilation, focused on interpreting specific observations, to global, three dimensional models that quantify the links between atmospheric composition, global biogeochemical cycles, oceanic processes, and climate change.

While the measurements of atmospheric composition from low Earth orbit using passive remote sensing is fairly mature, scientists have yet to demonstrate the measurement of atmospheric gas phase species with high temporal resolution enabled by sentinel orbits (e.g., geostationary, Lagrange points). The passive LEO measurements carried out today are sufficiently mature that some (most notably ozone column and profile, and water vapor profile) can be transitioned to an operational agency; others remain to be done for the first time. Exploring the sun's effects on atmospheric chemistry and composition is an example of a needed new measurement. Earth's climate is controlled by the solar radiation incident upon the Earth and the associated feedbacks within the Earth system. Solar-driven ionization of the upper atmosphere modifies the ozone levels and the dynamics of the stratosphere. Ion penetration to the troposphere may affect aerosol nucleation and hence cloud formation. None of these effects are well understood, but all are expected to be highly sensitive to variations in the solar power spectrum, in particular UV radiation. However, our understanding of the spectral variability of solar radiation is very poor. A Sun-Earth Mission at the L1 Lagrange Point will advance considerably our understanding of the above processes by providing continuous measurements of atmospheric composition from the surface to outer space, together with measurements of solar activity and of the solar wind. It will enable considerable improvement of Sun-Earth connections in the next generation of Earth climate forecasts.

### *2.3.2 Climate and Weather*

NASA's activities in climate and weather are targeted toward the long and short-term processes generally associated with the fluid parts of the Earth system - i.e. the atmosphere and the ocean, and, in the case of climate, the ice cover that can significantly influence the behavior of each of these.

Weather processes, which occur on scales of hours to weeks, are primarily atmospheric in nature, and can have profound economic and social implications. Weather is commonly thought of in terms of temperature, humidity, precipitation, cloudiness, visibility, and wind. But one of the most critical weather variable is precipitation (rain or snow), as it can have important implications for vegetation health, natural disasters such as hurricanes, floods and landslides, significantly disrupt transportation, or profoundly impact the economic success or failure of the agriculture industry. In addition, precipitation ties in directly to other key considerations within NASA's Earth science program, such as the water and energy cycles. As a result, much of the weather-related mission planning has to date been closely linked to observing precipitation and understanding its underlying processes, such as cloud microphysics. Additional parameters observed to understand weather include surface temperatures, cloud distributions, ocean wind characteristics, etc. The main objectives in the area of weather related investigations are to enable accurate forecasts of precipitation, hurricane landfall, and severe storms.

Since the launch of the earliest satellites 45 years ago, NASA has invested heavily and successfully in weather-related space-based observations, and a robust operational capability for many of the key parameters has been developed. Current and near-term efforts continue to be targeted toward improved precipitation measurement capabilities and cloud microphysics, as well as the three-dimensional distribution of clouds. Given the demonstrated capability of a number of measurements pioneered over previous decades, and the technological challenges associated with meeting some of the highest priority needs for weather, the hardware part of NASA's investment in weather research has recently been limited, with increasing emphasis on assuring the use of NASA-produced data to improve weather forecasting. A critical future investment, however, is in direct observations of global winds, as can be achieved with doppler lidar, to fill important gaps in our understanding of global atmospheric circulation, and the associated implications for the energy cycle and the transport of water and aerosols. Development of additional capabilities, such as high-resolution temperature and humidity profiling is needed to acquire near-surface information, definitions of fronts, and determination of cloud layers in order to interface with finer-scale models. These will likely require active sounding techniques, as we are approaching the limit of passive capabilities.

Climate is typically characterized in terms of probability distribution functions averaged over months and longer, but for the purposes of mission planning, we do not consider periods much longer than several decades. While this research focus benefits considerably from investments in other areas, such as atmospheric composition, specific climate related activities are targeted towards (a) improving multi-decadal climate projection, (b) seasonal-to-interannual prediction of temperatures, precipitation, and drought, and (c) understanding and predicting sea level rise. These are achieved by advancing our understanding of the interactions among the oceans, atmosphere, and cryosphere. Ocean processes are both the driver and the memory of climate variability and change, and as such, many of the efforts in this area are related to understanding ocean circulation processes through the observation and modeling of parameters that

affect circulation. These include sea surface height, ocean salinity, surface winds, temperature characteristics, etc. Observations that support our ability to monitor these characteristics and understand their interactions with the rest of the Earth system are of high priority.

The most dramatically changing element of the climate system is the Earth's ice cover that part of the Earth system that helps keep the planet cool by reflecting most of the incoming solar energy and is believed to have been responsible for past abrupt climate changes. Sea ice has a significant impact on ocean circulation, through its direct exchanges of energy, mass, and salt with the ocean. It also influences atmospheric processes by modulating the moisture and energy exchanges between the atmosphere and the ocean. As a result, observations of sea ice thickness are needed to complement the currently routine spatial measurements, especially in the Arctic where the ice cover is shrinking dramatically. Similarly, ice on land is of critical importance and is an observational priority, not just in terms of climate processes, but also sea level.

Apart from ocean thermal expansion, the most dramatic effects on sea level, which is estimated to be rising at nearly 2 mm/yr, are likely to come from the Earth's glaciers and ice sheets. These ice masses store the equivalent nearly 70 meters of sea level, and were the likely source of rapid sea level rise (5 mm/yr) at the end of the last ice age. Observations to date show remarkable changes in parts of the Earth's vast ice sheets and suggest potential instability; consequently, the need to monitor these changes and understand the underlying mechanisms is critical, if we are to understand the potential impacts in coastal regions. This can be achieved by building on the current ice elevation and mass change measurements and determining the amount and nature of discharge by measuring velocities and ice sheet thickness, as well as time-variable gravity measurements.

Ocean observation capabilities for sea level are fairly mature, but current sampling with nadir-only altimetry leaves wide gaps between tracks, which diminishes its ability to measure both turbulent transports in the open ocean and coastal sea level. Sea level rise is not spatially uniform: different coastal areas will be affected differently. In order to maximize societal benefits, consistent high-accuracy measurements are needed at significantly increased spatial density. Also needed are improved technologies for observations in coastal regions, where sea level is affected by the intense winds of storms and there are strong ties to marine life. In the same sense, there is a need to tie the ocean vector winds to be measured by NPOESS to the accurate time series developed during the 1990s and early 2000s with scatterometry.

Climate is very sensitive to cloud processes, through their ability to change the Earth's radiative energy balance. Current climate models have such large uncertainties in unresolved cloud physics that their feedbacks are not well understood. Key properties include cloud cover, height, thickness, ice/water phase, and particle size. Several missions will contribute to improving cloud physics in climate models, as well as to observing the small decadal changes in cloud properties that are sufficient to change climate sensitivity. These missions include the Cal/Val mission to assure sufficient

measurement stability, aerosol missions, and active lidar and radar cloud 2-D and 3-D profiling missions.

Crucial to the long time series with extremely high accuracy needed to study a changing climate is the need for providing 'benchmark measurements', a satellite system with very high accuracy to which all orbiting weather and research satellites are tied. The transfer radiometers should cover the full solar and infrared spectrum to calibrate radiometers, spectrometers, and interferometers from 0.3 to 100 µm, the full earth spectrum that drives climate change from solar scattering/absorption through thermal emission/absorption.

The relationship between climate, Sun, and atmospheric composition was addressed in the previous section.

Climate and weather, though they operate on different time scales, both involve the distribution of energy and mass within the fluid elements of the Earth system. As such, the observing and modeling capabilities offer an important complement to one another, and a coordinated investment in these activities, coupled with those in atmospheric composition and water will have significant payoffs.

### *2.3.3 Water*

Water is both a key resource in environmental sustainability as well as a primary component in the Earth's energy budget. Yet, uncertainties remain large. While the global mean rainfall is projected to increase, climate forecast models differ on the expected change in precipitation at regional scales. Of great concern is the uncertainty of projected rainfall in semi-arid regions such as southwest US. The important role that extreme weather events play in these regions is currently difficult to forecast at any time scales. Before useful predictions of precipitation and snowfall can be made, it is imperative that we fully understand the movement of water, and the causes for the apparent variability of the global water cycle—from evaporation, to condensation, to precipitation, to storage terms of snow, ice, soil moisture and underground aquifers, to runoff, and ultimately back to evaporation. Only if the entire process is fully understood can we confidently predict changes that are necessary to guide societal use of water resources. To that end, one must first formulate a number of questions that deal with the closure of the whole water cycle:

1) Is the global water cycle accelerating?

- Can we observe the evaporation, precipitation, and storage well enough to close the atmospheric water cycle and understand the root causes for any changes?
- Can we observe the storage of water in terms of snow, soil moisture, surface water and aquifers, and river runoff to fully understand the transfer of water from one reservoir to another? Is this water balance consistent with the atmospheric branch of the water cycle?

2) How do natural and anthropogenic processes and factors affect water quality?

It's important to link the study of the water cycle to the rest of the Earth system. These include the role of aerosols in affecting cloud properties (which affect regional precipitation and the partitioning of energy between the surface and the atmosphere. Biology also plays a role in partitioning water between the surface terrestrial biosphere and the atmosphere.

The atmospheric water cycle (evaporation, precipitation, and storage) can be addressed today only in part. Rain has been measured successfully from satellites with a combination of radars and microwave radiometers, but measuring falling snow remains a challenge. Over large regions where snow and ice storage is not an issue, soil moisture is the largest storage term. It can be measured with low frequency active and passive microwave sensors. Evaporation rate is inferred from other sufficiently comprehensive measurements. The Global Precipitation Mission (GPM) and the soil moisture mission Hydros will make important progress in this branch of the hydrologic cycle. Both precipitation and soil moisture have significant application components of their own. Before a true closure experiment can be carried out, better evaporation measurements will have to be made.

The terrestrial water cycle is equally challenging. Precipitation must balance evaporation plus surface storage. Here soil moisture, snow, ice and surface water storage, including lakes, rivers and wetlands, plus underground aquifer storage, and the transport between them must be considered. Snow and ice can both be measured through combinations of active and passive microwave sensors, while water storage in lakes and rivers can be obtained through interferometric radar techniques and laser altimetry. Changes in ground water can be derived from detailed gravitational measurements. When flown in conjunction, such missions will help close the terrestrial water cycle. Like the atmospheric water cycle, this component also has significant and immediate practical applications in terms of fresh water availability and river runoff projections.

Water quality, important for both environmental and economic health, is perhaps the most difficult parameter to measure from space, requiring measurements of dissolved oxygen, turbidity, and chlorophyll. A combination of space-based and in-situ observations offers the greatest opportunity for progress in this area.

Together, these experiments are critical to gain confidence in our description of the water cycle that is required before useful forecasts can be made. Significant societal benefits can be derived from the individual measurements. Knowing the global and regional amount of precipitation has great social value even if the entire global water cycle is not yet fully understood. The same is true for soil moisture, for snow accumulations, and for surface water and river discharges. Some of these parameters should be measured individually in preparation for a great experiment in which all of the parameters are measured simultaneously from different vantage points.

### *2.3.4 Life*

As far as we know, Earth is the only planetary body that is home to life. Life is evolved, organized, dynamic and abundant and these complexities are revealed on a global scale in the Earth's biosphere. Earth science provides the opportunity to understand our planet and at the same time explore the dynamics and functions of a fully evolved and developed life system. The functioning of life on Earth helps regulate climate through the emission of trace gases and it provides important ecosystem services upon which economic systems and human health depend. However, our understanding of life and its interaction with the Earth system is far from complete.

The approach to the Life line of inquiry is to discover fundamental dynamics of the biosphere, answer key questions related to the carbon cycle and the functioning of ecosystems in natural and disturbed states, and integrate this understanding into the larger Earth System framework. Life on Earth helps regulate climate through emission of trace gases,. Carefully planned missions can move the science from our current indirect assessments of biomass stocks to direct determinations of biosphere dynamics directly coupled with the other elements of the Earth system. In this way, we endeavor to develop a predictive understanding of the living Earth and its role in the Earth System.

The Life program has a focused scientific strategy to guide the development and deployment of measurements, based on five general challenges:

1) *Observe global changes in biomass and stocks:* observe ecosystem function and process and its role on the global carbon cycle; improve direct measurements of carbon stocks and biomass, and the fluxes of carbon, beginning with assessments of global distribution through characterization of change, dynamics, and processes

2) *Mechanics of ecosystems:* gain a broad, process-level understanding of all facets of the biosphere as a life-support system, including biodiversity and ecosystem function.

3) *Influence of the dominant species on Earth:* observe and predict how human activities affect the Earth system.

4) *Connections:* understand the role of the biosphere in the Earth system and its interaction with and influence upon climate, atmospheric composition, water, solid Earth, and solar input. Collaborative missions with other disciplines will enable synergy across the Earth sciences and with the Sun-Solar Connection Roadmap.

5) *Life here and beyond:* synthesize our measurements to identify the key signatures of Life to complement and support discovery missions; aid in the development of exploration observers such as the Terrestrial Planet Finder.

One clear focus for the Life roadmap is to gain a predictive understanding of the global carbon cycle, with particular reference to its dynamics, controls, and influence from and on human activities. The carbon cycle is both regulated by climate and is influenced by it. Using the carbon cycle as an emphasis provides a strategic focus for measurement

missions. A predictive knowledge of the carbon cycle is fundamental to understanding all biogeochemical cycles on Earth and its role in climate. An assessment of the carbon cycle requires measurement of all pools of carbon and the fluxes among them. Knowledge of how ecosystem metabolism provides sources and sinks of carbon is absolutely critical. Several key measurement categories can be identified:

- *High-resolution $CO_2$.* Measurements of atmospheric concentrations and profiles of $CO_2$, $CH_4$, and other greenhouse gases with sufficient accuracy to characterize sub-regional carbon emissions and sequestration are a priority.
- *Vegetation Structure, Biomass, and Disturbance.* Vegetation height profiles over Earth's land surface are needed to quantify land biomass and carbon stocks, quantify ecosystem recovery following disturbance, and characterize habitats.
- *Plant Physiology and Functional Types.* Observations of plant functional types and physiological function are required for both land and ocean. Current understanding is limited by a lack of quantitative information on the variety, distribution, abundance, and variability of plant groups with important ecological functions.
- *Coastal and Open Ocean Carbon. Coastal and Open Ocean Carbon.* Measurements of carbon stocks in the coastal and global ocean are required beyond the present capability of determining chlorophyll concentrations.

Near-term missions focus on basic measurements of changes in carbon storage on land and in the oceans. The NPP mission will enable measurements of changes in the biosphere, including land and ocean productivity, vegetation phenology, fires, and other important variables at kilometer spatial scales. These measurements would continue operationally on NPOESS (VIIRS and LCDM/OLI) The Climate program's Cal/Val mission will help insure the quality of the VIIRS data on NPP and NPOESS. While these missions focus on carbon storage, OCO will make atmospheric column measurements of $CO_2$ which will be used to assess the variability of carbon sources and sinks and their causes (shared with Atmospheric Composition).

The next phase of missions should provide better quantification of both storage and flux parameters, as well as forcing parameters. A High-resolution $CO_2$ mission in tandem with an Aerosol mission will provide $CO_2$ profiles in the atmosphere, allowing increased analysis of sources and sinks. A proof-of-concept Biomass mission can focus on providing global, mapped estimates of above ground vegetation biomass. A flagship mission in the 2020 timeframe should focus on plant physiology and functional types both on land and in the ocean. This mission can provide high-spectral-resolution imagery for quantifying plant abundances, distributions, and carbon fluxes on appropriate space/time scales. Integrating with this flagship mission should be a Biomass dynamics follow-on mission, which will directly measure changes in above-ground carbon stocks. A Photosynthetic Efficiency mission can directly assess plant and algal physiological status using pulsed lidar technology. An Advanced Land Cover measurement mission would measure land cover and use change measured at high spatial resolution with the ability to discriminate plant functional types and human created land cover features.

Three missions are needed to assess the ocean biosphere and its role in the carbon cycle. The first is a Coastal / Global Ocean Carbon mission, which will quantify dissolved organic carbon pools in open ocean and coastal environments. This mission should be followed by Ocean Particle Profile and Ocean Carbon Storage missions, which are aimed at assessing vertical profiles of particle abundances in the upper ocean and all pools of carbon, respectively. These missions will all contribute to understanding the ocean ecosystem dynamics and its role in the carbon cycle.

The Life program can contribute to supporting other Strategic Roadmap areas. For instance the suite of Life observing platforms recommended here can be marshaled to gain a better indicator signature for life where it may occur. The development of a special mission to quantify and test a *bio-signature for life* using high-resolution spectral imagery would be an important experimental contribution to other exploration and discovery missions. Finally, solar processes influence the biosphere, and the biosphere can influence the climate impacts of solar variations. Hence, there are strong links between the Life program and the objectives of the Sun-Solar Connection roadmap (SRM10).

### *2.3.5 Solid Earth*

In 2002 NASA's Solid Earth Science Working Group identified the six scientific challenges of highest priority for the agency's Solid Earth Science Program for the next quarter century. Those challenges, still unmet, are to answer the following questions:

(1) What is the nature of deformation at plate boundaries, and what are the implications for earthquake hazards?
(2) How do tectonics and climate interact to shape the Earth's surface and create natural hazards?
(3) What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change?
(4) How do magmatic systems evolve, and under what conditions do volcanoes erupt?
(5) What are the dynamics of the mantle and crust, and how does the Earth's surface respond?
(6) What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

To address the factors that control the spatial and temporal patterns of earthquakes and earthquake-generated tsunamis, space-based observations are needed for synoptic measurements of the strain field through the entire earthquake cycle, including episodes of aseismic accumulation of strain. Such measurements will provide insights into how stress is transferred between faults, the fraction of strain that is accommodated seismically, and ultimately how faults fail. Diverse temporal and spatial scales for the governing processes dictate a variety of specific observational approaches. Satellites devoted to Interferometric Synthetic Aperture Radar (InSAR) measurements together with Global Positional System (GPS) networks are needed to provide dense, frequent sampling and high-accuracy observations of changes at the Earth's surface. Existing and planned seismic networks and borehole sensors operated by other agencies will complement space-based low-frequency sounders, and highly accurate gravity

measurements can help to characterize subsurface regions subject to seismic hazards. One or more satellites dedicated to InSAR measurements will provide, for North America, an essential component of the EarthScope Program, other elements of which have recently been initiated with funding from the U.S. National Science Foundation.

The land surface evolves both by the actions of man and by such natural forces as tectonic deformation and transient hydrologic and biologic influences on erosion and deposition. During severe storms, how floods progress and landslides are generated depends on topography, soil characteristics, vegetation, and rainfall intensity. Similar interactions determine how flood waves migrate through a catchment and how much sediment is eroded, transported, and deposited during a storm. Remotely sensed data play an integral role in reconstructing the recent history of the land surface and in predicting hazards due to events such as floods and landslides. Information needed to address this challenge includes surface, subsurface, and hydrologic characteristics. These categories have a range of observational requirements. Quantities that change rapidly, such as river stage or precipitation, call for hourly measurements, whereas others might require only seasonal measurements (e.g., vegetation) or occasional (5–10 yr) quantification (for example, soil composition and thickness). The ability to acquire such data in real- or near-real time and to integrate that information with quantitative models are requisite to the development of a capability to predict the timing and magnitude of floods and the heightened risk of landslides during storms, particularly in remote, poorly monitored areas.

Paleo-environmental and historical data have clearly documented sea-level changes in the past, and new scientific information on the nature and causes of sea-level change and the development of a quantitative predictive capability are therefore of utmost importance for the future. The solid Earth plays an important role in this issue, because of the time-varying response of the solid Earth to changes in surface loading by oceans and ice masses. More generally, this topic — addressed above in the Climate section — is inherently an interdisciplinary scientific problem impacted by many programs within NASA as well as the efforts of other federal and international agencies.

The eruptive power and often-long intervals of quiet dormancy render volcanoes both difficult objects of study and dangerous geographic neighbors to population centers. The threat of eruption is always there, but because eruptions are episodic, the fastest route to general understanding is to take advantage of observations of volcanic activity on a global scale. Including remote terrestrial and undersea volcanoes, there are thousands of volcanic centers whose level of activity is poorly known. Indicators of activity include surface deformation, seismicity, changes in gravity, fluxes of gasses, and actual eruptions. Little is known, however, of how these phenomena are interrelated. The physical mechanisms that cause surface deformation and those that control the rates and styles of eruptions are similarly poorly understood. An ability to predict the timing, magnitude, and style of volcanic eruptions should be achievable with improved global observations and physical models.

Mantle convection is the engine responsible for plate motions, seismicity, volcanism, and mountain building. The deformation of the Earth's surface required to accommodate plate tectonics occurs primarily along plate boundary faults and relatively broad zones of deformation adjacent to the plate boundaries in the continents. The forces that drive the motions of the plates, however, are not well quantified. The global gravity field and long-wavelength topography provide key integrative measures of density anomalies associated with mantle convection, although their interpretation requires information on the structure of the tectonic plates and the variation of viscosity within the mantle. Improved information on plate characteristics and mantle viscosity can come, in turn, from measurements of the time-dependent response of global gravity, topography, and Earth rotation to loading and unloading by glaciers, oceans, and other forcings.

Although it is widely recognized that a dynamo operating in the fluid outer core generates the Earth's magnetic field, the details of how that dynamo works remain far from understood. Over the past 150 years, the main (axial dipole) component of the Earth's magnetic field has decayed by nearly 10%, a rate 10 times faster than if the dynamo were simply switched off. Intriguingly, this decay rate is characteristic of magnetic reversals, which paleomagnetic observations have shown occur on average, though with great variability, about once every half million years. The recent dipole decay is due largely to changes in the field in the vicinity of the South Atlantic Ocean. This pattern is connected to the growth of the South Atlantic Magnetic Anomaly, an area in which the field at the Earth's surface is now about 35% weaker than would be expected. This hole in the field impacts the radiation dosage of satellites in low-altitude orbits. Addressing such questions as how the South Atlantic Magnetic Anomaly will evolve and whether the main field is reversing requires long-term observations by constellations of satellites combined with numerical modeling of the Earth’s core dynamo.

The interconnected nature of Earth science means that the most challenging issues in the field today bridge several disciplines. As such, defining the measurement requirements to address these challenges is best done through a unified observational strategy. Such a broad strategy incorporates diverse methodologies (including space-borne and ground measurements), technological advances, and complementarity among observations. NASA’s Solid Earth Science Working Group in 2002 recommended the following observational strategies to address the fundamental challenges to solid Earth science and society: (1) Surface deformation; (2) high-resolution topography; (3) variability of Earth's magnetic field; (4) variability of Earth's gravity field; and (5) imaging spectroscopy of Earth's changing surface. Continued development of space geodetic networks and the International Terrestrial Reference Frame, as well as investment in promising techniques and observations, such as subsurface imaging using low-frequency sounders, are important components of an overall program.

### *2.3.6 Human Interactions*

We have not identified a separate activity for the role of humans in the Earth system. This is considered a crosscutting line of inquiry, to which each of the other lines of inquiry contribute. Human activities are changing the biosphere and can place the life support system of this planet at risk. As we enter the 21st century, we face significant scientific

and engineering challenges as environmental changes occur at an accelerating rate. We are experiencing rapid climate and ecological shifts, the degradation of freshwater resources, the globalization of disease, the threat of biological and chemical warfare and terrorism, and the more complex question of long-term environmental security. We are seeing the impact of multiple stressors on environmental systems, yielding changes that require new science and innovation to understand. These developments present enormous intellectual challenges in the need to address combinations of factors, such as the interactions between human activity and natural cycles, to address environmental challenges. In response to these challenges, scientists have begun conceptualizing new approaches to problems, reaching across traditional disciplinary boundaries to study complex environmental systems *in toto*. Researchers are also creating new linkages between basic and applied scientific endeavors.

It is important to understand the complex interactions between human systems and natural systems, and this understanding will come from measurements tied to models. Observations of land cover and land use change and other actions of humans will aid in the development of prognostic models of human disturbance to the Earth system that can link to the other Earth science areas.

## 2.4 Strategic Roadmap Integration Objectives

No individual measurement, mission, or model can answer the set of guiding questions identified in Section 2.2. They can be fully addressed only through the integration of investigation systems into national (and international) observation systems, such as the Integrated Earth Observation System (IEOS) or the Global Earth Observation System of Systems (GEOSS). Because the capacity to answer guiding questions emerges through the integrated results of multiple scientific investigations, this document also identifies three **strategic roadmap integration objectives**. These are: Exploration and Discovery; Continuous Awareness; and Developing Perspectives (Fig. 1).

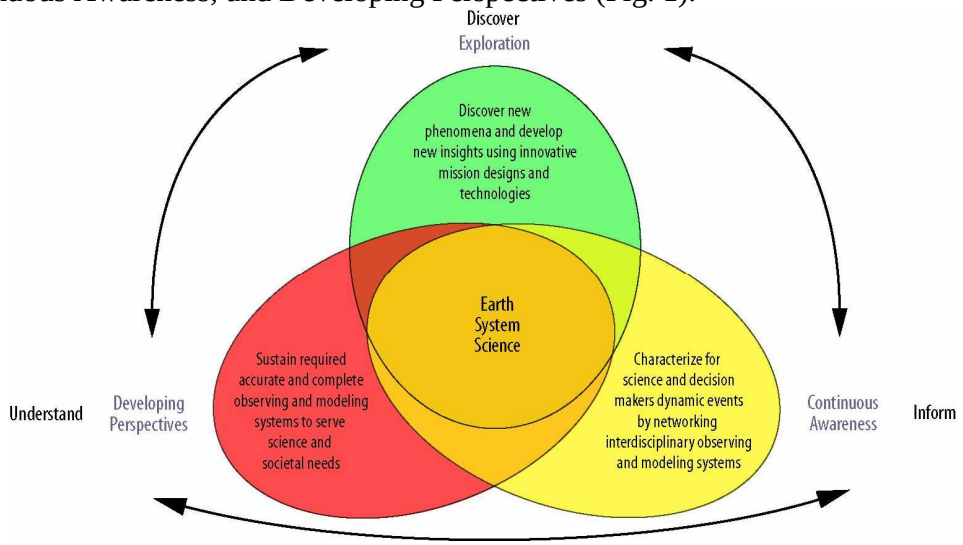



Figure 1: Our three strategic roadmap integration objectives represent different approaches to understanding the Earth system that converge to represent the whole of Earth system science.

### *2.4.1 Exploration and Discovery*

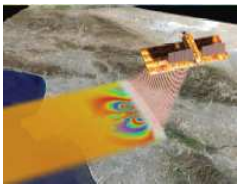
*Explore unknown aspects of the Earth system by implementing new investigations enabled by new insights, technologies, capabilities, and vantage points.*

This objective focuses on the idea of exploration for the sake of uncovering new and exciting aspects of the Earth system, including exploring phenomena we cannot yet sample, places we've never seen, and processes we don't yet understand; such as the Earth's interior, or the bottom of the ice sheets and the oceans. It traces to the NASA strategic objective for this roadmap in several ways. It contributes to all three elements: space-based observations, assimilation of new measurements, and the development of new technology and capabilities. In order to explore the frontiers of Earth science, a global perspective only available from space, is required. In order to interpret guiding measurement data from space-based observations, the results must be assimilated into existing infrastructure. Resulting models must be run and results analyzed in order to understand the findings. Thus, implicit in this objective is the need for new technology and capabilities; these are included as part of the objective itself.

Exploration and Discovery of Surface Change with InSAR

EXAMPLE

NASA has always pioneered technical and scientific breakthroughs, and the use of Interferometric Synthetic Aperture Radar for studying how the surface of a planet changes is an ideal example of an exploratory mission for discovering insights on surface topographic change me. Clearly rated the highest priority measurement of the solid Earth science community, mm-level deformation measurements of the surface due to plate tectonics, subsidence, magma injection and other phenomena may lead to revolutionary forecasting of – and mitigation from – natural hazards like earthquakes and volcanoes.



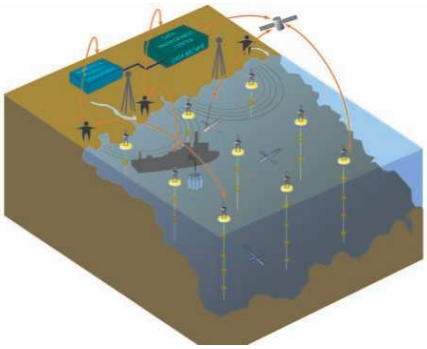
### *2.4.2 Continuous Awareness*

*Develop new scientific understanding of dynamic processes and demonstrate capabilities useful for decision support by providing prompt recognition and adaptive observation of dynamic events through the networking of distributed observing and modeling systems.*

This objective focuses on understanding the short-term variability in the Earth system. Understanding will be gained by combining measurements from multiple space platforms, ground-based and in situ observations, with modeling and validation efforts, in an intelligent fashion. The continuous awareness integration objective touches on all three elements of the NASA strategic objective for this roadmap. In order to achieve this objective, not only must the global perspective of space be used, but a broad variety of vantage points and observing techniques. This will help characterize the Earth's behavior over a range of vertical, horizontal, and temporal resolutions. The real-time assimilation of new measurements into the science and policy-making communities is an implicit part of the objective, and presents a unique challenge. The development of new technology and capabilities for this objective takes the form of a systems push rather than a technology push. The idealized end state—to view all possible phenomena on all parts of the globe continually—is a challenge, and requires development of new system concepts and advanced data processing methods to handle the massive influx of incoming data.

Continuous Awareness of Coastal Zones
EXAMPLE

The coasts are where we live and play, set sail for trade routes and harvest for their rich marine life. The coasts are also a unique interface between the land and sea and atmosphere. The only way to truly understand the complex interactions of diverse natural phenomena and human influence is to use a continuous awareness approach of simultaneous, independent measurements. The addition of satellite measurements of ocean color (Sea Surface Reflectance) at high temporal and spatial resolution, in conjunction with ocean surface currents, winds, and topography, to already-existing in situ measurements would be able to link the bio-geophysical parameters to phenomena like harmful algal blooms, sea level rise, ecosystem health, storm water runoff – and their consequences for humans. The greatest scientific and societal benefits accrue when continuous awareness clusters are used to make sure the system is greater than the sum of its parts.



A coastal continuous awareness system could consist of:

- In situ arrays
- Hyperspectral imagers
- Along-track interferometers
- Scatterometers

Cable arrays of in situ sensors and floating buoys are making measurements and expanding in regions like Monterey and Los Angeles, California: MARS, MOOS, SCCOOS programs

### 2.4.3 *Developing Perspectives*

*Enable new scientific understanding of long-term Earth processes and trends by sustaining and integrating comprehensive global observing and modeling systems.*

This objective is focused on identifying key parameters of the Earth system that will help understand its long-term variability. To do this, NASA must develop technologies, and then implement initial observing systems capable of measuring these parameters to the required exquisite accuracy and consistency over long time scales, particularly important for long-term climate studies. It is expected that partner agencies will continue the measurements over such timescales, as part of the Integrated Earth Observation System. NASA must engage with these partner agencies to execute a smooth transition from research to operations. We envision "climate calibration observatories," launched and maintained by NASA, charged with making climate-quality "benchmark" radiometric observations, with stringent calibration and stability requirements (typically down to the 0.1% level). NASA must also ensure the existence, accessibility, and frequent improvement of long time series of data, through a combination of active data management and active research. To extract the most societal benefit from this information, we need a vigorous numerical modeling capability, focused on long-term climate trends (and quite different from the modeling capability required by the continuous awareness integration objective.)

Developing Perspectives traces to the NASA strategic objective for this roadmap. First, space-based observations are necessary in order to achieve the global perspective this integration objective aims to accomplish. Also, there is a need for new technologies to be developed to provide the capabilities required for this objective, such as very-long-term consistent observations. For example, a mission pushing the technological limits of absolute accuracy, designed to tie data from less accurate missions (which add space-time coverage) is a challenge uniquely suited for NASA.

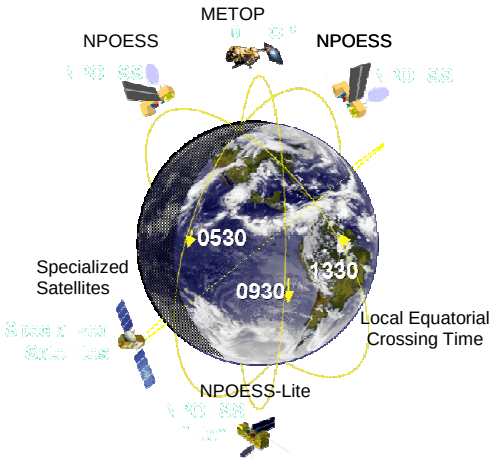
Developing Perspectives with Atmospheric Chemistry Cal/Val Mission
EXAMPLE

Investigative missions (such as Aura, OCO and Glory) will provide essential information regarding atmospheric chemistry. As these missions provide a preliminary understanding of atmospheric issues, ***their observations will serve as the beginning of environmental data records*** that can provide critical information on patterns of the changing climate.

NPOESS (right) is a tri-agency (NASA, NOAA, DoD) effort to leverage and combine environmental satellite activities; its mission is to provide a national, operational, polar-orbiting remote-sensing capability, incorporating new technologies from NASA. NPOESS will monitor several elements of the Earth system, ***creating 55 environmental data records***. NOAA will maintain a long-term archive and provide the data to the worldwide community.

NPOESS data will provide societal benefits:

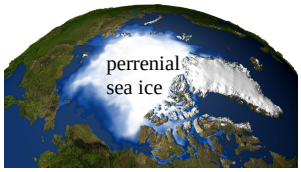
- Weather observations and predictions
- Ozone measurements
- Climate monitoring and prediction




For a smooth transition between investigative missions and NPOESS measurements, and thus ***to generate the quality of climate data needed a mission designated for calibration and validation is critical.***

A Walk through Exploration, Awareness, and Perspective: Sea Ice

EXAMPLE




In many cases, we learn about elements of the Earth system and their interactions with the rest of the system first through discovery, by just observing, then through awareness, when we have enough information to develop an understanding of the processes and how they work, and finally through perspective when we understand the long-term changes, and the roles of these elements in the larger system. Our past present and future observations of sea ice offer clear examples of each of these stages.

Exploration

The launch of the first visible imaging polar orbiting satellites, allowed the first comprehensive view of the Earth's sea ice cover under cloud-free conditions during polar day. In the years and decades that followed, we were able to use multi-channel microwave instruments to observe continuously under all weather conditions ice extent (1973: single-channel radiometer), ice concentration and type (1978: multi-channel radiometer), ice deformation (1995: synthetic aperture radar), and most recently ice thickness (1991: Radar altimetry, and 2003: laser altimetry, with ongoing developments in VHF sounding). Each of these advances enabled the development, validation, and utilization of the first large-scale models of polar sea ice cover. Ice thickness remains a new area for new discoveries, as it has not been well sampled yet, and the thickness distribution and changes in ice cover, remain largely unknown.

Continuous Awareness

These new discoveries, when coupled with models and other observations, allow scientists to address important issues in Earth system science such as understanding the interactions between the ocean, ice cover, and atmosphere. These interactions have significant implications for atmospheric and oceanic circulation, and thus weather and climate. Achieving a clear understanding of how these processes work has been enabled by observations of: ice margin changes (passive microwave radiometry), details of lead formation (synthetic aperture radar), surface temperatures (infrared, and passive microwave), ice thickness, (altimetry, VHF sounding), snow depth on sea ice (passive microwave), ice motion (visible, scatterometry, passive microwave), surface reflectance (visible), and surface irradiance (combinations of solar irradiance and atmospheric optical measurements) This suite of observations and associated process models allows the development of a comprehensive understanding of sea ice behavior, its interactions with the ocean and atmosphere, and its influence on climate and weather.

Developing Perspectives

To understand the long-term behavior of sea ice, the different characteristics between Arctic and Antarctic sea ice cover, and the role of sea ice within the larger Earth system, following the knowledge gained through the awareness efforts, ongoing monitoring is needed of the spatial characteristics of the ice cover (its spatial extent, and the size and locations of openings within the ice cover), its movement, and its spatially variable thickness. These are the parameters for which a long-term observing capability should be implemented to appropriately "develop perspectives" and flow from past, present, and future observational capabilities.

*Guiding science questions lead to fundamental scientific objectives with practical applications, which link to the integration objectives of the roadmap.*

# 3 Formulating the Roadmap

## 3.1 Context

In the early years of space exploration (1960's to 1980's), NASA Earth science was focused on demonstrating the feasibility of remote sensing of the Earth from space. This was followed by the EOS era (1980's to early 2000's), during which the concept of investigating the Earth as a system from space matured. The strategic implementation stages for Earth Science and Applications link to this history and trace to the strategic roadmap objective and the national goal for space exploration (Figure 2). The next decade (2005 – 2015) will begin building a foundation for comprehensive observing and modeling by focusing on atmospheric composition, climate and weather. The following decade (2015-2025) will expand our view of Earth and reach into society by shifting focus to water, life and solid Earth characteristics of the system. The decade after will result in an integrated, comprehensive and sustained "information web" for Planet Earth, which is the fully developed U.S. Integrated Earth Observation System (IEOS). NASA's role within that system will be to continue to pursue new science questions and to investigate aspects of the Earth system that we have not yet explored.


Figure 2: Flowdown from national goal for space exploration to the objective of this roadmap and its relationship to the past, present and future of NASA Earth Science.

## 3.2 Developing the investigation timeline

In developing our investigation timeline, we envisioned a series of linked, overlapping 'lines of inquiry', each spanning an approximate 25-year interval (Figure 3). Initial investigations along each line of inquiry would tend to be exploratory in nature. This would be followed by the start of a period of "awareness clusters" of investigations. Next comes a period of perspectives investigations, as key parameters are identified and preparations are made to sustain them over the long term. Exploratory missions may continue throughout most of the timeline, as our scientific knowledge and/or technology advances.

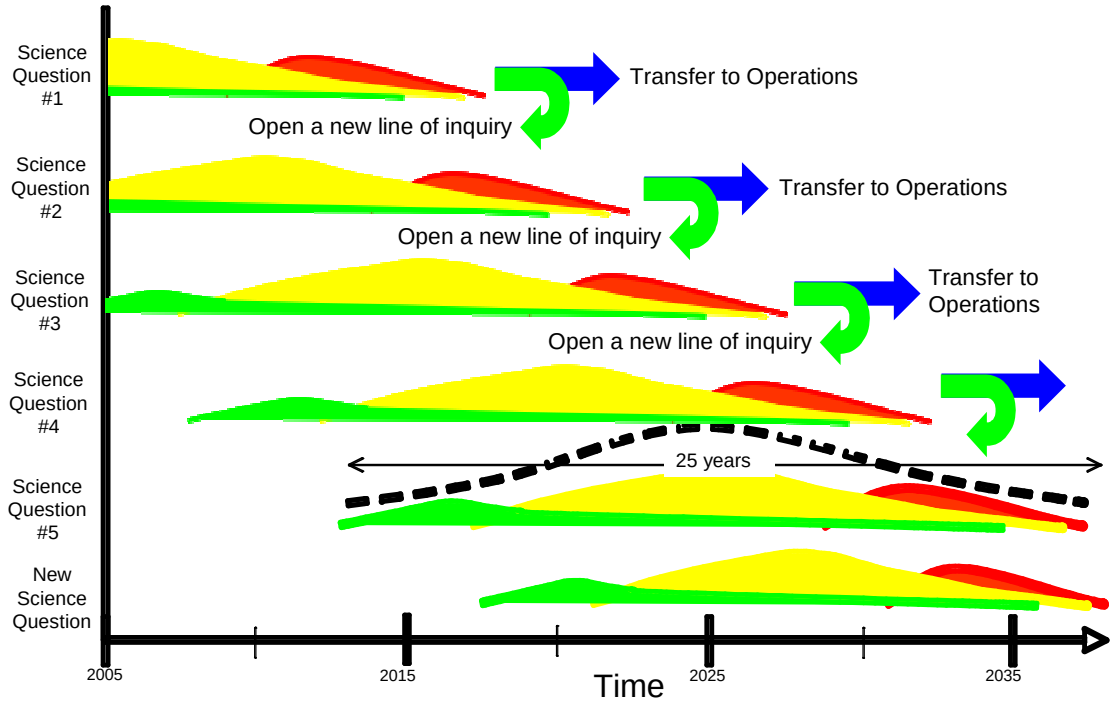



Figure 3: Notional timeline showing exploratory investigations (green), awareness investigations (yellow), and perspectives investigations (red).

*Awareness clusters focus efforts on answering particular science questions in a given line of inquiry by coordinating and connecting information from multiple space and airborne observations, in situ sensors, and modeling systems during the focus time period.*

Each line of inquiry is targeted at one of the 5 guiding science questions discussed in Section 2.2. Investigations laid out along the line of inquiry are designed to address the achievements set out for each guiding question. Towards the end of each line of inquiry, two outcomes are illustrated. The first is a transfer to operations, i.e., measurements are sustained over the long term by an operational agency. The second outcome is the

opening of a new line of inquiry, which enters an exploratory phase. Both may be possible – as they mature, some (but not all) key measurements are transferred to operations, while a breakthrough in technology or scientific discovery may bring to the surface new questions.

To determine the recommended order of the awareness clusters linked to each scientific objective, we evaluated the current state of each line of inquiry, based on the current mission set and NASA's near-term plans. As confirmation, we examined the maturity of all of the measurements in each science area using the Measurement Maturity Index, as described in section 3.4.2.

Investigations were prioritized by the Committee based on the criteria set out in section 2.4, then laid out in sequence on the timeline. To implement the roadmap, we assumed that a balanced portfolio of mission classes, including small, medium, large and flagship missions, would be available. Consideration was given to producing an affordable mission set, which led to spacing out the investigations.

## 3.3 Pathways and Stages

Figure 4 illustrates the pathways and stages for NASA Earth science over the next three decades, shown in three tiers. The first is designed to open up new areas of science inquiry through exploratory investigations that target the unknown characteristics of the Earth system. The second tier is designed to address the scientific objectives in sequence, with the order of the sequence and activities within each dependent on the overall scientific maturity of that line of inquiry. In each case, the initial activities are discovery-oriented (green), followed by a period of continuous awareness (yellow), then the development of a long-term perspective (red). The third tier (shown as blue boxes) matures our ability to manage information about the Earth system over the three decades.

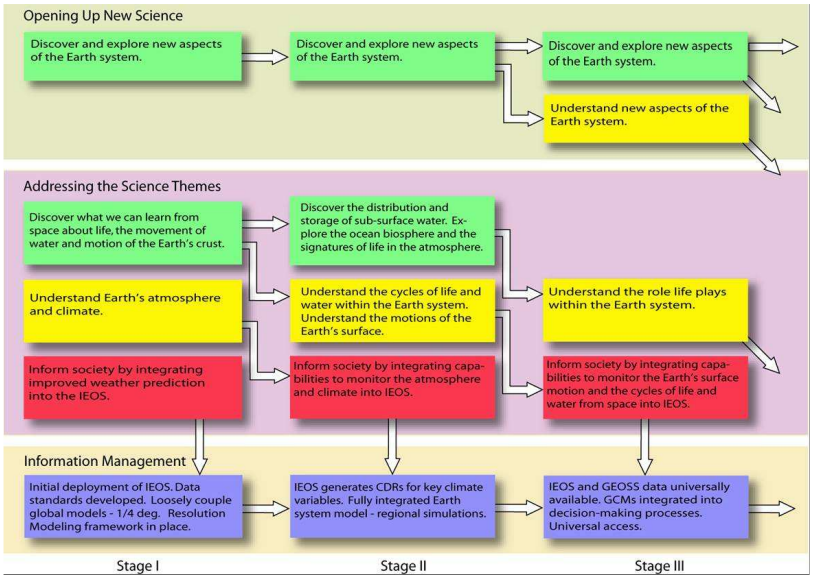



Figure 4. Pathways and stages for NASA Earth science over the next three decades.

### *3.3.1 Stage I: Building a foundation for comprehensive observing and modeling*

In Stage I (2005-2015), we will begin building a foundation for comprehensive observing and modeling by focusing on atmospheric composition, climate, and weather. Through collaboration with NOAA, we expect that by the end of this stage we should be exploiting new NASA observing capabilities and research to improve operational environmental satellites and weather forecasting models. Exploratory activities are planned for the water, life and solid earth lines of inquiry, in preparation for a more intensive look at these questions in the following decade. We expect that data standards for long-term monitoring will be developed as the IEOS is initially deployed, and that fully integrated global Earth System models will be available by 2015, with higher resolution regional simulations in various disciplines by that timeframe. The coupling technology (Earth System Modeling Framework) will simplify the swapping of model components.

### *3.3.2 Stage II: Expanding our view of Earth and reach into society*

In Stage II (2015-2025), we expand our view of Earth and reach into society by focusing on water, life, and solid Earth lines of inquiry. Towards the start of this stage we anticipate handing off responsibility for monitoring aspects of atmospheric composition and climate to NPOESS. Critical to this handoff are some core NASA activities that will enhance the value of NPOESS for science, such as calibration/validation, and funding of science data analysis from NPOESS data streams. Exploratory activities continue to round out our knowledge of the cycles of life and water, and to look for unknown aspects of the Earth system. We expect that our partners in the US IEOS will be producing ‘gold standard’ climate data records by the end of this decade, and that Global Climate Models will be fully integrated together, with some regional level simulations under way.

### *3.3.3 Stage III: Fully instrumented Earth system networked to predictive models, serving science and decision makers*

In Stage III (2025-2035) we will integrate a comprehensive and sustained “information web” for Planet Earth and open up new lines of science inquiry through discovery. During this stage we should be able to hand off responsibility for monitoring aspects of life, water, and solid Earth to the appropriate operational partners in the US IEOS. Exploratory activities continue to look for unknown aspects of the Earth system. We expect that information derived from IEOS and GEOSS will be universally available and accessible by the end of this decade (much like weather forecasts today), and that Global Climate Models will be firmly embedded in decision-making processes. We envision a fully integrated Earth system model at this stage with universal, high-speed access to the information it provides. As society moves towards sustained management of the Earth system, we expect NASA to be at the forefront in providing the science-based information that policy and decision-makers will need.

## 3.4 Prioritization Criteria

### *3.4.1 Criteria used*

Prioritizing investigations is at the heart of the roadmap, and was done with considerable thought and a defined, logical process. At the core of the roadmap is the time-ordering of activities based on scoring of scientific, technical, and societal relevance with an emphasis on maximizing efficiency of related measurements. This is the idea of 'awareness clusters,' a time period during which activity is focused on answering particular science questions in a given line of inquiry by coordinating and connecting information from multiple space and airborne observations, in situ sensors, modeling systems, and validation efforts.

An investigation list was created starting from the Earth Science Technology Office (ESTO) database of investigations and mission concepts, and continuing with science community documents like the Solid Earth Science Working Group report, the Earth-Sun System: Potential Roadmap and Mission Development Activities Document (Dec. 23, 2004), the Committee on Earth Observation Satellites handbook, EOS data record lists, and NOAA climate and weather measurement requirements. These measurements and missions were then evaluated against our prioritization criteria, listed below:

- ***Does the investigation advance science?***
- ***Does the investigation support decision-makers?***
- ***Does the investigation benefit society?***
- ***Is the investigation consistent with recommendations of national priorities?***

In terms of the potential to advance science, we considered whether there was significant potential to make a major scientific breakthrough, and whether a particular investigation supported NASA's overall mission. With respect to decision support, consideration was given to NASA's responsibilities to the Climate Change Science Program (CCSP) and IEOS, and whether a particular investigation addressed nationally important applications. We also weighed the potential to reduce uncertainty in predictions, and the social importance of the science question addressed. In examining the benefits to society, we looked at the extent to which an investigation might help protect vital needs (such as water and clean air), or lead to reductions in disruptions to daily life (e.g. through disaster mitigation and warning). We asked ourselves whether an investigation would have a high likelihood of educating the public. Does it have linkages to multiple disciplines?

This prioritization is subject to reasonable constraints on the available budget, the technological readiness of a given measurement, and the maturity of the measurement within a given line of science inquiry. Naturally, broader community input and the results of the NRC Decadal Study will augment the detail and appropriateness of this prioritization system and resulting timeline.

### *3.4.2 The Measurement Maturity Index*

To determine the current state of each line of inquiry the Committee developed the concept of the measurement maturity index (MMI) for space-based measurements. The MMI encapsulates both the scientific maturity of a measurement and its readiness to transition to operational use. It is a subjective maturity descriptor of a specific measurement by a specific technique to be used with other considerations, not as a stand-alone number for decision-making. Carefully applied, it can be used to help decide how to progress with a measurement. As an aggregate measure the distribution of measurement maturity values within a given line of inquiry could be used as an indicator of a well-balanced program that includes new as well as maturing measurement capabilities. The Committee believes that the measurement maturity index could be a valuable tool, and that it could be generalized beyond space measurement to all measurement types (for example, in situ, airborne, etc.). The Committee discussed but did not have time to explore the concept of a complementary measure of model maturity and the need to plan and manage the matching of future observation outputs with future model inputs.

There are eight MMI levels (Table 2). MMI-1 refers to a parameter that is thought to be significant, for example, as a driver or indicator of climate change that has not been measured yet. An example of MMI-1 is ocean mixed-layer depth, which may be critical for understanding the ocean biosphere, but has not yet been measured or derived from remote sensing data. MMI-8 refers to a measurement for which the transition from research to operations is complete, that is routinely used in decision support systems. An example of MMI-8 is the capability to monitor day-to-day weather patterns, which has already successfully transitioned from NASA to NOAA.

| Measurement Maturity Index | Definition for Space-based Measurements | Example Measurement Technique | |
|---|---|---|---|
| MMI-1 | Parameter thought to be significant. Not measured yet. | Ocean Mixed Layer Depth | Discovery |
| MMI-2 | Measurement feasibility demonstrated. Parameter shown to be significant in one or more Earth system models. | Ice thickness | Discovery |
| MMI-3 | Measurement from space demonstrated in a pathfinder mission. Parameter shown to be significant across multiple Earth system models. Pilot program for decision support initiated | Sea Ice Thickness | Discovery |
| MMI-4 | Measurement demonstrated in a pathfinder mission Parameter shown to be significant across multiple Earth system models. Pilot program for decision support ongoing. | Precipitation | Discovery / Awareness |
| MMI-5 | Measurement demonstrated over a sustained period. Parameter generally accepted to be a key measurement to be sustained over long periods. | Land Surface Temperature | Awareness |
| MMI-6 | Measurement demonstrated over a sustained period. Parameter demonstrated to add value to an existing decision support tool or process. | Sea surface topography | Awareness / Perspective |
| MMI-7 | Measurement demonstrated over a sustained period. Measurement ready for transfer to operational use. | Stratospheric Ozone (high vert. resolution) | Perspective |
| MMI-8 | Transition from research to operations complete. Parameter routinely used in an existing decision support tool or policy process. | Daily weather patterns | Perspective |

Table 2: Definition of Measurement Maturity Index levels for space-based measurements. Approximate mapping to Integration Objectives is shown on the right-hand side.

As measurement maturity levels are advanced, clearly multiple activities will need to progress (Figure 5). Technology development and improvement will occur for lower levels of MMI (1-3). Somewhere between MMI-2 and MMI-3, a pathfinder spaceborne mission is launched, followed by an operational precursor mission between levels 4 and 5, and then an operational mission at level 6. At lower MMI-levels, the measurement will be incorporated into Earth system models in a rudimentary fashion, reaching demonstration of significance across multiple models by MMI-3. By MMI-5, the parameter is generally accepted as a key measurement that it is critical to sustain over long periods. Atmospheric $CO_2$ and sea level are examples of such key parameters. Embedding the measurement in decision support starts early in this process, with pilot programs beginning at level 4, and a completion of the handoff from research to operations by level 6.

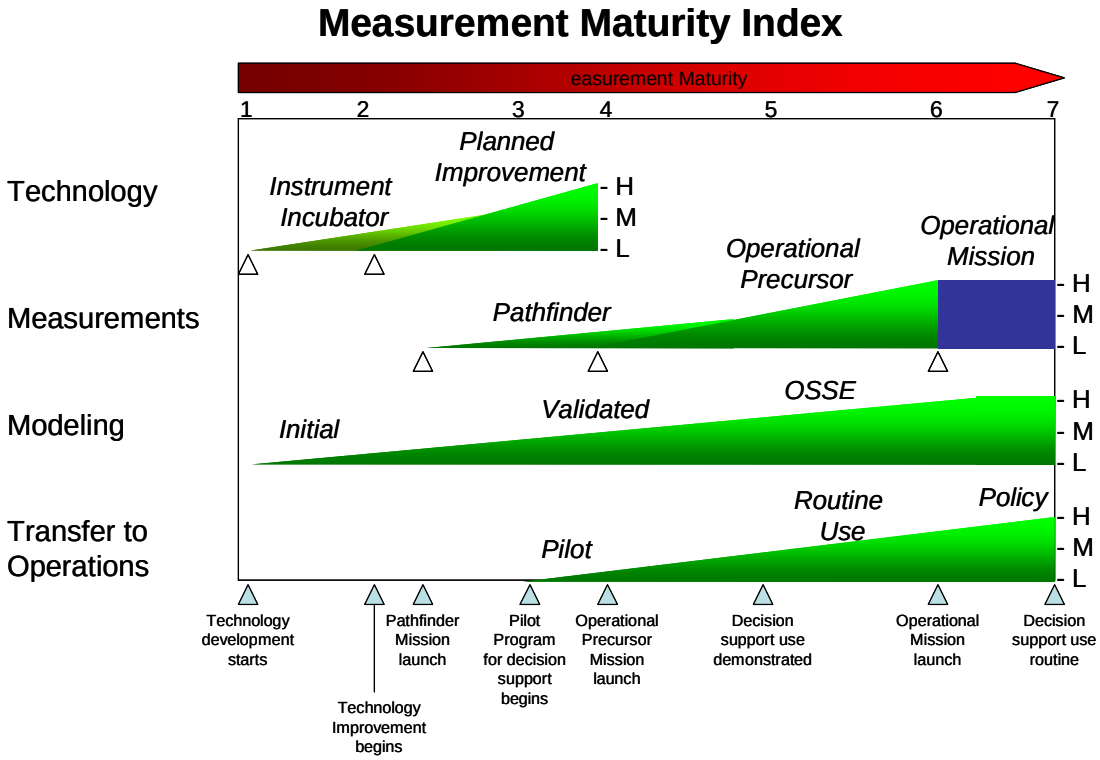



Figure 5: The Measurement Maturity Index and underlying activities that result in advancing maturity for a given measurement.

Note that not all measurements are expected to progress to MMI-level 8 – this will depend on the needs of operational agencies, and our improved understanding of its significance to either science or operational use as each measurement matures.

*The Earth Science and Applications roadmap was formulated by defining pathways and stages across three decades. Careful thought was given to prioritization of investigations, and a new metric - the Measurement Maturity Index - was developed and used by the Committee.*

# 4 Implementation Framework

## 4.1 Time-ordering based on Awareness Clusters

The sequence of the mission clusters is a fundamental aspect of our roadmap that will guide current and future investments. It includes missions throughout that address each of the science goals at any given time. The "cluster" structure is an indication of where NASA should place its organizational focus, but missions in any given science cluster often serve the interests of other science themes. The cluster sequence in our timeline will not be finalized until the National Research Council has completed its decadal survey, and appropriate vetting has been completed, but it was arrived at by examining recent, current, and approved near-term missions, maturity of various measurement concepts, and scientific needs.

The first cluster, Atmospheric Composition, results from the fact that there have been substantial investments recently in this area, suggesting we are already in the Awareness phase. The Climate/Weather follows second, because it flows logically from the atmospheric composition cluster, which will address key issues in the atmospheric aspects of climate and weather. Currently there are important climate missions in the queue. The third cluster, the distribution and transport of water is integrally linked to the atmospheric and climate processes, and there are several approved water-related missions are planned for the 2010 time frame that would catalyze the Water cluster. For these reasons, the ordering of the first three clusters has a clear and rational basis.

The remaining two science areas, Life and Solid Earth, are every bit as important, and the overall success of the Earth Applications from Space Strategic Roadmap would be greatly enhanced if these later clusters could be advanced to an earlier time period, as doing so would maximize the opportunity to examine cross-disciplinary processes and their interactions. However, this would require significantly more resources than the current Earth science budget affords *and* acceleration of the development of technology for active sensors (which both of these science areas rely heavily upon.) The Committee feels, however, that such up-front investments would be well worth making.

As discussed in section 2.2, we have not identified a separate cluster for the role of humans in the Earth system - this is considered a cross-cutting line of inquiry, to which each of the other lines of inquiry contributes.

As a check on our approach to time-ordering of the awareness clusters, the measurement maturity index was evaluated across the suite of measurements applicable to a given line of science inquiry (Table 3). This evaluation is subjective; a more careful examination of current MMI levels and their desired future states across measurement clusters deserves further study.

| Measurements | MMI level (2005) |
|---|---|
| ATMOSPHERIC COMPOSITION AND CLIMATE | |
| Atm Temp Profile | 5 |
| Atm Moisture Profile | 5 |
| Total precipitable water | 8 |
| Cloud Cover & Layers | 5 |
| Cloud Opt Thick & Part Size | 4 |
| Cloud Liquid Water | 3 |
| Cloud Ice Water Path | 3 |
| Atm Wind Profile | |
| Stratosphere | 1 |
| Troposphere (using clouds/water vapor) | 8 |
| Troposphere (using aerosols/molec) | 1 |
| Lightning | 5 |
| Aerosols | |
| Total | 5 |
| Stratosphere | 3 |
| Troposphere | 3 |
| Ozone | |
| Stratosphere | 7 |
| Troposphere | 8 |
| Albedo | 7 |
| Solar Irradiance | 7 |
| Solar UV Irradiance | 7 |
| Energy Balance | 5 |
| Atmospheric Chemistry | |
| Stratospheric Chemistry | 6 |
| Tropospheric Chemistry | 3 |
| Sea Ice Cover | 8 |
| Ice Surface Topography | 4 |
| Sea Ice Thickness | 3 |

| Measurements | MMI level (2005) |
|---|---|
| WATER | |
| Sea Surface Wind | |
| Open Ocean | 6 |
| Coastal | 2 |
| Sea Surface Temp | 8 |
| Sea Surface Topography | 7 |
| Ocean wave height | |
| Open Ocean | 5 |
| Coastal | 2 |
| Net Heat Flux | 3 |
| Ocean Salinity | 3 |
| Ocean Currents & Circulation | |
| Open Ocean | 2 |
| Coastal | 2 |
| Snow Cover | 6 |
| Snow Depth, Water Eq, ... | 3 |
| Freeze/Thaw Transition | 3 |
| River Discharge/Stage Ht | 2 |
| Fresh water availability | 2 |
| Fresh water quality | 2 |
| Precipitation | 5 |
| Soil Moisture | 3 |

| Measurements | MMI level (2005) |
|---|---|
| LIFE | |
| Vegetation Index | 5 |
| Primary Productivity | 4 |
| Land Cover/Land Use | 5 |
| Top & Sub Canopy Biomass | |
| Biomass | 3 |
| Vegetation Structure | 3 |
| Photosynthetic Efficiency | 1 |
| Plant Physiology & Function types | 1 |
| Ocean Color | |
| Open Ocean | 5 |
| Coastal | 5 |
| Ocean Mixed Layer Depth | |
| Open Ocean | 1 |
| Coastal | 1 |
| Ocean Particulate Organics | 3 |
| SOLID EARTH | |
| Land Surface Deformation | 3 |
| Land Surface Topography | 4 |
| Land Surface Composition | 5 |
| Land Surface Temp | 5 |
| Gravity Field | 4 |
| Earth's Magnetic Field | 6 |
| Land Ice Cover & Topography | |
| Ice sheet thickness | 2 |
| Ice mass balance | 4 |
| Ice sheet internal layering | 2 |
| Fires | 3 |

Table 3: MMI evaluations for measurements associated with each line of inquiry; shaded boxes indicate environmental data records (EDRs) which may be produced by NPOESS.

Our interpretation of the results in Tables 3 is that they appear to confirm that we are already in the awareness clusters for atmospheric composition and climate/weather, while we are still in the exploratory stage for life, water and solid earth. Based on the notional timeline we set up in Figure 3, this means that the gap between the land surface deformation and atmospheric temperature profile measurements, for example, is about fifteen years.

## 4.2 Scientific Investigations and Anticipated Achievements by Stage

Table 4 summarizes the anticipated achievements by decadal stage, across all of the science questions. The sections that follow describe the decadal stages and indicate the investigation and notional mission that correspond to the achievements, summarized in the achievement table in the Executive Summary.

### *4.2.1 Stage I: Building a foundation for comprehensive observing and modeling -- Focus on atmospheric composition, climate and weather*

For each of line of science inquiry we have identified a set of achievements arranged by decade. Table 5 shows the relationship between the expected achievements for the first stage, the investigations needed to realize each achievement and the (notional) missions we expect will implement those investigations. Missions are designated by the instrument suite expected to meet the measurement objective and the vantage point (orbit) for the platform. In some cases, we can already anticipate that a mission is expected to make

| | 2005-2015 | 2015-2025 | 2025-2035 & Beyond |
|---|---|---|---|
| Exploration & Discovery | • Accurate assessment of carbon sequestration on land<br>• Time-dependent deformation maps of fault zones, volcanoes, slopes and ice sheets<br>• Comprehensive assessment of changes in ice cover<br>• New opportunities for exploration & discovery | • Characterize water distribution in root zone; improved weather and climate prediction<br>• Major contribution to understanding ocean biosphere<br>• Pathfinder measurement to complement the Terrestrial Planet Finder mission; characterize signatures of life in IR spectra<br>• Quantify the dynamics of Greenland and Antarctic ice sheet motion<br>• New opportunities for exploration & discovery | • Pursuing answers to questions we don't yet know to ask in 2005, enabled by:<br>– Robust, distributed autonomy,<br>– Bio- & nano-technology sensors,<br>– Very large microwave/optical apertures, etc. |
| Continuous Awareness | • Distinguishing anthropogenic and natural aerosols and their effects on climate<br>• Improved understanding of sources of aerosols, long-range transport, ozone variability, & sun-atmosphere interactions.<br>• Comparison with Icesat results; determine ice sheet contribution to sea level to within 0.05 mm/yr<br>• Determine contribution of mesoscale ocean eddies to global energy budget<br>• Understand feedback processes in the Earth's atmosphere consistent with observed time scales of solar variability of total and spectral irradiance<br>• Quantify snow water equivalent, areal extent; water resources planning; links to biogeochemistry<br>• Quantify CO2 flux at all levels in the atmosphere | • Comparison with Icesat results; improve assessments of ice sheet contributions to sea level; determine nature and causes of rapid changes in sea ice<br>• Measurements of tropospheric winds over land & ocean directly for weather forecasts; improve ocean circulation models with wind and surface currents in coastal and open ocean<br>• Quantify cloud feedback in the climate system; enable verification of improved cloud/climate models<br>• Quantify dynamics of surface water storage & availability at monthly and longer timescales; freshwater and flood monitoring and prediction; derived global discharge<br>• Combined with temperatures and models to estimate thermal expansion of the ocean to within 0.05 mm/yr; assess potential for shut-down of dominant circulation patterns; quantify near-surface water storage<br>• Quantify dynamics of subsurface storage; role of groundwater variations in climate; water availability; estimate sea level equivalent stored on land to 0.05 mm/yr<br>• Quantify H2O content of clouds<br>• Quantify 3-D structure of rainfall<br>• Quantify variations in freshwater quality, links to anthropogenic activities, land use and biogeochemistry<br>• Accurate assessment of carbon sequestration, and CO2 drawdown in coastal zones and over global scales<br>• Functional grouping of vegetation on land and algal groups in ocean, to improve estimates of carbon flux<br>• Estimate decadal and interannual carbon flux in vegetation on land<br>• Understanding governing processes of deformation at high spatial/temporal resolution<br>• Detection of volcanic and tectonic activity, land use change<br>• Determine topography and conditions beneath the ice sheet<br>• Improved understanding of the contribution of solid Earth, oceanographic, and hydrological process to gravity field<br>• Improved understanding of short-period variation in the main field, crustal remnant fields, and mantle current-induced fields | • Assessment of plant and algal physiological status and productivity<br>• Linking volcanic and tectonic activity, land use change<br>• Improved global topography and in conjunction with SRTM data first global measurement of topographic change |
| Developing Perspectives | • Insure smooth handoff of operational measurements and accurate calibration of NPOESS observations for science use | • Understanding of "fast" processes like convection and cloud evolution<br>• First daily 3-D global measurements of the Earth's atmosphere and trace gasses<br>• Successful hand-off to operational agency of capability to monitor and predict water vapor and temperature change<br>• Narrow the uncertainties in climate sensitivity for both regional and global climate change. Includes regional cloud feedback and both direct and indirect aerosol forcing | • Soil moisture in forested areas; improved weather and climate prediction; understanding of links with ecology, biogeochemistry<br>• Continuous, global monitoring of rainfall; direct input to climate models and weather tracking/forecasting<br>• Successful hand-off to operational agency of capability to monitor and predict water availability<br>• Short repeat from GEO will provide decision support users knowledge of coastal zone changes in carbon, algal blooms, water quality<br>• Land cover use and change measured at high resolution, relationship to society, natural changes<br>• Rapid access to deforming area of interest globally for forecasting outcomes |
| | • Fully integrated Earth System model to synthesize (assimilate) all observations of the Earth system and predict the evolution of interacting components<br>• Global mesoscale weather models<br>• Climate models resolving weather<br>• Earth System Modeling Framework implemented nationally | • Models and data assimilation systems integral to the observing system and decision support systems, including future mission design<br>• Evolve technologies, observations, models, & knowledge systems for science & operational systems | • Fully integrated Earth System model and assimilation system with data distribution portals for simple high speed access to all aspects of the Earth System<br>• Continue to evolve technologies, observations, models, & knowledge systems for science & operational systems |

Table 4: Roadmap achievements arranged by decade and by integration objectives

more than one measurement. Such missions are indicated by a number of blue dots in the mission column entry in Table 5. The aerosols mission, for example, is expected to achieve both aerosol objectives while also measuring high-resolution $CO_2$. Whether the investigation addresses an exploration, awareness, or perspective achievement is indicated by the background color in each row.

Table 5 lists the *known* achievements we can expect in this decade. We also want to leave room for the *unknown*: exploratory missions that address new areas of science or are enabled by breakthroughs in technology. We believe this was the original intent behind the ESSP program and recommend NASA return to that intent.

| Line of inquiry | Investigation | Notional Mission | Achievement |
|---|---|---|---|
| Atmos. Comp. | Aerosols impact on climate through clouds, anthropogenic additions | Multi-angle spectropolarimetric imaging; 3-D aerosol profiling (LEO) • | Distinguishing anthropogenic and natural aerosols and their effects on climate |
| | Global atmospheric composition | UV/Vis/NIR imaging (Sentinel Orbit, L1 or GEO) • • | Improved understanding of sources of aerosols, long-range transport, ozone variability, & sun-atmosphere interactions. |
| | Atmospheric composition (Cal/Val) | Cal/Val Free-flyer (LEO) | Insure smooth handoff of operational measurements and accurate calibration of NPOESS observations for science use |
| Climate/ Weather | Ice elevation changes / sea-ice thickness | High-resolution ice altimetry (LEO) | Comparison with Icesat results; determine ice sheet contributions to sea level to within 0.05 mm/yr |
| | Ocean circulation | 3-D ocean altimetry (LEO) | Determine contribution of mesoscale ocean eddies to global energy budget |
| | Solar influence on climate | Hyperspectral imaging instrument for solar UV, EUV, X-rays (L1) • • | Understand feedback processes in the Earth's atmosphere consistent with observed time scales of solar variability of total and spectral irradiance |
| | Climate Data Records (Cal/Val) | Cal/Val Free-flyer (LEO) | Insure smooth handoff of operational measurements and accurate calibration of NPOESS observations for science use |
| Water | Snow-water distribution | SAR and/or passive microwave (LEO) | Quantify snow water equivalent, areal extent; water resources planning; links to biogeochemistry |
| Life | Biomass and Vegetation Structure | Combined 3-D structure and multispectral imaging (e.g., radar, lidar & multispectral Visible imager) (LEO) • • • | First accurate assessment of carbon sequestration on land |
| | High-resolution CO2 | 3-D laser profiling (LEO) • | Quantify $CO_2$ flux at all levels in the atmosphere |
| Solid Earth | Rates of change of surface positions and strains | Precision geodetic imaging (e.g., L-band InSAR) (LEO) | Time-dependent deformation maps of fault zones, volcanoes, slopes and ice sheets; comprehensive assessment of changes in ice cover |

Table 5: Stage I achievements for each line of inquiry mapped to scientific investigations and missions for the first decade. Background color indicates whether the investigation objective is predominantly exploration (green), awareness (yellow), or perspective (red). Blue dots indicate dual-purpose missions.

| Line of inquiry | Investigation | Notional Mission | Achievement |
|---|---|---|---|
| Atmos. Comp. | Behavior of water vapor, clouds, aerosols, and ozone in the upper troposphere | Wide-swatch microwave 3-D sounding (e.g., nadir and limb) (MEO) | Understanding of "fast" processes like convection and cloud evolution |
| | Global greenhouse gas distribution and change | Continuous, spectrally resolved Solar occultation (L2) | First daily 3-D global measurements of the Earth's atmosphere and trace gasses |
| Climate/ Weather | Ice Elevation Changes/Sea Ice Thickness | High-resolution ice altimetry (LEO) • | Comparison with Icesat results; improve assessments of ice sheet contributions to sea level; determine nature and causes of rapid changes in sea ice |
| | Ice Sheet Thickness/Bottom Topography | Ice penetrating radar (LEO) • | Quantify the dynamics of Greenland and Antarctic ice sheet motion |
| | Global tropospheric winds | Combined ocean surface/ lower atmosphere winds (LEO) | Measurements of tropospheric winds over land & ocean directly for weather forecasts; improve ocean circulation models with wind and surface currents in coastal and open ocean |
| | Cloud Feedback | 3-D clouds -- Cloudsat-Calipso follow-on (LEO) | Quantify cloud feedback in the climate system; enable verification of improved cloud/climate models. |
| | Temperature/Humidity Change | Cal/Val instruments for NPOESS follow-on (LEO) | Successful hand-off to operational agency of capability to monitor and predict water vapor and temperature change |
| | 3-D cloud microphysics and aerosol distribution | Wide-swath 3-D cloud and aerosol profiling (LEO) | Narrow the uncertainties in climate sensitivity for both regional and global climate change. Includes regional cloud feedback and both direct and indirect aerosol forcing |
| Water | Rivers, wetlands, surface water storage | Precision/ interferometric altimetry (LEO) | Quantify dynamics of surface water storage and availability at monthly and longer timescales; freshwater, flood monitoring, and prediction; derived global discharge |
| | Ocean salinity/soil moisture | Microwave radar/ radiometry - Aquarius/ Hydros follow-on (LEO) | Combined with temperatures and models to estimate thermal expansion of the ocean to within 0.05 mm/yr; assess potential for shut-down of dominant circulation patterns; quantify near-surface water storage |
| | Groundwater storage | Time-variable gravity – GRACE follow-on (LEO) • • | Quantify dynamics of subsurface storage; role of groundwater variations in climate; water availability; estimate sea level equivalent stored on land to 0.05 mm/yr |
| | Cloud water, ice content and distribution | 3-D profiling -- Cloudsat-Calipso follow-on (LEO) | Quantify H2O content of clouds |
| | Rain process/ distribution | 3-D rain profiling (LEO) | Quantify 3-D structure of rainfall |
| | Water quality | Hyperpectral imaging (LEO) | Quantify variations in freshwater quality, links to anthropogenic activities, land use and biogeochemistry |
| | Root zone soil moisture | Ground penetrating active microwave (LEO) | characterize water distribution in root zone; improved weather and climate prediction |
| Life | Changes in dissolved organic and inorganic carbon pools for long-term storage of ocean carbon | High performance ocean color imaging (UV/Vis/NIR) (LEO or GEO), supporting sea surface temperature and salinity measurements. | Accurate assessment of carbon sequestration, and CO2 drawdown in coastal zones and over global scales |
| | Ocean particle profile and mixed layer depth | Upper ocean profiling (e.g., via blue/green lidar) (LEO) | Major contribution to understanding ocean biosphere |
| | Biosignatures of life | Hyperspectral imager (GEO or L1) | Pathfinder measurement to complement the Terrestrial Planet Finder mission; characterize signatures of life in IR spectra |
| | Plant functional groups on land and in ocean | High performance hyperspectral UV/Vis/NIR imaging (LEO or GEO) | Functional grouping of vegetation on land and algal groups in ocean, to improve model estimates of carbon flux |
| | Biomass Dynamics | Combined 3-D structure and multispectral imaging (e.g., radar, lidar, & multispectral Visible imaging) (LEO) | Estimate decadal and interannual carbon flux in vegetation on land |
| Solid Earth | Rates of change of surface positions and strains | Frequent, precision geodetic imaging (MEO constellation) | Understanding governing processes of deformation at high spatial/temporal resolution |
| | Ice Elevation/Thickness | Ice penetrating radar (LEO) • | Determine topography and conditions beneath the ice sheet |
| | Time-varying global gravity field | Time-variable gravity – GRACE follow-on (LEO) • • | Improved understanding of the contribution of solid Earth, oceanographic, and hydrological process to gravity field |
| | Time-varying global magnetic field | Distributed magnetometry (e.g., 12-sat constellation, LEO, 300-800 km, low-inclination & polar orbits) | Improved understanding of short-period variation in the main field, crustal remnant fields, and mantle current-induced fields |

Table 6: Stage II achievements for each line of inquiry mapped to scientific investigations and missions for the second decade. Background color indicates whether the investigation objective is predominantly exploration (green), awareness (yellow), or perspective (red). Blue dots indicate dual-purpose missions.

### *4.2.2 Stage II: Extending our view of Earth and reach into society -- Focus on water, life and solid earth*

Table 6 shows the relationship between the expected achievements for this second stage, the investigations needed to realize each achievement, and the missions we expect will implement those investigations. Whether the investigation addresses an exploration,

awareness or perspective achievement is again indicated by the background color in each row. We will also leave room for true exploratory missions in this decade to open up new areas of science or take advantage of breakthroughs in technology.

### *4.2.3 Stage III: Fully instrumented Earth system networked to predictive models serving science and decision makers – Focus on new science questions and lines of inquiry*

Stage III will result in an integrated, comprehensive and sustained "information web" for Planet Earth, the U.S. Integrated Earth Observation System (IEOS). NASA's role within the IEOS will be to continue to pursue new science questions and to investigate aspects of the Earth system that we have not yet explored. Table 7 shows the relationship between the expected achievements for this third stage, the investigations needed to realize each achievement and the missions we expect will implement those investigations. Whether the investigation addresses an exploration, awareness, or perspective achievement is indicated by the background color in each row. We will also leave room for true exploratory missions in this decade to open up new areas of science or take advantage of breakthroughs in technology. Although this table lists no entries for atmospheric composition or climate and weather lines of inquiry, we fully expect that new technologies and new science questions will open up new investigations, missions, and achievements for these areas, as well as lead to new lines of inquiry.

| | **Investigation** | **Notional Mission** | **Achievement** |
|---|---|---|---|
| **Water** | Global soil moisture | Passive/ active microwave (MEO) | Soil moisture in forested areas; improved weather and climate prediction; understanding of links with ecology, biogeochemistry |
| | Global precipitation | Active/ passive microwave (3 GEO) | Continuous, global monitoring of rainfall; direct input to climate models and weather tracking/forecasting |
| | Fresh Water Availability (Cal/Val mission) | Cal/Val instruments for NPOESS follow-on | Successful hand-off to operational agency of capability to monitor and predict water availability |
| **Life** | Changes in dissolved organic and inorganic carbon pools for long-term storage of ocean carbon | High performance ocean color imager (UV/Vis/NIR) (GEO); supporting sea surface temperature and salinity measurements. | Short repeat from GEO will provide decision support users knowledge of coastal zone changes in carbon, algal blooms, water quality |
| | Advanced land cover changes | Hyperspectral UVVis/NIR imaging (LEO) | Land cover use and change measured at high resolution, relationship to society, natural changes |
| | Photosynthetic efficiency | Combined 3-D structure and multispectral imaging (e.g., lidar and multispectral Vis imaging) (LEO) | Assessment of plant and algal physiological status and productivity |
| **Solid Earth** | Rates of change of surface positions and strains | High temporal resolution geodetic imaging (GEO) | Rapid access to deforming area of interest globally for forecasting outcomes |
| | Earth's surface thermal changes | Multispectral imaging in thermal IR (LEO) | Linking volcanic and tectonic activity, land use change |
| | High resolution global land topography | 3-D land structure (e.g., Lidar and/or InSAR) (LEO) | Improved global topography and in conjunction with SRTM data first global measurement of topographic change |

Table 7: Stage III achievements for each line of inquiry mapped to scientific investigations and missions for the third decade. Background color indicates whether the investigation objective is predominantly exploration (green), awareness (yellow), or perspective (red).

## 4.3 Modeling & Data Management

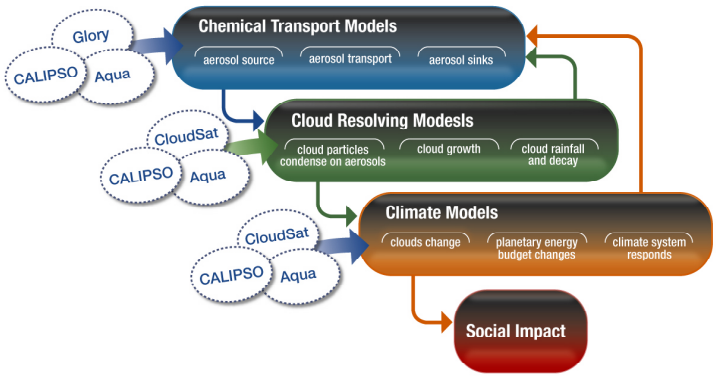
### *4.3.1 Modeling*

A recent Nature editorial (Nature, 5 May 2005, v. 435) posed the question: "What is the difference between a live cat and a dead one? A dead cat is a collection of its component parts. A live cat is the emergent behavior of the system incorporating those parts." The editorial was describing the pursuit of systems biology, but the same analogy can be applied to Earth System Science. While it is important to understand the individual components or disciplines, it is the interaction of those disciplines that determines the functioning of the complete Earth System. "The technical wizardry of the *Earth Observations* and the attendant vast data sets obtained are only part of the *Earth* system approach – a system is not fully understood until a quantitative model can be built."

NASA makes space based and ancillary observations not simply to demonstrate technology, but to address specific gaps in our knowledge and to reduce uncertainty. The modeling system, which assimilates the disparate observations, provides the critical link between the raw measurements and the ability make the complex information readily available to the community and to improve decision support tools used by the operational agencies. Those tools in turn inform policy and management decisions. Easy, intuitive access to the data and model output allow "what if" type queries to inspire both the general public and the next generation of scientists and engineers.

Assimilation is fundamental to the Earth System modeling effort. Because there will be completely new and novel observations, and increasing amounts and frequency of data, assimilation will be one of the major challenges and it will require a focused research effort.

Once a model is developed and verified against observations, it should be used in the first step of identifying and prioritizing new observation systems. The model in turn, through the use of simulated observations using OSSE's (Observation System Simulation Experiments), can be used to determine the impact of a particular observation on improving model predictions. Determining the sensitivity of the prediction to the simulated measurement can help prioritize the technology investments for new space missions.

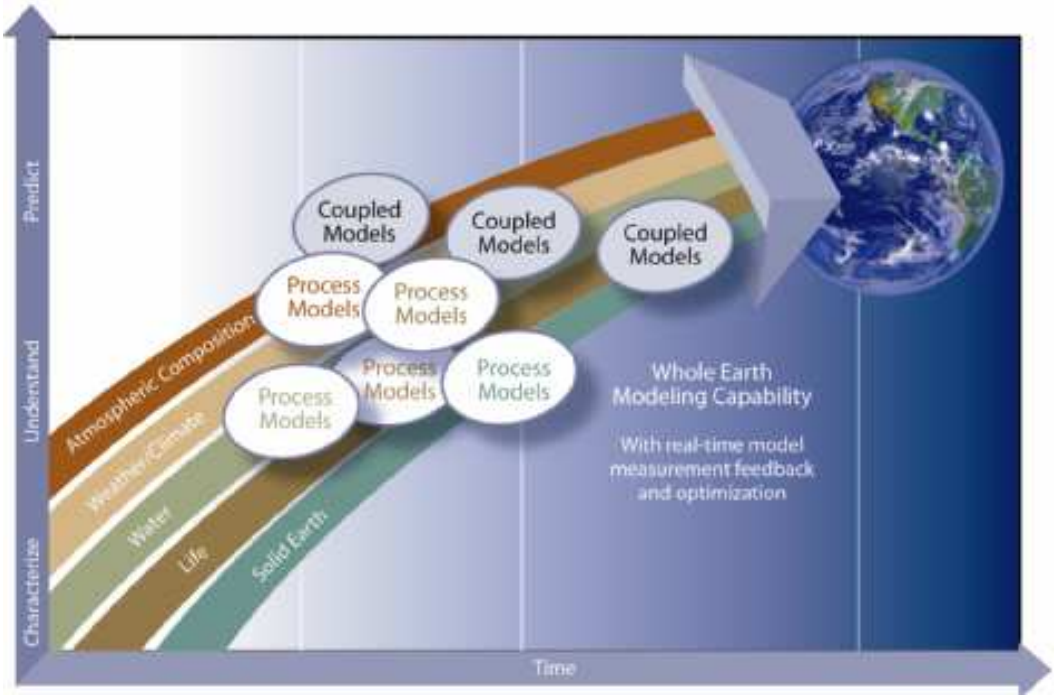



New approaches using multi-scale and multi-discipline modeling solve key climate challenges (those with largest climate uncertainty)

The idealized end-state for Earth System Science is to have a systems approach that observes all key Earth system variables and assimilate that information into a framework

of integrated, interacting models that include each of the major subsystems: oceans, atmosphere, cryosphere, biosphere and solid Earth. This system will provide quantitative predictive capability that will continually be evaluated against the observations. Together with their partners, NASA will enable a robust Earth system predictive capability that represents the community consensus of current knowledge.

New discovery observations will illuminate completely new processes, which will continually provide a challenge to the modelers to understand and assimilate. Continuous awareness will provide data on time scales and comprehensiveness never before seen that will challenge the ability of the modelers to keep pace with the physics, mathematics and assimilation techniques required. For developing perspectives a key will be rigorously defining the observation requirements for absolute accuracy, long-term stability and precision as a function of the observation variable, time scale and space scale. Included in such a requirement is the ability to prioritize the impact of an observable on constraining the accuracy of the desired prediction.




Accomplishing this end-state of a fully integrated Earth system model will require the infrastructure with the necessary high end computing capability and software engineering and visualization environments. This is more fully discussed in the Advanced Modeling, Simulation and Analysis Capability Roadmap 14. Also critical is the concept of an Earth System Modeling Framework (ESMF) that will allow the necessary multi-agency, multi-national effort. Each building block of the integrated model must be built and tested in a community-modeling environment in which multiple models operate and 'learn' from each other. Based on this, a consensus model will emerge, representing the mean state of the model space. The competing models will continue to evolve, based on the stream of observations and model evaluations; the consensus model will be periodically updated,

based on these evaluations. There will still be a spectrum of effort from pure research to "operational" prediction. In such a community-modeling environment, paradoxes and unexplained phenomena will emerge, focusing research efforts on the highest payoff questions. An ESMF, such as described here, can only be developed by a large consortium of international partners, US agencies and academic partners.

Because such large, complex model and data assimilation systems are much larger and more expensive than what a single researcher, or even a handful can do, they should be considered as 'missions' in themselves, including technology development (for example, the Earth System Modeling Framework, software to couple models developed by different groups or multiprocessor hardware with extremely fast communications among processors), system engineering to ensure that components provided by commercial vendors and different scientists work well together, data management to ensure that many outsiders can study the results, etc. It is estimated that the required infrastructure support will be equivalent on an annual basis to that of a small satellite mission. The goal cannot be accomplished by simply stripping off a portion of the satellite mission budgets as has been done in the past.

The Capability Roadmap 14 describes 3 levels of investment. Level 1 is a minimal, but expanded investment, where MS&A (modeling, simulation and analysis) capabilities are developed on a highly focused and near-term schedule to expand the applications base. Level 2 represents the lowest level of investment in which integration is fostered and developed for use across the agency. Level 3 represents the highest investment level over the longest time period having the greatest benefit. Significant MS&A systems are developed in which distinctions among science, engineering and operations are diminished and involves outside agencies beyond NASA. The recommendation of the Capability Roadmap team varies between 0.5% of the program (in this case Earth Science) budget for a minimal, "Level 1" investment to 2% to satisfy up to the "Level 3" investment.

| Accomplishments | | | |
|---|---|---|---|
| 2005 | 2015 | 2025 | 2035 |
| • Coupled global climate models – 1 deg resolution<br>• Earth System Modeling Framework implemented<br>• Global mesoscale weather models<br>• Weather forecasts improved by use of satellite data (AIRS, MODIS) | • Fully integrated Earth System model to synthesize (assimilate) all observations of the Earth system and predict the evolution of interacting components<br>• Climate models resolving weather<br>• Earth System Modeling Framework implemented nationally | • Models and data assimilation systems integral to the observing system and decision support systems, including future mission design | • Fully integrated Earth System model and assimilation system with data distribution portals for simple high speed access to all aspects of the Earth System |
| Required Infrastructure | | | |
| Dedicated Network<br>(1 Gb/s sustained)<br>Performance<br>(1-50 TeraFLOPS)<br>Memory<br>(40 GB) | Dedicated Network<br>(100's Gb/s sustained)<br>Performance<br>(PetaFLOPS)<br>Memory<br>(5 TB) | Dedicated Network<br>(10 Tb/s sustained)<br>Performance<br>(100's of PetaFLOPS)<br>Memory<br>(1 PB) | Dedicated Network<br>(100's Tb to Pb/s sustained)<br>Performance<br>(1000 PetaFLOPS)<br>Memory<br>(100's PB) |

Modeling accomplishments and required infrastructure by decade

### *4.3.2 Data Management and Data Stewardship*

The goal of data management for an Earth Information System is to get the fruits of the NASA and international investments in Earth observations and modeling into forms that can readily be used by scientists, decision makers, and the general public. With easy, high speed access to the wide range of Earth Science information, users should be inspired to ask their own "what if" types of questions. There is a significant effort in the basic needs for defining data formats, storage media, long term storage plans, etc. But the real utility in data management is getting the appropriate Earth System information into the hands of those that need it.

Earth observation and model results will be developed by a diverse set of national and international systems. Observations will be acquired by international constellations of satellites, such as the currently operating "A-Train." Key considerations will be the capability to access information from non-NASA observing and modeling systems, and the national and international investments in the capacity to move large volumes of data, such as the National Lambda-Rail, a major initiative of U.S. research universities and private sector technology companies to provide a national scale infrastructure for research and experimentation in networking technologies and applications.

Observations must be organized in appropriate data format so that they can be used by models. Each data set must be vetted in the issues of data stewardship, data formatting, and data management.

Data stewardship consists of the application of rigorous analyses and oversight to ensure that data sets meet the needs of users. Data stewardship can be categorized into two primary areas: observing system performance monitoring and the development of homogeneous time series, where the adjective homogeneous is used to indicate the removal of changes in the time series that may have arisen for reasons unrelated to Earth system changes. These are important steps for creating Climate Data Records (CDR) which are used to perform detection and attribution studies of changes in the earth systems. This is particularly important in the context of long-term changes since most measurement missions last for several years while information is needed to detect changes in the multi-decade to century time scales.

Data management also includes data services, data access and visualization, data collection, long term data archiving, and data inventories. It is important to plan the strategy keeping in mind the goal of developing the system of systems. The ultimate goal is to have an integrated system, but at the same time, people should be able to query the system and get the answer they need.

There should be a clearly defined path whereby the NASA research and development observation and model results would get to the operational agencies with responsibilities for specific Earth system aspects and national applications. The key is the difficult and complex interface between the raw observations and model output and the information that can be useful to decision makers, from major national and international policy

decisions, to casual decisions by the general public. Models and data visualization tools are important components in extracting the information into useful forms.

#### *4.3.3 Relation to Objectives/Stages/Pathways*

Models and measurements must be at matching levels of maturity if the clustering approach recommended in this roadmap is to succeed. Requirements for modeling and data management for each stage need further definition, so NASA can allocate appropriate levels of resources to these activities.

#### *4.3.4 Transition to operations.*

Given its role as a research and development agency, NASA will facilitate integration by operational agencies through merging and coordinating the Earth System modeling objectives from many organizations. The result will ensure that validated Earth system predictions are delivered in a timely manner and in a usable form. Through its systems analysis, engineering, and international leadership NASA can provide the breakthrough scientific missions and modeling efforts that, through partnerships, can be transitioned to Operational agencies at the appropriate time.

*The ultimate goal is to have high bandwidth, universal access to Earth System information that is available via an easily queried Earth System portal, Imagine a map- or globe-based query system where scientists, educators and policy-makers can obtain up-to-the-minute information about specific locations or regions of the planet, and can compare it to information from the past.*

### 4.4 Decision Criteria

The decision points for this roadmap will be determined at decadal reviews of the program by the National Research Council. We expect that our successors will have to answer tough questions about the current and future program at each decision point. At the transition points between stages (both I to II, and II to III), there will be common evaluations to make.

Typical decision questions may be:

- What new lines of inquiry have been opened up by the discoveries we have made?
- Are each of the themes currently categorized appropriately in their phases of Exploration, Continuous Awareness, and Perspectives?
    - Have the current clusters made the expected scientific and technical progress?
    - When appropriate, have the partnerships and planning for the transition from research to operations made the expected progress?
    - Have society's priorities shifted, and what are the implications for the ordering of our clusters?
- What missions have slipped in our projected timeline and how does that affect our clustering and future mission choices?

- Have technologies evolved that enable unanticipated yet much needed measurement capabilities?
- What other opportunities/partnerships have arisen that may modify priority or alter implementation constraints?

At the transition point between stages I and II the specific questions we might anticipate asking may focus on specific mission status and scientific justification. For example, by around 2015, will the atmospheric chemistry flagship mission have been launched and preparing measurements for handover to NOAA? A corollary is then to ask, if that mission is successful, what other missions must be flown to calibrate for/handoff to the NPOESS follow-on in 2025? NASA will also need to prioritize based on technological and scientific maturity. When entering Stage II, is the Water cycle (the next planned cluster) prepared to enter the multimission continuous awareness decade?

As our knowledge of the Earth system advances, we expect that the maturity of our questions will also. At the transition point between stages II and III the kind of questions we might anticipate asking include whether it is possible to handoff or plan handoff of Water cycle, Life cycle and/or Solid Earth measurements to an operational partner? If during Stage II many atmospheric composition measurements are being maintained by NOAA, what are the next generation exploration measurements? Society will have changed in the next two decades and may expect NASA to take a more active role in monitoring efforts to mitigate climate change. Given the strong program emphasis for solid Earth surface deformation, by the beginning of Stage III have we shown predictive capability for earthquakes, volcanoes, and other events with InSAR data?

The results of answering these questions will result in an evolving program and mission timelines, as illustrated in section 4.6.

## 4.5 The Roadmap Timeline

The timeline developed for this roadmap (Figure 6) shows the five lines of science inquiry with investigations laid out on each, shown as diamonds on the line. Each diamond represents the launch of a mission designed to implement that investigation. To relate an investigation to a specific mission, refer to Tables 5-7. To develop the roadmap, we assumed a balanced portfolio of missions, including small, medium, large and flagship classes. Larger diamonds are intended to represent investigations so challenging or critical to a given line of inquiry that they warrant a flagship mission. Missions already selected for flight before 2010 are indicated as white diamonds on the timeline. A sixth track shows the line of exploratory investigations to open up new lines of science inquiry or to take advantage of breakthroughs in technology.

Overlaid on top of each line of inquiry is a representation of the Exploration, Awareness, and Perspectives mission timeline. This is intended to indicate time periods when spaceborne measurements take place, mapped against each of our three strategic integration objectives. The diamond representing each investigation is also colored to distinguish whether it corresponds to an Exploration, Awareness or Perspectives activity.

[Note that other activities critical to the success of this roadmap, such as technology development, modeling, data management, and research and analysis, are not depicted on Figure 6.] Thus Exploration investigations (green) occur most frequently at the beginning of a line of inquiry, but may continue almost to the end if important discoveries are made. Awareness investigations (yellow) start at the beginning of an "awareness cluster" on each line of inquiry and are concentrated in the middle of the timeline. Perspectives investigations (red) occur relatively late on the timeline, and are targeted at handing off from research to operations.

One mission in 2013 serves a dual role in meeting the investigation needs of both the atmospheric composition line and the climate/weather line. It is also tagged as a joint mission on the SRM 10 (Sun-Earth System) timeline. In the 2010 – 2020 timeframe, we have identified several other instances where it is already clear that more than one investigation can be served by a single mission, as indicated by the blue dots in Tables 5 and 6. The secondary investigation(s) appear in Figure 6 as "ghosted" diamond symbols with gray text. To identify other examples of dual-purpose missions, and partnership arrangements, so that this roadmap can be implemented in the most cost-effective way, requires that a vigorous and continuous Earth science advanced studies activity be reinstated without delay.

Figure 6 does not try to represent the connections to specific launch dates of relevant missions by NASA's operational partners [with a few near-term exceptions, such as the white diamond representing the launch of the Operational Land Imager (OLI) on the National Polar Orbiting Environmental Satellite System (NPOESS) to fulfill the requirements of the Landsat Data Continuity Mission (LDCM)]. The transition of research capabilities to operational missions that are off this timeline is represented by blue arrows. Placement is not intended to indicate that these transitions only occur at the end of a focused investigation. Green arrows along each line of inquiry indicate that a new line of inquiry has opened up through discovery; again, this could occur at any point along the timeline, not just at the end.

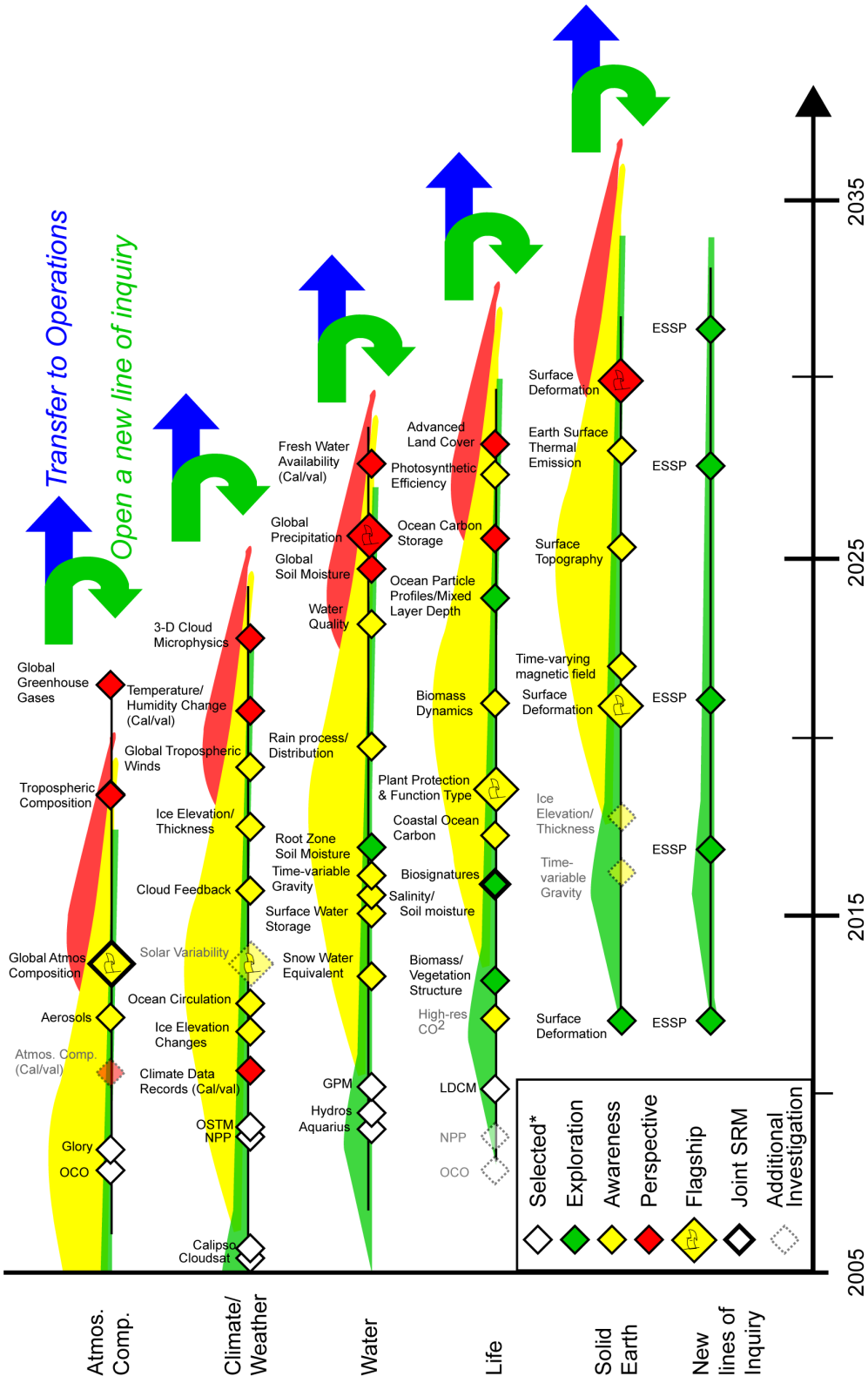



Figure 6: The Earth Science and Applications Roadmap, showing missions laid out along each line of science inquiry in priority order.

## 4.6 Summary of Key Program Milestones, Options, & Decision Points

Flexibility is a critical component of this roadmap. As expected with any visionary roadmap over a 30-year timeframe, changes are expected, especially in the out years. The overall goal of the roadmap is to develop a logical framework for evaluating programmatic and mission-oriented decision, and then to present the current scenario and best-estimate projections over the next three decades. Built into the roadmap is the opportunity for change due to natural evolution of the program or unexpected developments

NASA may reevaluate the entire program, a science theme, or a specific mission at any time. These decision points may include Decadal Reviews and impacting events, such as a scientific discovery, funding changes, or new programmatic direction. As illustrated in various scenarios in Figure 7, decision point changes may result in new lines of scientific inquiry, extended program lifetimes, reordering of mission launches or clusters, refocused missions and research.

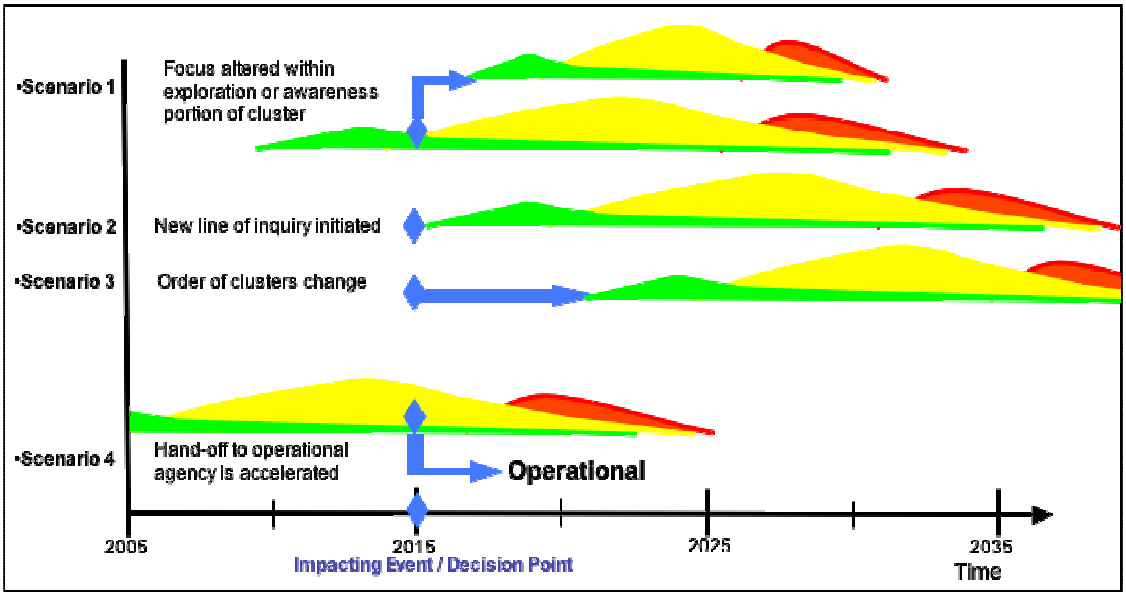



Figure 7: Roadmap timeline flexibility is illustrated with sample scenarios of changes that impact the emphasis, timing, and priority of science clusters.

Key program milestones are the Decadal Reviews between Stages I and II (in 2015), and Stages II and III (2025). As discussed in section 3.4, NASA and the broader Earth science community will need to evaluate the effectiveness of all aspects of the program to date. Have transition to operation goals been met? How have new discoveries changed the prioritization criteria previously defined? At each of these Decadal reviews, NASA has many options to reconfigure the program while still maintaining the long-term structural goals. The Decadal Reviews will have many similar judgments to evaluate on the program, as well as timeline-specific evaluations: in 2015 is the Water Cycle Continuous Awareness cluster ready to be implemented? In 2025 has Life and Carbon Cycle

measurements reached a high enough maturity level to transition to operations? Decadal Reviews will also be the appropriate time to adjust the roadmap to reflect evolution of non-NASA agencies. If NOAA or another operational agency has realized the usefulness of a particular NASA measurement for decision support, the program may accelerate mission launches to enable a swifter transition to operations (Scenario 4, Figure 7)

The Earth Science program must be responsive on shorter timescales than decadal reviews as well, particularly to radical changes in scientific knowledge or technological capability, both within the Earth sciences as well as outside their direct fields, but which may impact national interests.

As science clusters progress through an estimated 25-year lifecycle and the emphasis shifts from primarily exploration to transitional operations and long-term perspectives on processes, it is likely that exciting and unpredicted discoveries will revolutionize our understanding and demand major changes in the 30-year plan. New lines of inquiry can be initiated at any time to refocus resources on these opportunities.

Successful implementation of any science roadmap will include evaluation as to whether specific science goals have been met. One scenario is that the measurement maturity index (MMI) level be used as a metric for planning scientific progress and assessing the balance of a portfolio of investigations. For specific missions there should be an MMI goal to be achieved. In this way, we can evaluate the effectiveness of a mission and the balance of the program. For example, in the Climate/Weather line of inquiry, a mission to study Cloud structure and feedbacks in 2016 will be an evolution from the "exploratory" Cloudsat and Calipso missions (MMI 3). The mission and related "awareness cluster" activities should realize an increase in MMI level to 6. Then, a requirement of the 'perspectives' 3-D Cloud Microphysics mission in 2022 should be to reach MMI-7, which indicates proven usefulness for decision support systems and readiness for transfer to of the capability to an operational agency.

In order to keep the roadmap as current and responsive as possible, it is recommended that NASA work with the Earth science community to implement highly-focused roadmapping activities every three years to stay abreast of changes between NRC Decadal Reviews.

Nearly all of NASA's Earth science and applications from space missions have substantial international participation, ranging from simple data sharing arrangements to ground validation to provision of instruments, satellite buses and launch services for space missions. Careful consideration should be given to this within the context of the GEOSS as this roadmap is implemented.

*Successful implementation of this roadmap will require a balanced, carefully planned program of missions of several classes, research, modeling and data management.*

# 5 Most Critical Inter-Roadmap Dependencies, Technical Capabilities and Infrastructure

In this section we summarize linkages between this roadmap and other strategic and capability roadmaps. We also address the infrastructure needs to implement the roadmap.

## 5.1 Strategic Linkages

Perhaps the ***strongest links*** to other strategic roadmaps ***are those objectives shared with the Sun-Solar System Connection Roadmap (SRM 10)***. Determining the cause of changes in Earth's climate through joint investigation of the effects of solar variability on Earth's climate and upper atmospheric chemistry dynamics is a high priority objective for both roadmaps. In addition, joint efforts to predict solar variability and local space weather in order to mitigate impacts on society are highly desired.

Other synergistic linkages exist in the area of planetary models (e.g. geophysical models, atmospheric models, etc.), understanding the signatures of life in the spectra of life-sustaining planets (SRM 4), and in studying extreme environments with the Mars and Solar System Exploration Roadmaps (SRMs 2 and 3, respectively). ***Understanding the shared geology and formation of the Earth-Moon system*** is another synergistic research area between this roadmap and the lunar roadmap (SRM 1).

Finally, aerospace innovation for a new generation of platforms in support of NASA's Earth science related measurements is highly desirable and provides a natural link to the Aeronautics technology roadmap (SRM 11).

The following table and Figure 8 summarize the linkages to other strategic roadmaps.

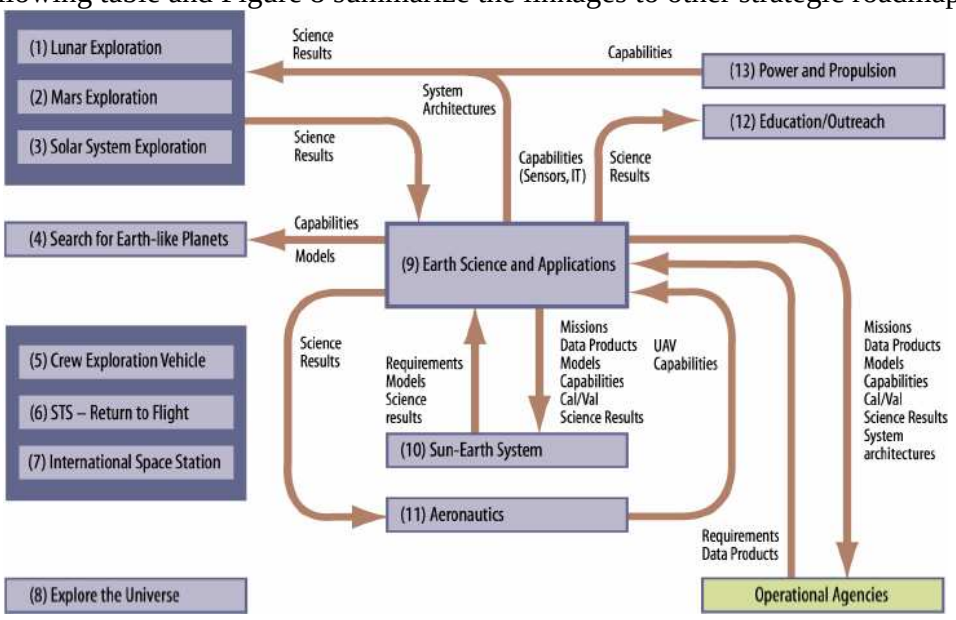



Figure 8: The Earth science roadmap shares common interests with several others.

| Strategic Roadmap | Title | Linkage Type | Description | Related Roadmap Events | Timeline |
|---|---|---|---|---|---|
| 1. Lunar Exploration | Understanding the shared geology and formation of the Earth and the Moon | Enhancing | Earth/Moon formation, early history (esp. before the oldest rocks found on Earth), bombardment record, and other shared events. The moon is a "witness plate" to the environment in which life on the Earth arose and evolved. | TBD - RM interim report not available | TBD - RM interim report not available |
| 2. Mars Exploration | Planetary Models | Synergistic | Models developed for Earth have application to those developed for Mars and other terrestrial planets. This would include seismic models, geophysical models, meteorological models, atmospheric models, climate models, etc. | Earth and Mars investigations in the first time frame of both roadmaps | 2005-2015 |
| 2. Mars Exploration | Understanding extreme environments | Synergistic | Mars has spectacular features that offer extremes compared to Earth, such as topography and dust storms. Analog sites on Earth can provide remote sensing opportunities for understanding images from Mars. | Related to investigations in the "Discovery" objective of Earth roadmap | 2005-2015 |
| 1. Lunar Exploration &2. Mars Exploration & 3. Solar System Exploration | Common Remote Sensing Instrumentation, Modeling and Data Analysis Infrastructure | Enhancing | Earth science approaches and capabilities for measurement, processing of scientific data, and advanced modeling techniques related to data interoperability, can benefit Lunar, Mars and other planetary sciences, and increase scientific return and discovery, prediction, and decision making process. | Missions in Sr 9 centered on Solid Earth, Life, Climate/Weather, Atmosphere | All |
| 4. Earth-Like Planet | Understanding Earth as example of terrestrial planet | Synergistic | Enhanced understanding of biomakers - detecting signature of life in the spectra of life sustaining planets | Related to Life missions in the Earth roadmap and Planet Characterization missions in the Earth-like planet roadmap | 2015-2025 |
| 10. Sun-Solar System Connection | Understanding changes in Earth's climate | Enhancing | Joint investigation of the effects of solar variability on Earth's climate and upper atmospheric chemistry dynamics include understanding of radiative forcing processes, energy input from dynamic magnetosphere, and solar energetic particle input | Complementary or joint upper atmospheric missions (e.g. joint mission at L1) | 2015-2025; 2025-2035 |
| 10. Sun-Solar System Connection | Understanding ozone depletion | Enhancing | Joint efforts to understand ozone depletion in the polar winter night as a result of energetic particle precipitation | Complementary or joint upper atmospheric missions | 2015-2025 |
| 10. Sun-Solar System Connection | Understanding and Mitigating societal impacts of solar variability | Enhancing | Joint efforts to predict solar variability and local space weather in order to mitigate impacts on society (e.g. communications, power grids, and air traffic routing). Specification aides in evaluating and correlating identified impacts with space weather, while future prediction capabilities will enable impact avoidance and/or mitigation. | Complementary or joint modeling and assimilation programs for end-to-end integration of Earth-Sun system | All |
| 11. Aeronautics Technology | Uninhabited Aerial Vehicle (UAV) Development | Enhancing | Aerospace innovation for a new generation of platforms in support of NASA's end-to-end science strategy | Related to Atmospheric measurements in the Earth roadmap | 2005-2015 |

## 5.2 Capability Roadmaps

The implementation of this strategic roadmap's scientific and integration objectives is closely coupled to key technological innovations in the future. Here, we summarize the key technology capabilities needed to implement the objectives outlined in this roadmap and the links to the capability roadmaps.

This roadmap has articulated the objectives of discovery and awareness. Numerous coordinated observing sensors and real-time modeling and assimilation capabilities are required to achieve these objectives. As a result***, sensor web/ model web autonomy capability development*** is of high priority and has ***direct linkage to the autonomous systems and robotics roadmap (CRM 9)***.

Related to the above, ***the capacity to connect multiple observing and modeling systems into synergistic networks or system of systems*** is required. To achieve the awareness and perspective objectives of this roadmap, intensive modeling and analysis is required. This provides a direct ***link to the modeling, simulation, and analysis roadmap (CRM 13)***.

Furthermore, key technologies in the area of ***telescopes, instruments and sensors*** are required to perform key measurement goals of this roadmap. Several technological achievements in the area of ***nanotechnology*** significantly enhance our measurement capabilities.

The following table summarizes linkages to the capability roadmaps.

| **SR 9 (Earth) Linkages to Capability Roadmaps** | | | | | |
|---|---|---|---|---|---|
| **Capability Roadmap** | **Capability** | **Linkage Type** | **Description** | **Related Roadmap Events** | **Timeframe** |
| 3. Telescopes | 2-5 m deployable collectors | Enabling | active and passive optical measurements from low- to high-Earth orbit. Areal cost <$1K/m2, areal density <0.5 kg/m2. | Climate/Weather; Life | 2015-2025 |
| 3. Telescopes | 50-m deformable deployable RF reflectors | Enabling | Coherent active radiofrequency measurements require closed-loop dynamic wavefront correction in order to optimize system response. | Solid Earth | 2015-2020 |
| 9. Autonomous systems and robotics | Sensor web autonomy | Enabling | Automating the sensorweb/ modelweb to observe dynamic phenomena and accelerate the pace of discovery and awareness | All -integration across themes | All |
| 11. Instruments & Sensors | Interferometric SAR | Enabling | Large (400-700 m^2), deployable antennas, high efficiency rad-rad T/R modules, digital beam formation (DFB) rad-hard processor | Solid Earth; water | 2005-2015; 2015-2025 |
| 11. Instruments & Sensors | Millimeter wave RAR, SAR, and Interferometry | Enabling | Large deployable antenna, electronic beam formation, high freq. T/R modules | Climater/Weather | 2015-2025 |
| 11. Instruments & Sensors | Passive synthetic aperture microwave imagers | Enabling | Low power MMIC receiver, massively parallel digital correlator, rad-hard processor | Atmosphere; climate/weather; water | 2015-2020 |
| 11. Instruments & Sensors | Visible and IR detector arrays and readouts | Enabling | Rad-hard large format arrays | Life; atmosphere | 2005-2015; 2015-2025 |
| 11. Instruments & Sensors | Doppler Wind profilers | Enabling | energy, +/- 5 GHz, 10 msec tunability and frequency lock settling time | Climater/Weather | 2005-2015 |
| 13. Modeling, Simulation, Analysis | Capacity to connect multiple observing and modeling systems into synergistic networks/ system of systems | Enabling | Sensorweb/modelweb simulators and systems analysis capacity to advance the state-of-the-art in distributed collaborative observing and modeling | All -integration across themes | All |
| 15. Nanotechnology | Ultra-high strength, lighter, and multi-functional materials (100x stronger than steel), i.e., large lightweight antenna | Enhancing | materials will enhance mission success while also saving on overall costs of missions due to less mass, longer durability | All | All |
| 15. Nanotechnology | High efficiency power generation and storage | Enhancing | greatly enhance any space based mission by requiring less mass and fewer complex "power capture" systems that could potentially be "single point failure nodes" | All | All |
| 15. Nanotechnology | High miniaturized spacecraft systems and instruments | Enhancing | High miniaturized spacecraft systems, instruments (including lasers), smaller, radiation tolerant and less power consuming electronics would mean less mass and less power required to meet mission goals | All | All |

Priorities in advanced technologies needed for future Earth Science missions can be broadly categorized into two areas: Observing Technology Needs, and Information and Computing Technology Needs. These areas included technologies summarized in the following.

## Observing Technology Needs

Passive optical imaging systems for measurement of land surface, vegetation, ocean, and atmosphere will need improved optical and spectral separation systems to allow reductions in mass and cost; detectors with high pixels counts; and on-board processing to reduce data transmission requirements.

Passive microwave systems for measurements of atmospheric characteristics, precipitation, soil moisture, and ice and snow will need large, lightweight antenna with multiple-frequency capability; low cost and mass microwave integrated circuits; and low-noise, high-frequency receivers.

Active optical systems for measuring atmospheric composition will need lightweight, high power, conductively cooled, high efficiency reliable laser systems.

Active microwave systems for measurements of precipitation, clouds, land surface topography, and ice and snow will need large, lightweight, deployable antenna systems; and radio frequency capability and digital subsystems with reduced mass and cost.

Formation flying to form large, multi-spacecraft antennas will need precision ranging, precision station-keeping, and autonomous operation.

**Information and Computing Technology Needs**

On-board data processing will adapt commercial technology to achieve fault-tolerant, high-performance space processors, networks, and storage. Advances in space communications are needed to enable adaptable communications by developing high speed networks and protocols for dynamic space links

In the area of Mission Automation development is needed in real-time event detection and image recognition, self-tending spacecraft and instruments, and high-level command language for sensor re-targeting.

High-performance computing improves Earth-process models by developing next generation computer modeling techniques, optimizing performance, and developing architectural frameworks to promote model integration

The area of Information Synthesis (e.g., deriving data information from extremely large complex discovery, visualization, and multi-mission data sets; provide tools to assist scientific access to knowledge) requires further developments in analysis including real-time science processing and distribution.

The Earth science roadmap's primary linkages are with the Sun-Solar System roadmap, and concern a shared desire for joint investigations of the effects of solar variability on the Earth's climate and upper atmospheric chemistry dynamics. The roadmap also shares interests with all three exploration roadmaps, Earth-like planets, and Aeronautics.

There are several technological advances needed to complete the integration objectives of Discovery & Exploration, Continuous Awareness, and Developing Perspectives. These needs provide linkages to several capability roadmaps, including: Telescopes; Autonomous Systems and Robotics; Instruments and Sensors; Modeling, Simulation, and Analysis; and Nanotechnology.

***Collaboration with each of these groups is the recommended next step in the development of the Earth science roadmap timeline.***

## 5.3 Infrastructure Needs

NASA and US Aerospace industry are very well equipped to implement this roadmap. NASA Centers such as GSFC and JPL have an excellent record of success in managing the development and operation of most of NASA's Earth science missions. With the right level of investment in technology the NASA centers, combined with industry can provide the advanced instrumentation required to fulfill the measurement needs. The US aerospace industry, provided its base is not eroded, can easily meet the projected

spacecraft and launch vehicle needs. The Earth science community has become increasingly sophisticated in analysis of Earth science data and modeling. The EOSDIS distributes and archives terabytes of data from the current fleet of eighteen satellites, serving thousands of users.

The research and analysis budget will need to be sustained throughout the period of this roadmap so that new ideas and synergies across disciplines are given the support they need. Also needed are adequate and sustained investments in new instrument technologies along with opportunities to mature those technologies through flight demonstration. The maturation of new and existing instrument concepts will be crucial to the successful execution of this roadmap. NASA's end-to-end science relies upon the sustained capacity for airborne remote and in situ measurements from suborbital assets, as well as the world-wide ability to deploy ocean and ground-based systems.

The cost and complexity of integrated models of the Earth system are expected to increase to the point where major modeling systems and their support infrastructure will need to be managed in a manner similar to space missions. These systems will require sustained management and the investment in operations and regular upgrades or replacements over the decades so that NASA has access to the necessary computational capacity to achieve its predictive objectives. The network of commercial and NASA ground stations will probably have to support a significant expansion in data volume over the next couple of decades – the network's suitability for that task needs further study. NASA's requirements for modeling the Earth system, data management, and assimilation, will need to be re-evaluated as the awareness clusters are realized. Further, there are concerns over the need for a policy for managing our data over the long term, and the need for a coherent strategy and adequate support for the transfer of capability from research (NASA) to operations (NOAA or other agencies).

We are positioned for success in implementing this roadmap, but some areas of investment in technology and infrastructure require urgent attention.

# 6 Conclusions and Near-term Recommendations

Earth science and applications from space has come a long way since the 1960 launch of the first Earth observing satellites. The field of Earth system science that emerged in the 1980's and the subsequent era of the Earth Observing Satellites have shown us many of the key connections and helped us understand how much more we could learn over the coming decades.

This roadmap outlines a vigorous, robust, yet likely affordable program of investigations for the nation that, if implemented, would give NASA's Earth science program a glorious future, to exceed its glorious past. That future is integral to NASA's quest to explore our solar system, yet responsive to society's needs here on Earth.

This roadmap offers a structured approach to deciding which investigations to do and in what order. It addresses several of the concerns expressed in the NRC Decadal survey's interim report (April, 2005). We have proposed a new metric, the measurement maturity index, which can be used to assess and help plan the progress of measurements within a given line of science inquiry. The roadmap identifies potential off-ramps for current and future activities, which can be handed off to operational agencies. Further, this is done over timescales that allow NASA and its partners within U.S. Integrated Earth Observation System (IEOS) to plan accordingly. The roadmap recognizes NASA's leading role in research and development for the IEOS. It reasserts NASA Earth science as an exciting avenue for exploration and discovery, attracting the brightest and best to our field.

We recommend four near-term actions that NASA can begin work on immediately, as well as longer-term steps for which NASA should begin planning.

This roadmap was built on the assumption that the NASA missions currently in formulation and implementation would be completed as planned, and these missions are the foundation of this roadmap. The next step must be to work with the science community through working groups aligned with each line of inquiry and with the broader community through the NRC Decadal survey. NASA Earth science needs a vigorous and ongoing advanced studies program, to assess mission costs and technology readiness, to work out the most cost-effective ways to achieve our goals, and to start pre-formulation studies for new missions prior to 2007. *NASA should review its investment in Earth system modeling in light of our recommendations and work with NOAA to ensure the longevity of the climate data records collected thus far and their continuity into the future.* Lastly, to avoid a potential gap in the US Earth observation program, the Committee recommends that NASA allocate funds to start formulation of several new missions as soon as possible.

**Near-term recommendations**:

1. ***Complete the approved program*** in a timely fashion, including the next Earth System Science Pathfinder Announcement of Opportunity. This roadmap was built on the assumption that the NASA missions currently in formulation and implementation would be completed as planned, and these missions are the foundation of this roadmap.

2. ***Add advanced planning funding for future Earth Science and Applications missions*** from Space. The following near-term missions and our first flagship mission (listed in order of launch dates) need to be studied immediately to accomplish our recommended timeline:
    - Cal/Val Mission
    - Ice Elevation Changes
    - Surface Deformation
    - Ocean Surface Topography
    - Aerosols and high resolution CO2
    - First Flagship Mission – L1 Atmospheric Composition/Solar influence on Climate

3. ***Fund the advanced planning for the first awareness investigation focus:*** atmospheric chemistry, including technology, missions, models, networks, educational opportunities, and international cooperation.

4. ***Fund at least one new start*** for the missions above in FY'07 or FY '08 and the others as soon as possible after that.

# Appendices

## A Roadmap Background and Team Members

Roadmap Background

This ***Strategic Roadmap*** **(SRM)** is one of a set of high-level national roadmaps that form the foundation of National Aeronautics and Space Administration's (NASA's) strategic plan for the next 30 years (2005 to 2035). These roadmaps explore options and establish pathways for achievement of NASA's strategic objectives, which in turn articulate how NASA will fulfill its vision and mission for the nation. A companion set of ***Capability Roadmaps*** recommends approaches for providing technical capabilities judged to be critical to NASA's future programs.

Each roadmap was developed by a committee of nationally-recognized scientists, engineers, educators, visionaries, and managers. Committees were co-chaired by senior individuals from NASA Headquarters, a NASA Center, and outside NASA. Committee membership consisted of individuals from NASA/JPL/ other government agencies, academia, and industry, in approximately equal proportions.

The roadmaps provide NASA with high-level guidance and recommendations for the achievement of Agency requirements. The roadmap Committees considered and incorporated the reports and priorities of NASA advisory committees, including legacy theme roadmapping activities, National Research Council (NRC) "decadal surveys," and other strategic guidance.

**Earth Science and Applications from Space Strategic Roadmap Committee Participants**

**Roadmap Committee Members**

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Charles Kennel, Scripps Institution of Oceanography, co-chair
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Chris Kummerow
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# B National policy framework and External Constituencies

NASA's Earth science and applications from space responds to multiple presidential initiatives, National Space Policy, and current policies on broad access to information. NASA's science and innovation for Earth science and applications from space are relevant to multiple services for citizens that are the business of government (identified in the Federal Enterprise Architecture Business Reference Model).

## B.1 Presidential Initiatives:

NASA has a critical role in implementing several recent major Presidential directives or initiatives, including:

- Climate Change Research;
- U.S. Integrated Earth Observation System;
- U.S. Ocean Action Plan; and
- Vision for Space Exploration.

NASA's programs addressing Earth science and applications from space are *essential* to the success of the first three presidential initiatives listed above, and will surely prove to be so to the fourth. NASA's contributions to the Earth sciences are unique, numerous, and critically important to future efforts to protect life and property, facilitate responsible environmental stewardship, and understand the Earth system.

### *B.1.1 Climate Change Research*

Recognizing the importance of the climate change issue, President Bush has created an interagency, Cabinet-level committee, co-chaired by the Secretaries of Commerce and Energy, to coordinate and prioritize Federal research on global climate science and advance cleaner energy technologies.[1] This committee develops policy recommendations for the President and oversees the sub-cabinet interagency programs on climate science and energy technologies.

In July 2003, Energy Secretary Abraham, Commerce Secretary Evans, and White House Science Adviser Marburger released a 10-Year comprehensive Strategic Plan for the U.S. Climate Change. The plan describes a strategy for developing knowledge of variability and change in climate and related environmental and human systems, and for encouraging the application of this knowledge. After reviewing the Strategic Plan, the National Research Council commended its scope and content, stating that "[t]he plan articulates a guiding vision, is appropriately ambitious, and is broad in scope. It encompasses activities related to areas of longstanding importance as well as new or enhanced cross disciplinary efforts. Advancing science on all fronts identified by the program will be of vital importance to the nation."

[1] White House web page, "Addressing Global Climate Change," accessed May 9, 2005, URL http://www.whitehouse.gov/ceq/global-change.html

### *B.1.2 The U.S. Integrated Earth Observation System*

On April 18, 2005, the White House announced the release of the Strategic Plan for the U.S. Integrated Earth Observation System (IEOS).[2] The plan will serve as the framework for the U.S. contribution to the Global Earth Observation System of Systems (GEOSS), a ten-year implementation plan involving nearly 60 countries to develop an integrated observation system to realize specific societal benefits. The U.S. hosted the world's first global Earth Observation Summit held in Washington, D.C. on July 31, 2003.

The U.S. government now has an over-arching strategy for integrating Earth Observations aimed at achieving identified societal benefits (observations required for leading edge research are identified and prioritized with the science community via the National Research Council). Previously there were pieces via science programs such as the Climate Change Science Program, but now the U.S. IEOS provides a coherent, overarching, broad strategy

The U.S. IEOS Strategic Plan is organized around nine specific societal benefits, providing a coherent and politically compelling rationale of crosscutting societal, scientific, and economic imperatives. These nine societal benefit areas are:

- Improve weather forecasting
- Reduce loss of life and property from disaster
- Protect and monitor our ocean resource
- Understand, assess, predict, mitigate, and adapt to climate variability and change
- Support sustainable agriculture and forestry, and combat land degradation
- Understand the effect of environmental factors on human health and well-being
- Develop the capacity to make ecological forecasts
- Protect and monitor water resources
- Monitor and manage energy resources

The U.S. IEOS Strategic Plan identifies (and recommends to OMB for investment) specific near-term opportunities.

An interagency working group made up of 15 federal agencies and 3 White House offices developed the U.S. strategic plan under the auspices of the National Science and Technology Council (NSTC) Committee on Environment and Natural Resources (CENR). The interagency working group was recently succeeded by a standing subcommittee under CENR called the United States Group on Earth Observation (US GEO), which will continue to develop implementation and integration plans for the United States system, and to provide input into the implementation of the global system of systems.

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[2] White House Office of Science and Technology Policy release, "U.S. Releases Earth Observation Strategic Plan to Take The Pulse of the Planet, April 18, 2005, URL http://www.ostp.gov/html/IEOSrelease4-18-05.pdf

### *B.1.3 U.S. Ocean Action Plan*

On September 20, 2004, the U.S. Commission on Ocean Policy completed a thorough and expansive report, "An Ocean Blueprint for the 21st Century." On December 17, 2004, the President submitted to Congress his formal response, the *U.S. Ocean Action Plan*. The Bush Administration is focused on achieving meaningful results—making our oceans, coasts, and Great Lakes cleaner, healthier, and more productive. President Bush established by Executive Order a Cabinet-level "Committee on Ocean Policy" to coordinate the activities of executive branch departments and agencies regarding ocean-related matters in an integrated and effective manner to advance the environmental and economic interests of present and future generations of Americans.[3]

### *B.1.4 Vision for Space Exploration*

A Renewed Spirit of Discovery: On January 14, 2004, President Bush announced a new vision for the Nation's space exploration program. The President committed the United States to a long-term human and robotic program to explore the solar system, starting with a return to the Moon that will ultimately enable future exploration of Mars and other destinations. The benefits of space technology are far-reaching and affect the lives of every American. Space exploration has yielded advances in communications, weather forecasting, electronics, and countless other fields.

## B.2 National Space Policy and NASA's Legislated Roles:

### *B.2.1 U.S. Commercial Remote Sensing Space Policy.*

In 2002 the United States Government began a broad review of U.S. space policies to adjust to the domestic and international developments in recent years that affect U.S. space capabilities.[4] The last update of the National Space Policy had been in 1996.[5] To date, the White House has released two major National Space Policy documents, the U.S. Commercial Remote Sensing Space Policy[6] in 2003 and A Renewed Spirit of Discovery[7] in 2004 (summarized in the previous section). The fundamental goal of U.S. commercial remote sensing space policy is to advance and protect U.S. national security and foreign policy interests by maintaining the nation's leadership in remote sensing space activities, and by sustaining and enhancing the U.S. remote sensing industry. Doing so will also foster economic growth, contribute to environmental stewardship, and enable scientific

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[3] Web page, "Committee on Ocean Policy," accessed May 9, 2005, URL http://ocean.ceq.gov/

[4] As recommended, for example, by "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, the Honorable D. Rumsfeld,, chair, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

[5] The White House, National Science and Technology Council "Fact Sheet, National Space Policy," September 19, 1996, URL http://www.ostp.gov/NSTC/html/fs/fs-5.html. The actual policy statement is classified, and only this fact sheet is publicly available.

[6] White House Fact Sheet, "U.S. Commercial Remote Sensing Space Policy," May 13, 2003, URL http://www.whitehouse.gov/news/releases/2003/05/20030513-8.html

[7] White House Web Page, "President Bush Announces New Vision for Space Exploration Program," URL http://www.whitehouse.gov/infocus/space/index.html

and technological excellence. NASA serves as the lead agency for research and development in civil space activities. This policy requires that NASA:

- Rely to the maximum practical extent on U.S. commercial remote sensing space capabilities for filling imagery and geospatial needs.
- Focus U.S. Government remote sensing space systems on meeting needs that cannot be effectively, affordably, and reliably satisfied by commercial providers because of economic factors, civil mission needs, national security concerns, or foreign policy concerns.
- Develop a long-term, sustainable relationship between the U.S. Government and the U.S. commercial remote sensing space industry.
- Continue a program of long-term observation, research, and analysis of the Earth's land, oceans, atmosphere, and their interactions.
- Work with the DoC/NOAA, the DoD, the Intelligence Community, and the DoE to identify, develop, demonstrate, and transition advanced technologies to U.S. Earth observation satellite systems.

*B.2.2. The Space Act:*

The National Aeronautics and Space Act was initiated by the U.S. Congress in 1958, and helps define NASA's role within the U.S. government. It lists "the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space" as the first objective for NASA. It states that it is NASA's responsibility, regarding Earth science, to:

- Plan, direct, and conduct aeronautical and space activities
- Arrange for participation by the scientific community in planning scientific measurements and observations to be made through use of aeronautical and space vehicles, and conduct or arrange for the conduct of such measurements and observations
- Provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof
- Seek and encourage, to the maximum extent possible, the fullest commercial use of space
- Encourage and provide for Federal Government use of commercially provided space services and hardware, consistent with the requirements of the Federal Government
- Develop and carry out a comprehensive program of research, technology, and monitoring of the phenomena of the upper atmosphere as to provide for an understanding of and to maintain the chemical and physical integrity of the Earth's upper atmosphere
- Implement an appropriate research, technology, and monitoring program that will promote an understanding of the physics and chemistry of the Earth's upper atmosphere

NASA has been engaged in scientific remote sensing of the Earth from space from its beginnings as an agency, and this "as only NASA can" role has been affirmed and detailed in succeeding versions of the National Space Policy. [8]

*B.2.3 Land Remote Sensing Policy:*

In October of 1992, the Land Remote Sensing Policy Act was signed into law, and called for changes to the Landsat system. It calls for continued management of Landsat as an unclassified program by NASA and the DoD, maintained archiving of global Landsat data, and availability of Landsat data to non-profit users at lowest possible cost. In March 2005, a multi-agency group led by the Office of Science and Technology Policy reached a decision to secure continuity of Landsat type data via the National Polar-orbiting Operational Environmental Satellite System.

## B.3 National Policies on Broad Access to Information:

Providing access to information and observations about the Earth is a fundamental responsibility for NASA under both the Space Act and the President's Management Agenda.

- One of NASA's functions as listed in the Space Act is to "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." NASA's Earth Observing System Data and Information System provides over 29 million data products in response to 2.1 million queries each year.
- Within the President's Management Agenda, Expanded Electronic Government is one of the five government-wide goals to improve federal management and deliver results that matter to the American people. [9] Geospatial One Stop is an intergovernmental project in support of the President's Initiative for E-government. Geospatial One Stop builds upon its partnership with the Federal Geographic Data Committee (FGDC) to improve the ability of the public and government to use geospatial information to support the business of government and facilitate decision-making.[10] As a major source of Earth observations, NASA is one of the 19 member agencies in the FGDC established under OMB Circular A-16.[11] NASA's Distributed Active Archive Centers (DAACs) and Research, Education and Applications Solutions Network (REASoN) projects contribute to the U.S. capacity for data management of Earth observations. NASA is

[8] U.S. Public Law, "The National Aeronautics and Space Act of 1958," Public Law number 85-568, as Amended, URL http://www.hq.nasa.gov/ogc/spaceact.html,

[9] The Executive Office of the President, Office of Management and Budget, "The President's Management Agenda," Fiscal Year 2002, URL http://www.whitehouse.gov/omb/budget/fy2002/mgmt.pdf

[10] Web Page, "National Spatial Data Infrastructure, Geospatial One-Stop," URL http://www.geo-one-stop.gov/

[11] "OMB Circular A-16, Revised," August 19, 2002, URL http://www.whitehouse.gov/omb/circulars/a016/a016_rev.html

recognized for the Geospatial interoperability and participation in the OpenGIS Consortium and the FGDC.[12]

## B.4 Relevance of NASA's science and innovation

Earth science and applications research is relevant to the business of the U.S. Government. The Federal Enterprise Architecture Business Reference Model is a function-driven framework for describing the business operations of the Federal Government independent of the agencies that perform them (see figure below).

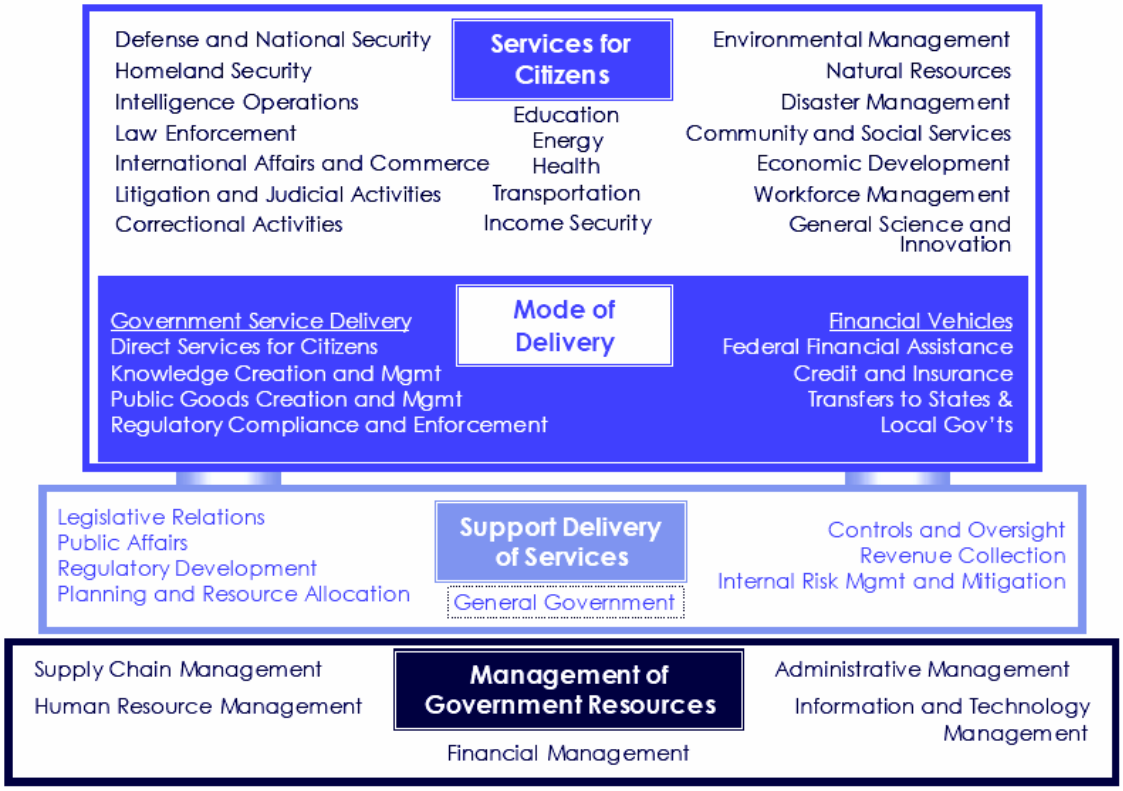



**Figure B.2: Federal Enterprise Architecture Business Reference Model**

The NASA's Applied Sciences program is pursing twelve applications of national priority in partnership with the U.S. government agencies that have management or regulatory mandates to provide these services to citizens.[13] The twelve NASA applications of national importance are:

[12] Web page, "NASA Contributions to GEO and IWGEO," accessed Oct. 6, 2004, URL http://earth.nasa.gov/visions/geoss.html

[13] NASA Office of Earth Science, "Earth Science Applications Plan," July 2004, URL http://www.earth.nasa.gov/visions/AppPlan.pdf. The most recent versions of the Applications Roadmaps are on pages 36 to 61.

**Table A.2: Twelve Applications of National Priority**

| | |
|---|---|
| Agricultural Efficiency | Ecological Forecasting |
| Air Quality | Renewable Energy |
| Aviation | Homeland Security |
| Carbon Management | Invasive Species |
| Coastal Management | Public Health |
| Disaster Management | Water Management |

NASA provides general science and innovation as its service to citizens, delivered through knowledge creation and management, yet the results are relevant to the broad business of Government.

# C Unique Education and Outreach Opportunities Associated with NASA Earth Science and Applications from Space

Human beings are born with curiosity and imagination in abundance, with a natural desire for exploration and discovery. NASA recognizes its unique position to inspire the public through its fascinating science results from Earth and space, and propel the youth of our nation forward to be the scientists, engineers, and scientifically-literate leaders of tomorrow. Whether looking out into the unfathomable expanses of the universe, monitoring sea surface temperatures as they change through a year, witnessing the inundation of powerful tsunamis, registering atmospheric disturbances, or measuring gas levels, NASA delivers mesmerizing views that capture our eyes, turn our heads, and provide us with the opportunity to grasp events in a profound way. The spark of excitement and flash of awe kindles the flame of desire for exploration, discovery, and understanding. In preparing the "next generation of explorers," NASA must exercise its leadership in science, technology, engineering, and mathematics (STEM) education.

In order to adequately prepare the workforce of tomorrow, NASA needs not only to engage the public and inspire them towards careers in science and technology, but also to systemically support educators at all levels and venues to effectively communicate NASA science to all learners. NASA's Earth science research has particular relevance to key understandings youth are expected to achieve through their education [NSES, 1995]. NASA's may exercise powerful influence through its leadership in information infrastructure, systems thinking and modeling, research and development of new technologies, and applications of research to benefit society.

## C.1 The Power of e-Education

NASA must continue to drive the development and application of innovations in information infrastructures and learning technologies, which make it possible to bring the results from our missions to learners in ways meaningful in their own lives. Digital information infrastructures provide learners of all ages inside and outside of the classroom with ready access to Earth system science resources. NASA is engaged in the ongoing production of very large geospatial data sets spanning the full spectrum of spatial and temporal scales. The challenge is to turn these vast quantities of data and information into knowledge products useful for education and communication to policy-makers.

We see a classroom of the future full of students who are explorers and educators who facilitate student discovery and learning. From a young age, learners are engaged in research and discovery through team-based projects that build and benefit their communities. NASA's comprehensive sensorweb for planet Earth is an essential element of this future, providing access to the real-time state of the planet through data from an integrated suite of sensors and data archives. Models to assimilate these data assist the student in building on past knowledge to understand the current state and forecast the future. The comprehensive data sets available from clusters of missions through the continuous awareness vision and NASA's recognition of the importance of the

educational application of these data result in development of education-focused databases and visualization tools. These resources make it possible for students to participate in unique opportunities, such as climate, weather, or natural hazards forecasting activities and to "fly-through" data sets on student-generated paths based on their research questions. Life-long learners use these expanding data resources, models, and the shared expertise of the scientific community to improve their understanding of the planet, enhance their quality of life, promote their self-expression, satisfy their curiosity, and advance their research.

## C.2 Role of Systems Thinking and Modeling

Systems thinking and modeling are essential components at the forefront of both NASA science and effective education. Earth is a system in which physical and chemical processes interact in complex cycles that involve the geosphere, atmosphere, hydrosphere, and biosphere. NASA's systems approach to studying Earth science provides the viewpoint from which we can ask a wide range of questions about the Earth and its evolution. Computer simulations of the Earth system are essential tools for the scientific community, both to answer research questions and to provide science-based knowledge to inform the public and policy makers. From the educational perspective, systems and models are unifying concepts across the sciences and are essential for students to understand as they develop their scientific literacy. NASA's scientific and personnel assets position it to make a unique contribution to development of an understanding of systems and models in education. Furthermore, the models developed by NASA scientists, in collaboration with their research partners, could be simplified and modified to address curriculum standards and support inquiry-based learning of a broad spectrum of learners.

## C.3 Meaningful and Effective Implementation of Educational and Public Engagement

NASA research and development shapes our future in many ways. Technological breakthroughs improve our lives and lead to new commercial enterprises. New scientific insights enhance our ability to protect citizens from natural hazards and understand the world around us. In addition to working to develop an educated populace, well informed about NASA science, technologies, exploration, and discovery, NASA must intentionally pursue opportunities to build the workforce of tomorrow that will continue our discoveries into the future. In order to do this, NASA must proactively implement strategies to seek linkages to the educational community, specifically becoming involved on the state level in order to address state-level standards for education and learning. Building on programs that inspire, motivate, educate, and prepare students and their teachers through K-12 into undergraduate programs, NASA must also provide opportunities for students and researchers to become meaningfully engaged with NASA research, extending into collaborations with the private sector. These efforts must also intentionally include an emphasis on engaging populations historically underrepresented in science in the NASA adventure, such that these individuals see NASA as a desired, as well as a possible, career path. It is critical for the success of Earth science education at

NASA that opportunities are provided to open the science, technology, engineering, and math pipeline for all Americans, including underrepresented minorities.

## C.4 Connecting Science and Education

Applications derived by NASA from its research programs make a unique contribution to enhancing the daily lives of the public through access to weather forecasts and predictions of tectonic hazards as well as through information that explains how choices in our daily lives impact our community, country, and the world. Often the missing link between NASA discoveries and public understanding is clear and effective communication. Future NASA Earth science research goals should be clearly benchmarked with relevant science, math, technology, and geography education standards, as well as posed in language that engages the person on the street. For example, "Distinguishing anthropogenic and natural aerosols and their effects on climate" is more likely to engage the public when communicated in the context of familiar topics, such as "volcanoes, cancer, and quality of life." Expression of research goals and their advance distribution to the public would also increase ability of the public to be engaged and involved in NASA Earth System Science missions as they happen, rather than only after the fact. Even more importantly, advance knowledge will allow educators of all types to prepare exhibits and lessons to share the awe of real-time discoveries about our home planet.

In accomplishing all these goals, it is critical that NASA focus on the unique role it has in education, and to work in partnership with other agencies, nonprofits, industry, educational institutions, and professional societies to most effectively and efficiently reach the population of learners that NASA needs to address.

# D External Partnerships

## D.1 Evolution of External Relationships:

NASA has a broad constituency and web of partnerships for its work in exploring the dynamic Earth system. While many other agencies are engaged in Earth science, NASA brings the global view from space, providing the global context in which to understand local, regional and global scale change. NASA also brings, from an expertise in systems engineering, complex problem-solving proficiency to the daunting challenge of understanding and protecting our home planet.

Over the last two decades NASA has used its "systems" expertise to lead a revolution in the way we study and understand the Earth. *Earth System Science*, the move to an integrated "systems" approach and away from narrow discipline or single-issue research "stovepipes" was the key innovation that revolutionized Earth science. Armed with the recommendations of the 1988 "Bretherton" report, NASA led this revolution with the development of the Earth Observing System.[14] NASA engaged in a deliberate strategy of supporting interdisciplinary Earth system science research and education as a way of growing this capacity in the nation's research and education communities. The most recent refinement has been to identify science focus areas as key integrating themes that build upon the capabilities of the diverse Earth science disciplines towards an integrated, predictive capacity. Setting long term goals built on the integrated results of broad research questions helps NASA and the community to establish and maintain scientific balance and relevance.

Today, NASA's Earth system science program integrates across the full breadth of science disciplines. Some researchers look at the key physical components of the Earth system (e.g., geologists, oceanographers, atmospheric scientists). Some researchers look at the key biological components of the Earth system (e.g., ecologists, biogeochemists, astrobiologists). Some researchers look at the key dynamic processes that cut across the components of the Earth system (e.g., meteorologists, climatologists, biologists, ecologists, hydrologists). Some researchers look at the key impacts of the Earth system on humans and society (e.g., natural hazards and disasters; food and fiber/agriculture, fisheries, and forestry; energy use and management; human health effects). Others look at the key impacts of humans and society on the Earth system (e.g., land cover and land use change; industrial emissions; resource management practices).

NASA is one of a few U.S. government agencies whose mandates are purely for research and technology development, without management or regulatory authority and responsibility. This research independence and NASA's credibility as an unbiased broker of scientific results are important intangible assets that NASA brings to Earth science issues with significant management, policy, and economic implications. In addition, this

[14] Bretherton, F., chair, "Earth System Science, A Closer View," Report of the Earth System Sciences Committee, NASA Advisory Council, January 1988.

independent role provides NASA the opportunity to advance the state-of-the-practice in exploration of the dynamic Earth system and transition new capabilities to our management and operational partners in the U.S. government.

## D.2 External Constituencies and Corresponding NASA Roles:

As a result of this evolution in NASA's research relationships, NASA's Earth system science efforts are at the intersection of five major external constituencies. NASA's current roles reflect these external constituencies:

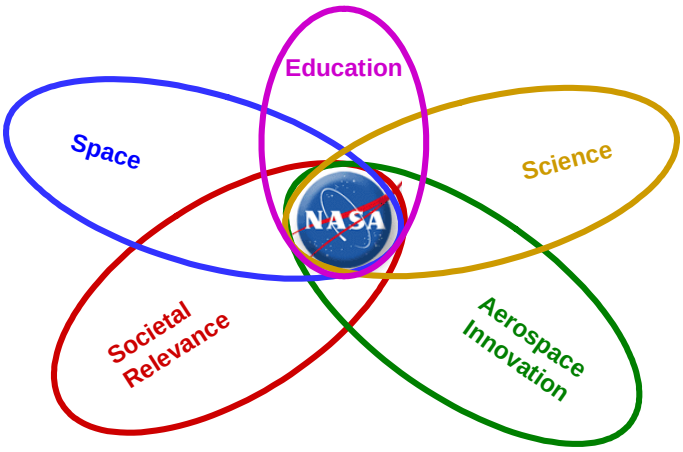



**Figure A.3: NASA's Major External Constituencies**

- **NASA is a Science Agency.** NASA conducts and sponsors research in key arenas where our air and space assets and our complex systems expertise can make defining contributions. NASA is a partner in the larger national and international science community, which is actively engaged in ground and space-based science of all types. NASA science priorities and implementation approaches are broadly reviewed through interagency committees, external advisory groups, and the National Academies.
- **NASA is a Space Agency.** NASA **defines** the leading edge of US civilian research and technology in and about space. NASA shares with the broader space community investments in launch capabilities and facilities, navigation and tracking facilities, etc. NASA coordinates with this broader community through a variety of mechanisms, including the Space Technology Alliance (with the National Security Space Community), the Committee on Earth Observation Satellites (CEOS, representing 41 international space-based Earth observation agencies and organizations), and the International Living With a Star initiative.
- **NASA is an Aerospace Innovation Agency.** NASA collaboratively addresses the technical challenges and develops capabilities to pursue its mission in partnership with the aerospace industry and technology sector. These include the aerospace companies that build our instruments, spacecraft, and supporting technologies as well as the academic researchers who develop new technological capabilities.

- **NASA enhances science, technology, engineering and mathematics education.** NASA addresses its mission to inspire the next generation of explorers through partnerships with the formal and informal education community. These partnerships enable an accessible, dynamic, and engaging learning environment for all citizens. This expands and deepens the Nation's appreciation and understanding of the Earth system and encourages pursuit of scientific and technical careers.
- **NASA's research is relevant to broad national priorities.** NASA conducts cutting-edge research that is relevant to society and human life. NASA's contributions are recognized and coordinated at the highest levels of the US government, such as the Committee on Climate Change Science and Technology Integration (CCCSTI) and the National Science and Technology Council (NSTC). NASA's Earth Science Applications Program is pursuing 12 applications of national priority in collaboration with over a dozen Federal agencies to enable NASA's Earth observations and research to improve the essential services these agencies provide to the Nation. NASA's Earth Science Applications program benchmarks practical uses of NASA-sponsored observations from remote sensing systems and predictions from scientific research and modeling. The approach is to enable the assimilation of science model and remote sensing mission outputs to serve as inputs to established partner agency decision support systems. The outcomes are manifest in enhanced decision support and the impacts are projected to result in significant socio-economic benefits.

**NASA's strength is in addressing these overlapping interests.** In many ways, the phrase "as only NASA can" in NASA's mission statement refers to these intersections. NASA is a science driven agency that serves the national interest. NASA addresses fundamental questions that inspire and motivate students. NASA is chartered under the space act to advance US leadership in aeronautical and space science and technology. If a NASA activity has compelling science or addresses critical national needs, while at the same time requiring the use of space or advanced aeronautical technologies, then that activity is a compelling match to NASA's overall charter, mission, and goals. If the activity can be pursued in a way that inspires and provides educational benefits, the match is even stronger.

### D.3 Examples of Current Relationships:

The following are selected examples of NASA research activities that are directly relevant to major external constituencies.

- The Cabinet-level National Science and Technology Council (NSTC) is the principal means for the President to coordinate science, space, and technology in the diverse parts of the Federal research and development enterprise. An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments.[15] The Council has four committees, including the Committee on Environment and Natural Resources (CENR), the

[15] Web Page, "National Science and Technology Council," accessed Oct. 1, 2004, URL http://ostp.gov/nstc/html/nstc.html

Committee on Science, and the Committee on Technology. NASA is an active participant in the NSTC activities related to Earth system science, including the Subcommittees on Global Change Research, Ecological Systems, and Disaster Reduction,[16] as well as the United States Group on Earth Observations.[17]

- NASA is the largest contributor to the U.S. Climate Change Research Program, an interagency program established by the Executive Office of the President to integrate the Congressionally-mandated US Global Change Research Program and the Administration's Climate Change Research Initiative. NASA also participates in the U.S. Climate Change Technology Program. These programs are under the Cabinet-level Committee on Climate Change Science and Technology Integration (CCCSTI), established by the President to provide recommendations on matters concerning climate change science and technology; address related Federal R&D funding issues; and coordinate with Office of Management and Budget on implementing its recommendations.[18]
- NASA is a member of the US Weather Research Program. The USWRP is a partnership among science and operational governmental agencies, and the academic and commercial communities. The broad purpose of the Program is to increase the resiliency of the Nation to weather; that is, to ensure that the federal, state and local governments, the private sector and general public make well-informed and timely weather-sensitive decisions with respect to past, present, and future weather conditions. To achieve this end requires that the scientific and service communities work together to advance weather observing capabilities and fundamental understanding of weather and to use this understanding to improve weather prediction and enhance weather services provided to the Nation.[19]
- NASA develops and launches the Nation's weather satellites under a reimbursable agreement with NOAA, and is working with NOAA and DoD on the next generation, converged civilian and military polar-orbiting operational environmental satellite system.
- NASA has about 200 agreements with over 60 foreign nations for activities that Earth science and applications from space, and is active participant in a variety of international research programs and organizations, including the International Geosphere-Biosphere Programme, World Meteorological Organization, the G-8 sponsored Committee on Earth Observation Satellites, and a new international effort to create a Global Earth Observation System of Systems (GEOSS).

## D.4 International Context:

Strengthening international co-operation on global Earth observation is on the world's agenda. Building upon the results of the 2002 World Summit on Sustainable

[16] Web Page, "Subcommittee on Natural Disaster Reduction," accessed Oct. 1, 2004, URL http://www.usgs.gov/sndr/

[17] Web Page, "Interagency Working Group on Earth Observations," accessed Oct. 1, 2004, URL http://iwgeo.ssc.nasa.gov/

[18] Web Page, "About the U.S. Climate Change Technology Program," accessed Oct. 1, 2004, URL http://www.climatetechnology.gov/about/index.htm

[19] Terms of Reference for the U.S. Weather Research Program (2001), URL http://box.mmm.ucar.edu/uswrp/program_organization/tor.html

Development,[20] the G-8 Leaders agreed at the Evian Summit in 2003 on an Action Plan on Science and Technology for Sustainable Development.[21] The Plan builds on U.S. initiatives to develop transformational technologies in three areas: energy, agriculture, and global observation.[22] Fifty-five nations now participate in the Group on Earth Observations (GEO) established as a permanent body at the third Earth Observation Summit in February 2005. At this summit these nations adopted the 10-year Implementation Plan for the Global Earth Observation System of Systems (GEOSS).

Nearly all of NASA's missions to Earth science and applications from space have substantial international participation, ranging from simple data sharing arrangements to ground validation to provision of instruments, satellite buses and launch services for space missions. We participate in the UNEP/WMO Triennial Ozone Assessment, the World Climate Research Program, the International Geosphere/Biosphere Programme, and the International Human Dimensions of Global Change Programme (IHDP). NASA scientists individually are key contributors to the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which conducts a quadrennial assessment of the state of knowledge of climate change. The IPCC was initiated under the United Nations Framework Convention on Climate Change in 1992. NASA's wide range of international partnerships is documented in the publication "Global Reach", prepared by the Office of External Relations. NASA participates in the Millennium Ecosystem Assessment through the provision of satellite data and the involvement of individual scientists.

## D.4 Linkage between national and international priorities

The following table (Table A.1) highlights key national priorities and their corresponding global context (with hyperlinks to relevant World Wide Web sources).

**Table A.1: National Programs in a Global Context**

| Priority | National Programs | International Programs |
|---|---|---|
| Vision for Exploration | Understanding the Earth as the foundation for Planetary Exploration and Search for Life | *"Pursue opportunities for international participation to support U.S. space exploration goals"* |
| Global Earth Observation | NSTC CENR United States Group on Earth Observations (US GEO) Integrated Earth Observation System, 15 Agencies) | Group on Earth Observations (GEO) Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan |
| Climate Change | Climate Change Science Program (CCSP, 13 Agencies) Climate Change Technology Program (CCTP, 11 Agencies) | Intergovernmental Panel on Climate Change (IPCC) |

[20] United Nations, "Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August-4 September 2002," A/CONF.199/20*, Pg. 63, URL http://ods-dds-ny.un.org/doc/UNDOC/GEN/N02/636/93/PDF/N0263693.pdf

[21] Summit Documents Web Page, "Science and Technology for Sustainable Development - A G8 Action Plan," Accessed Oct. 4, 2004, URL http://www.g8.fr/evian/english/navigation/2003_g8_summit/summit_documents/science_and_technology_for_sustainable_development_-_a_g8_action_plan.html

[22] White House Science and Technology Fact Sheet, "Fact Sheet: Action on Science and Technology," June 2, 2003, URL http://www.whitehouse.gov/news/releases/2003/06/20030602-15.html

| Priority | National Programs | International Programs |
|---|---|---|
| Natural Hazards | NSTC CENR Subcommittee on Natural Disaster Reduction (SNDR, 14 Agencies) | International Strategy for Disaster Reduction |
| President's Management Agenda: E-Government | Geospatial One-Stop (GOS, 12 Agencies) and the Federal Geographic Data Committee (FGDC, 19 Agencies) | World Summit on the Information Society |

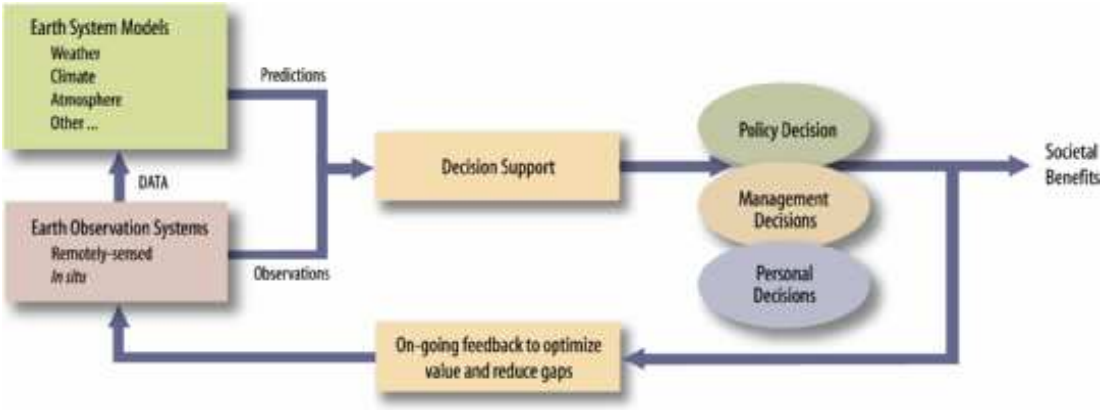
## D.5 Evolution of External Constituencies

In order to achieve the societal benefits of a global system of earth observations, the predecessor to the United States Group on Earth Observations of the CENR developed a coordinated, multi-year plan for a U.S. Integrated Earth Observation System. Development and evolution of NASA science and technology will be fundamental to implementing the goals set forth in this plan, and coordination among external constituencies ranging from local to international will be required.

The paradigm of improvements in weather observations and prediction through cooperation at local to global scales enables NASA to anticipate the need for advances in observing, networking, and modeling technologies, advances in scientific understanding, and the need to develop cooperative relationships with a highly diverse intergovernmental community. Many of the technology challenges will be driven by questions that require data and analysis at multiple spatial and temporal scales. These, in turn, will require networked observations from multiple, disparate sources. Increases in expectations of locally-specific predictive capabilities will drive the space-based networks to more strongly include airborne and in situ networks as part of the integrated system. This will drive more emphasis on understanding and modeling the effects of global processes at local scales of information needs. NASA will need to draw upon the expertise of other federal, state, and local entities in much the same manner that NASA and NOAA have worked together to assimilate in in situ, ground-based, aircraft-based, and satellite vantage points in progressively higher resolution weather prediction models for societal benefit.

The Strategic Plan for the U.S. Integrated Earth Observation System establishes a framework for linking observations to societal benefits. By using a unifying system architecture this framework ensures that current and evolving systems are interoperable and the solutions can be easily expanded, extended, and/or replicated to address future challenges.

The following figure is from the Strategic Plan for the U.S. Integrated Earth Observation System. It depicts how remotely-sensed and in situ Earth observation systems provide data to Earth system models, and how these systems provide observations and predictions to decision support systems (tools, assessments, etc.) to inform policy, management, and personal decisions that provide benefits to society. The figure shows an on-going feedback loop to optimize the value of the overall system and reduce gaps in the ability to deliver timely and relevant information.




NASA science and technology research advances and enables new Earth observation systems and Earth system models. NASA works with partner agencies to benchmark use of research observations and predictions for decision support relevant to policy and management decisions

# E Bibliography of Key Agency Documents and NRC Documents

The following is a list of relevant references organized around topic areas. Some documents were provided to the Committee members at the first meeting, and these documents are provided electronically. This list was drawn mainly from the Earth Science and Applications from Space Background Document (URL http://www.hq.nasa.gov/office/apio/pdf/earth/srm9plana.pdf). In some cases we have included web addresses (URLs) to on-line versions of the references. These were valid when the background document was prepared (Oct. 2004). Most but not all were updated or revalidated when this report was finalized (May 2005).

National Policy Framework:

- U.S. Public Law, "The National Aeronautics and Space Act of 1958," Public Law number 85-568, as Amended, URL http://www.hq.nasa.gov/ogc/spaceact.html
- The White House, National Science and Technology Council "Fact Sheet, National Space Policy," September 19, 1996, URL http://www.ostp.gov/NSTC/html/fs/fs-5.html. The actual policy statement is classified, and only this fact sheet is publicly available.
- White House Fact Sheet, "U.S. Commercial Remote Sensing Space Policy," May 13, 2003, URL http://www.whitehouse.gov/news/releases/2003/05/20030513-8.html
- White House Web Page, "President Bush Announces New Vision for Space Exploration Program," URL http://www.whitehouse.gov/infocus/space/index.html
- White House Web Page, "A Renewed Spirit of Discovery," January 23, 2004.
- Web Page, "National Science and Technology Council," accessed Oct. 1, 2004, URL http://ostp.gov/nstc/html/nstc.html
- "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, the Honorable D. Rumsfeld,, chair, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

National and International Coordination of Global Earth Observation Systems:

- The Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan (As adopted 16 February 2005), available from the Group on Earth Observations web page at URL http://earthobservations.org/
- Final DRAFT Global Earth Observation System of Systems GEOSS 10-Year Implementation Plan Reference Document, available from the Group on Earth Observations web page at URL http://earthobservations.org/
- Strategic Plan for the U.S. Integrated Earth Observation System, available from the United States Group on Earth Observations web page at URL http://iwgeo.ssc.nasa.gov/
- Integrated Plan for the U.S. Integrated Earth Observation System Technical Reference Documents, available from the United States Group on Earth Observations web page at URL http://iwgeo.ssc.nasa.gov/:
    - Agriculture Technical Reference Document

  - Climate Technical Reference Document
  - Disasters Technical Reference Document
  - Ecological Forecasts Technical Reference Document
  - Energy Technical Reference Document
  - Human Health Technical Reference Document
  - Integration Technical Reference Document
  - Oceans Technical Reference Document
  - Water Technical Reference Document
  - Weather Technical Reference Document
- Additional Background Documents:
  - United Nations, "Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August-4 September 2002," A/CONF.199/20*, URL http://daccessdds.un.org/doc/UNDOC/GEN/N03/204/23/PDF/N0320423.pdf?OpenElement
  - Summit Documents Web Page, "Science and Technology for Sustainable Development - A G8 Action Plan," URL http://www.g8.fr/evian/english/navigation/2003_g8_summit/summit_documents/science_and_technology_for_sustainable_development_-_a_g8_action_plan.html
  - White House Science and Technology Fact Sheet, "Fact Sheet: Action on Science and Technology," June 2, 2003, URL http://www.whitehouse.gov/news/releases/2003/06/20030602-15.html
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  - Web page, "NASA Contributions to GEO and IWGEO," URL http://earth.nasa.gov/visions/geoss.html

NASA's Transformation -- Key Reports and Planning:

- NASA Strategic Plan
- NASA, "The Vision for Space Exploration," NP-2004-01-334-HQ, February 2004.
- A Journey to Inspire, Innovate, and Discover, June 2004 (the Aldridge Commission Report).
- The Need to Transform the Structure and Management of NASA, Report of the Roles, Responsibilities And Structures ("Clarity") Team, June 24, 2004.
- A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report, January 30, 2004 (the Diaz Report).
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- Enhancing Mission Success -- A Framework for the Future, A Report by the NASA Chief Engineer and the NASA Integrated Action Team, January 2001.

NASA Earth Science Planning Activities:

- Earth Science Enterprise Strategy, October 1, 2003.
- NASA, "Earth Science Research Plan, 1/6/05 DRAFT." The previous version of this document is:
    - NASA, "Understanding Earth System Change: NASA's Earth Science Enterprise Research Strategy for 2000-2010," December 2000, available through URL http://www.earth.nasa.gov/visions/researchstrat/Research_Strategy.htm.
    - NASA Earth Science Focus Area Roadmaps. Updates to these roadmaps are included in the 1/6/05 DRAFT "Earth Science Research Plan. See URL http://www.earth.nasa.gov/roadmaps/index.html for the previous, versions of the roadmaps.
- NASA Report, "Earth Science Vision 2030 Working Group Report," March 2004, URL http://neptune.gsfc.nasa.gov/vision/Earth_Science_Vision_2030.pdf
- NASA, "Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions," March 3, 1999 (possibly less useful source representing earlier community involvement in planning NASA's future implementation).

NASA Earth Science and Applications Technology:

- "Earth-Sun System: Potential Roadmap and Mission Development Activities" explanatory cover sheet and December 23, 2004 presentation package. This contains the background information for George Komar's presentation at the January 2005 Committee meeting.
- See URL http://estips.gsfc.nasa.gov/ for access to the Earth Science Technology Integrated Planning System (ESTIPS). For examples of how NASA has engaged the community in developing and maintaining this database, see:
    - "Sensor & Platform Technology Requirements for Implementing NASA's Earth Science Research Strategy in the Next Decade: A Summary Report Based on the ESTO Technology Planning Workshop Held on March 5-6, 2003," available on the Web at URL http://estips.gsfc.nasa.gov/Home/docs/ESTOWorkhop20031.pdf
    - URL http://www.esto.nasa.gov/conferences/estc2004/ for information about the fourth annual Earth Science Technology Conference. To encourage greater participation, these annual conferences alternate between the East and West coasts.

NASA Earth Science Applications Planning Activities:

- NASA Office of Earth Science, "Earth Science Applications Plan," July 2004, URL http://www.earth.nasa.gov/visions/AppPlan.pdf. The most recent versions of the Applications Roadmaps are on pages 36 to 61.

NRC Decadal Survey:

- NASA, "Earth Science and Applications from Space: A Community Assessment and Strategy for the Future," Final version of charge to Committee, 11 August 2004.

- NRC, "Compilation of Comments on the Study and White Paper," Earth Science and Applications from Space, A Community Assessment and Strategy for the Future, August 17, 2004.

NRC and ESSAAC Advice to NASA and NASA's Responses:

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- Assessment of NASA's Draft Earth Science Enterprise Strategy (NRC, 2003)
- Enhancing NASA's Contribution to Polar Science (NRC, 2001)
- Review of NASA's Earth Science Enterprise Research Strategy for 2000-2010 (NRC, 2001)
- Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data (NRC, 2002)
- Transforming Remote Sensing Data into Information and Applications (NRC, 2001)
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- Using Remote Sensing in State and Local Government (NRC, 2003)
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- Report of the Task Group on Assessment of NASA Plans for Post-2002 Earth Observing Missions (NRC, 1999)
- Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond (NRC, 2004)
- Satellite Observations of the Earth's Environment (NRC, 2003)

NOTE: Some NRC reports relate to other topics (e.g., data policy, applications, weather, natural hazards, climate, or air quality) and are listed elsewhere.

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- Bretherton, F., chair, "Earth System Science, A Closer View," Report of the Earth System Sciences Committee, NASA Advisory Council, January 1988 (historical advice that led to EOS, the Earth Observing System).

National Information and Data Policy:

- The Executive Office of the President, Office of Management and Budget, "The President's Management Agenda," Fiscal Year 2002, URL http://www.whitehouse.gov/omb/budget/fy2002/mgmt.pdf
- Web Page, "National Spatial Data Infrastructure, Geospatial One-Stop," URL http://www.geo-one-stop.gov/
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- From Research to Operations in Weather Satellites and Numerical Weather Prediction – Crossing the Valley of Death (NRC, 2000)

National Natural Hazards Research and Applications:

- Web Page, "Subcommittee on Natural Disaster Reduction," accessed Oct. 1, 2004, URL http://www.usgs.gov/sndr/
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# F Acronym List

AIRS: Atmospheric InfraRed Sounder
APIO: Advanced Planning and Integration Office
ARC: Ames Research Center
Cal/Val: Calibration/Validation
CCCSTI: Committee on Climate Change Science and Technology Integration
CCSP: Climate Change Science Program
CCTP: Climate Change Technology Program
CENR: Committee on Environment and Natural Resources
CEOS: Committee on Earth Observation Satellites
CFC: Chlorofluorocarbon
CRM: Capability Roadmap
DAAC: Distributed Active Archive Center
DoC: Department of Commerce
DoD: Department of Defense
DoE: Department of Energy
EDR: Environmental Data Record
EOS: Earth Observing System
EOSDIS: Earth Observation System Data Information System
ESMF: Earth System Modeling Framework
ESSP: Earth System Science Pathfinder
ESTO: Earth Science Technology Office
FGDC: Federal Geographic Data Committee
FY: Fiscal Year
GB: Gigabytes
GEO: Geosynchronous Earth Orbit
GEOSS: Global Earth Observing System of Systems
GSFC: Goddard Space Flight Center
IEOS: International Earth Observing System
IHDP: International Human Dimensions of Global Change Programme
InSAR: Interferometric Synthetic Aperture Radar
IPCC: Intergovernmental Panel on Climate Change
IR: Infrared
JPL: Jet Propulsion Laboratory
L1: 1$^{st}$ Libration Point
LaRC: Langley Research Center
LDCM: Landsat Data Continuity Mission
LEO: Low Earth Orbit
MARS: Monterey Accelerated Research System
MMI: Measurement Maturity Index
MODIS: Moderate Resolution Imaging Spectroradiometer
MOOS: Monterey Bay Aquarium Research Institute Ocean Observation System
MS&A: Modeling, Simulation, and Analysis
NASA: National Aeronautics and Space Administration
NIR: Near Infrared

NIST: National Institute of Standards and Technology
NOAA: National Oceanic and Atmospheric Administration
NPOESS: National Polar Orbiting Environmental Satellite System
NPP: NPOESS Preparatory Project
NRC: National Research Council
NSF: National Science Foundation
NSTC: National Science and Technology Council
OCO: Orbiting Carbon Observatory
OLI: Operational Land Imager
OMB: Office of Management and Budget
PB: Petabytes
R&D: Research and Development
RC: Research Center
REASoN: Research, Education and Applications Solutions Network
SCCOOS: Southern California Coastal Ocean Observing System
SRM: Strategic Roadmap
STEM: Science Technology Engineering and Mathematics
TB: Terabytes
UAV: Unmanned Aerial Vehicle
UCAR: University Corporation for Atmospheric Research
UNEP: United Nations Environment Programme
USGEO: United States Group on Earth Observation
USGS: United States Geological Survey
USWRP: US Weather Research Program
UV: Ultraviolet
VHF: Very High Frequency
VIIRS: Visible Infrared Imager/Radiometer Suite
Vis: Visible
WMO: World Meteorological Organization