DYNAMIC EARTH:

GEO IMPERATIVES & FRONTIERS 2015–2020

NSF Advisory Committee for Geosciences

Dynamic Earth:
GEO Imperatives & Frontiers 2015–2020

NSF Advisory Committee for Geosciences
December 2014

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Foreword

On behalf of the National Science Foundation (NSF) Advisory Committee for Geosciences (AC GEO), I am pleased to share *Dynamic Earth: GEO Imperatives & Frontiers 2015–2020*. I was fortunate to have the opportunity to participate in the development of this document that outlines imperatives and frontier areas for NSF's Directorate for Geosciences (GEO) on a five-year time horizon. Periodically undertaking these strategic efforts is an important part of the work of AC GEO. These efforts allow us to take a broad view of geosciences research and education opportunities and directions and to work with GEO staff to turn this framework into solid research to meet the challenges of the next few years.

The document represents a well-considered, collective effort to articulate GEO-wide priorities and focus areas. We collected input and feedback from many sources including GEO program officers, professional society conferences, advisory committees, decadal surveys, town hall meetings, and working group collaborations between AC GEO members and GEO staff. NSF-level strategic goals, administration-level priorities and principles, and the perspectives of the four GEO Divisions are also captured in this "living" document. We intend that the document will be useful as high-level guidance for NSF program officers and other NSF staff, that it will communicate the compelling research goals of the Geosciences Directorate to interested parties, and that it will stimulate "bottom up" thinking from the community to provide further input on what researchers in the community consider to be the emerging frontiers for the Directorate and for its Divisions and Programs. Our goal is both to lay out a near-term plan for geosciences research supported by NSF and to highlight the importance and breadth of the scientific enterprise funded by GEO.

The committee recognizes the critical importance of GEO core research programs. They are the backbone and foundation for the high-level Imperatives and Frontiers described in this document. Support of these programs is the highest priority of the GEO Directorate.

Although it is not possible to include all GEO-supported basic science in this document, the committee recognizes the critical importance of GEO core research programs. While they may not all be mentioned by name, GEO basic research programs are the backbone and foundation for the high-level Imperatives and Frontiers described in this document. Support of these programs is the highest priority of the GEO Directorate. While this report views GEO on a macro level, the four division planning efforts will look more closely at specific core programs in their purview. The committee also recognizes that while it is an exciting time to be in the geosciences and undertaking potentially breakthrough research, it is also a challenging one. While the complexity of research projects has increased along with the demand for both financial and physical resources, the resources to support them have not kept pace with demand. Given the current economic climate and availability of Federal dollars, it is not likely that this scenario will change dramatically in the next five years. As such, the committee again stresses that supporting core research must be GEO's number one priority.

This document is unique in that it is the first opportunity to focus on the expanded mission of GEO. In fall 2012, then NSF Director Subra Suresh announced a realignment of several organizations. Part of this

realignment was to incorporate Polar Programs into GEO. While Polar and Geoscience Programs have always had a strong collaborative and inter-connected relationship, this change broadens GEO's purview and thus allows a holistic and comprehensive approach to planning and supporting research that encompasses the entire planet.

It is an exciting time to be at the forefront of such important and impactful scientific undertakings. GEO is primed to exert leadership in critical scientific areas of global significance. The NSF AC GEO looks forward to working with GEO to see that the science envisioned in this document is enabled.

Dr. George Hornberger
Vanderbilt University
Chair, Advisory Committee for Geosciences

Introduction

Background

One of the most important functions of the NSF Advisory Committee for Geosciences (AC GEO) is to provide strategic input into the GEO Directorate's long-range plans and partnership opportunities. Hence, AC GEO—in collaboration with NSF GEO staff—regularly engages in strategic exercises to lay out a broad agenda and direction for geoscience research and education opportunities. AC GEO is also tasked to serve as a liaison between GEO and the broad scientific research and education community served by GEO. To that end, AC GEO has been involved in numerous reports, workshops, meetings and informal interactions that capture current and anticipated areas of interest from the perspective of GEO and the community.

In 1999, the major long-range planning document, *NSF Geosciences Beyond 2000: Understanding and Predicting Earth's Environment and Habitability*, was released. This report developed a comprehensive vision of the science necessary to understand the complexity of planet Earth and the scope of programs and activities that GEO would address from 2001 to 2010. *NSF Geosciences Beyond 2000* identified key scientific areas and outlined a strategic balance between supporting high quality research, improving geoscience education and strengthening scientific capacity with the overarching goal of advancing understanding of the planet's integrated systems to benefit the nation. GEO continues to strive to maintain an appropriate balance of resources dedicated to research, infrastructure, education, and data and cyberinfrastructure to advance knowledge and nurture the next generation workforce.[1]

In 2009, AC GEO released *GEO Vision: Unraveling Earth's Complexities Through the Geosciences*, a call to action for the geosciences community and a series of recommendations to advance the state of geosciences. Developing this document included an examination of the underlying and cross-cutting foundational areas for the geosciences necessary to meet research challenges and related recommendations. *GEO Vision* (2009) outlined five priority research areas for the geosciences that continue to be major scientific drivers: the Dynamic Earth, Changing Climate, Earth and Life, Geosphere-Biosphere Connections and Water. In 2013, the former Advisory Committee for Polar Programs also released a report, *Recommendations for Polar Programs*, in which the committee laid out its advice on areas related to the Polar Regions including access, core research, systems, education, and people.

> *To comprehend the full range of physical, biological, and chemical processes of Earth's dynamic system, scientists must study deep-time records of these processes archived in the Earth's sedimentary carapace (crust) at all spatial and temporal scales. These records are fingerprints of the processes that produced them—processes that continue to shape the Earth. A deep-time perspective (spanning the billions of years of Earth history) through study of paleoclimate, paleobiology, crustal evolution and dynamics, and sedimentary resources is critical for predicting potential climate, energy, water, and other boundaries for human life on the planet.*
>
> *GEO Vision 2009*

GEO Imperatives and Frontiers

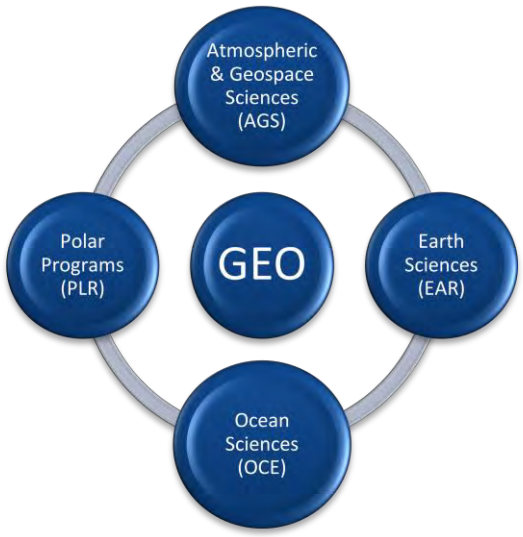
This newest strategic planning effort, *Dynamic Earth: GEO Imperatives and Frontiers 2015–2020*, builds on previous AC GEO reports and other strategic planning efforts within the community and NSF to fulfill GEO's mission to support research in the atmospheric, earth, geospace, ocean, and polar sciences.

[1] ***Additional information related to GEO's budget over time can be found by reviewing annual appropriations documents at http://www.nsf.gov/about/budget.***

Introduction

Within the GEO Directorate, Divisions are developing and refining division-level priorities that complement this report and provide a greater level of detail and insight into specific core research and program activities. This new document also reflects the fact that in 2012, the Division of Polar Programs[2] (PLR) joined with GEO. As a geographically focused division, PLR supports numerous scientific disciplines including traditional geosciences, astronomy and astrophysics, biology, and Arctic social sciences, as well as their integration. This merger provides GEO with a truly global perspective and reach. GEO is well-positioned to focus on ***Imperatives*** and ***Research Frontiers*** that complement and are bolstered by excellent core programs and all GEO staff.

This document is organized around four thematic areas: (1) Research, (2) Community Resources & Infrastructure, (3) Data and Cyberinfrastructure and (4) Education & Diversity. Each thematic area has supporting ***Imperatives –*** items at the GEO-wide level that must be accomplished in order to fulfill the potential of geoscience to advance knowledge and address critical national needs. In order to advance geoscience research in new directions, this document also identifies four examples of ***Research Frontiers*****:** Earth System Processes that Cross the Land/Ocean Interface; High Latitude Ocean-Atmosphere-Ice-Ecosystem Interactions and Processes; Urban Geosystem Science; and Early Earth. ***Research Frontiers*** are areas of growing interest in the GEO research community. The examples identified in this document, or other emerging themes may rise to the level of an **Imperative** if GEO and the community collectively agree that the timing is right for increased resources and effort. Frontier activities require an infusion of new resources in order to be fully supported.



NSF GEO supports research spanning the Atmospheric and Geospace, Earth, Ocean, and Polar sciences. As the primary U.S. supporter of fundamental research in the Polar Regions, GEO provides interagency leadership for U.S. polar activities.

On Solid Scientific Ground

The basic research at the heart of GEO's mission and supported by GEO advances scientific knowledge of the Earth's environment, including resources such as water, energy, minerals and biological diversity. GEO-supported research also underpins the critical needs to better understand, forecast, and respond to extreme events and geohazards (e.g., droughts, floods, earthquakes, volcanic eruptions, hurricanes, solar storms, tornadoes and other types of severe weather) and to improve adaptation to long-term changes in the environment, weather patterns, sea level and climate. GEO supports basic research that informs practices and policies regarding complex environmental issues such as resource

[2]The Division of Polar Programs was originally located within NSF's Directorate for Geosciences. In 1993, the Division was moved under the purview of the NSF Office of the Director and renamed the Office of Polar Programs for administrative reasons. In 2012, the Office of Polar Programs moved back into the Directorate for Geosciences assuming its original name, the Division of Polar Programs.

discovery, conservation and sustainability; water and energy availability; and species adaptation. Additionally, GEO provides platforms and infrastructure for basic research in scientific disciplines outside traditional geoscience fields, such as astronomy, physics, and anthropology in the Polar Regions.

GEO's education and outreach efforts bolster the nation's economy by preparing communities to understand and respond to living with our dynamic earth, as well as training an innovative and capable workforce. The GEO workforce includes geologically based sectors, such as the oil, gas, petroleum and mining industries; agricultural production; environmental services; information technology; hazard preparation and mitigation; groundwater industries; civil engineering and construction; government organizations and authorities; and research and exploration. Future geoscientists, such as hydrologists, geologists, glaciologists, meteorologists, oceanographers, seismologists, soil scientists, space scientists, and volcanologists, are paramount to ensuring that solid science guides our nation's conservation, management, safety and security strategies to meet critical societal and global challenges. GEO has a strong interest in promoting public participation and awareness of all the science it supports, as well as supporting and training the STEM workforce through extensive partnering with the Directorate for Education and Human Resources (EHR) on the Improving Undergraduate STEM Education (IUSE) effort.[3]

Partnerships and Paramount Connections

The considerable task of supporting and advancing the Imperatives and Frontiers in this report would not be possible without collaboration and partnerships. GEO actively reaches across organizational and disciplinary boundaries to leverage resources, tackle complex issues and share technology and data. Partnerships internal and external to NSF are necessary to bolster the resources and meet the goals of GEO.

GEO participates and plays a key role in various cross-agency efforts related to sustainability, environmental research and education, cyberinfrastructure, natural hazards and disasters. GEO participates in agency-wide efforts to support facilities for a wide array of these and additional science areas and is an important enabler of basic research. GEO also partners with EHR to broaden the participation of underrepresented groups in STEM through the IUSE effort and other activities.

Polar Biology Research Collaboration

Research station at Toolik Lake in Alaska.

The Arctic Long Term Ecological Research (LTER) Site at Toolik Lake Field Station is located in the foothills region of the North Slope of Alaska and includes the entire Toolik Lake watershed and the adjacent watershed of the upper Kuparuk River. The LTER site enables research aimed at understanding how tundra, streams and lakes function in the Arctic.

[3] ***NSF's emphasis on undergraduate STEM teaching and learning through evidence-based reforms, as well as enhancement of NSF's graduate fellowship programs, is guided by the Federal Science, Technology, Engineering, and Mathematics (STEM) Education 5-Year Strategic Plan*** ***http://www.whitehouse.gov/sites/default/files/microsites/ostp/stem_stratplan_2013.pdf***

GEO Partnerships

- NSF Directorates
- Academic community
- Professional societies
- Non-profit organizations
- Private foundations
- Private industry
- Federal Agencies [Department of Energy, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Geological Survey, U.S. Department of Defense, U.S. Department of Agriculture]
- Federal Funded Research and Development Centers (FFRDCs)
- State government & geological surveys
- International science agencies

External partnerships are also necessary to bolster GEO goals and leverage resources. For example, interagency partnerships are required to bridge the gap between the scientific-knowledge base supported by NSF's basic research mission and the missions of other federal agencies. GEO has been actively involved in various multiagency initiatives, such as U.S. Earth System Prediction Capability, United States Global Change Research Program, Ocean Research Priority Plan under the National Ocean Council, National Earthquake Hazards Reduction Program/Global Seismic Network and U.S. Weather Ready Nation. International relationships and activities also further GEO's reach and help catalyze the larger understanding of the Earth's systems. Because many GEO issues are global in scale, international partnerships are critical to maximize GEO-sponsored research. For example through the Division of Polar Programs, GEO supports and coordinates a broad array of research to ensure an active and influential role in the Antarctic Treaty System. Additionally, GEO is committed to efforts led by Future Earth and the Belmont Forum aimed at making advances in the arenas of water, coastal and Arctic sustainability and cyberinfrastructure. International partnerships are, and will continue to be, a necessity in addressing critical geosciences issues.

Increasingly, GEO is interested in connecting GEO basic research with the marketplace. GEO is participating in NSF-wide programs that promote partnerships between academic institutions and industry. GEO intends to enhance research in collaboration with industry partners to foster geoscience workforce pipeline retention, leverage funding and commercialize technologies that stem from basic research investigations and their evolving analytical and observational needs.

GEO's strong support for basic research as well as the collective efforts described above reflect and support NSF's strategic goals outlined in the *NSF Strategic Plan for 2014-2018*. Additionally, GEO supports Administration priorities for science and technology agencies[4], including:

- Earth observations
- Global Climate Change
- Information technology and high-performance computing
- National and Homeland security
- R&D for informed policy-making and management

Finally, GEO remains committed to transparency and accountability in all its procedures, consistent with Administration priorities and policies.

[4] *http://www.whitehouse.gov/sites/default/files/omb/memoranda/2014/m-14-11.pdf*

Introduction

How this Document is Organized

The thematic areas of Research, Community Resources & Infrastructure, Data & Cyberinfrastructure and Education & Diversity organize the remainder of this document. Each thematic area describes the GEO Directorate-level Imperatives identified for 2015-2020. The section following the Imperatives, *GEO Research Frontiers*, includes research topics that are currently viewed as strong interest areas for the Directorate that could be supported should additional resources become available. The GEO Research Frontiers topics will be revisited annually as part of the NSF GEO Program Officer science retreat and at future AC-GEO meetings.

Dynamic Earth: GEO Imperatives 2015-2020

Research
- Emphasis and Support for Basic Research (Core Programs)
- Hazards and Disasters
- Water Cycle

Community Resources & Infrastructure
- State-of-the-Art Facilities
- Ocean Observatories Initiative
- Logistics and Operations for the Polar Regions
- Next Generation Sun-Earth-System Community Models

Data & Cyber-infrastructure
- Community-Driven Cyberinfrastructure to Advance Data/Model-enabled Science and Education
- Harness the power of Computing and Computational Infrastructure
- Infrastructure for Observing Systems and Sensor Arrays
- Distributed Instrumentation and Facilities in Support of Research and Education

Education & Diversity
- Increase Undergraduate Exposure to and Enrollment in the Geosciences
- Prepare a Capable Geosciences Workforce
- Broaden Participation
- Public and Community-based Science
- Community resources for Research and Educational purposes

Dynamic Earth: Research Frontiers* (*subject to annual review)

Frontiers require an infusion of new resources to be supported. The Research Frontiers described in this document were developed from many sources including input from GEO program officers based on their interactions with the research community and their Principal Investigators. Other sources include national priorities outlined by the White House Office of Science and Technology Policy and the Office of Management and Budget.

GEO Imperatives in Research

NSF—one of the largest sources of federal dollars for basic research in the geosciences—is the only federal agency that supports the full breadth of the geosciences. NSF-supported geoscience basic research extends from the Earth's core out to the sun and encompasses the entire planet, from pole to pole, from the highest summit to the deepest ocean trench. The agency accounts for almost one quarter of federally obligated dollars in environmental sciences.[5]

Continue Strong Emphasis on and Support for Core Research

GEO advances understanding of our changing, complex planet and the many global processes that affect the Earth's system through support of basic research programs. Emphasizing and supporting core research in all its forms remains a GEO imperative and central to NSF's mission.

GEO advances understanding of our changing, complex planet and the many global processes that affect the Earth's system through support of basic research programs. Emphasizing and supporting core research in all its forms is GEO's most critical imperative and central to NSF's mission. GEO strives to meet this imperative by committing to support established programs dedicated to investigator-driven basic research aimed at achieving new knowledge through scientific discovery. GEO intends to maintain the culture of excellence in GEO core research programs including disciplinary, interdisciplinary, systems-level and community-driven science by encouraging and supporting interdisciplinary collaborations and participating in strategic NSF initiatives that advance GEO interests. While certain core research areas and priorities are highlighted in this document more than others, it is not an indication that the highlighted themes will overshadow the competitive award processes in GEO Divisions, where most of our fundamental discoveries are supported. This document should be considered in the context of ancillary GEO Division-specific planning reports, and efforts that complement and supplement the high-level priorities described herein.

An opportunity for strengthening core research lies in increased support of mid-scale research efforts. The 2012 National Science Board report *The National Science Foundation Support of Unsolicited Mid-Scale Research* (NSB 12-22) defined this research "as projects whose budgets fall between an amount higher than a typical NSF award and below that of a center." Enhancing emphasis on mid-scale research will provide opportunities for significant scientific advancement in core areas. While all areas of GEO research would benefit from mid-scale-level support, GEO Program Officers identified

Understanding Volcanic Systems

Erupting Kilauea - the youngest and southeastern-most volcano on the big island of Hawaii.

Understanding volcanic systems, or how magma moves beneath the Earth's surface, brings scientists closer to understanding the complexity of our planet's core. As magma is injected into the brittle upper crust, it erupts as lava and forms a new crust upon cooling. Scientists are investigating where magma is stored and how it moves through the core's geological "plumbing" network.

[5] ***"Environmental sciences" includes atmospheric sciences, geological sciences, oceanography. Source: NSF, Survey of Federal Funds for Research and Development.***

several needs including research across coastal boundaries, high pressure and temperature mineral physics collaboration, large-scale field studies, characterization of sub-glacial lake environments and improved space weather specification and forecasting.

Establish Collaborative Effort to Improve Understanding of and Resilience to Hazards and Extreme Natural Events

During the next five years, GEO intends to continue its support for key geohazards research through a new cross-divisional effort. Basic research in this area will deepen fundamental scientific understanding of natural processes underlying geohazards and extreme events and enable improved quantitative models and qualitative research that can enhance societal preparedness and resilience against such events. Research in geohazards is expected to have linkages with the NSF Directorates for Engineering (ENG); Biological Sciences (BIO); Social, Behavioral and Economic Sciences (SBE); Computer and Information Science and Engineering (CISE); and Mathematical and Physical Sciences (MPS), and with other Federal agencies including National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS). The program will support basic research that can enhance resilience and sustainable responses to extreme events and increase understanding of societal and economic interactions and impacts associated with hazards and disasters, such as droughts, floods, hypoxic zones, severe storms, extreme air pollution events, space weather events, earthquakes, landslides, sinkholes, toxic algal blooms, tsunamis, volcanic eruptions and wildfires.

Basic Research on Geohazards
Potential Areas of Inquiry

- Use adaptive sensor networks, portable systems, and real-time data assimilation to better understand the processes underlying extreme events and natural hazards and to improve short-time forecasting.
- Focus on regional "hot spots" such as high seismic activity zones and the Polar Regions to hasten predictive capabilities.
- Improve understanding and prediction of landslides by partitioning the contributing factors (e.g., sediment, erosion, precipitation, and hydrology).
- Increase understanding of fault behaviors contributing to earthquakes and tsunamis and improve system-scale modeling of coupled events.
- Tap the breadth of geoscience time scales to provide insight into future hazards.
- Improve warning times for and public response to tornadoes.
- Improve our understanding and forecasting of large space weather events and their potential impacts on our technology-dependent society.

Geohazards research will enhance:

- Understanding and forecasting of extreme events and geohazards and their impact on natural and human systems.
- Understanding of the fundamental processes underlying extreme events and geohazards on various spatial and temporal scales, and the variability inherent in such events and hazards.
- Quantitative models to improve understanding, mitigation, risks and resilience to extreme events.

GEO Imperatives in Research

Based on a history of investments in research related to natural hazards and resilience and the coupled natural-human system, NSF is well prepared to respond to this issue of critical national and international importance and to provide support for the scientific underpinnings necessary for informed policy-making and crisis management. GEO research priorities in this important area connect with and leverage investments made by U.S. and international agencies, such as the World Meteorological Organization's High Impact Weather Project and the USGS Volcanoes, Landslides, Earthquakes, and Floods reporting program; and the multi-agency National Space Weather Program.[6] For example, GEO supports an international research effort through COCONet, a GPS-Meteorological observing network in the Caribbean that helps to track severe weather and understand seismic and volcanic unrest. GEO will bring its leadership and unique federal research and education role to support research on hazards.

Moreover, the recent addition of Polar Programs to GEO expands the purview within the Directorate to understand extreme events linked to the Polar regions, as the poles are inherently central to the global climate system (e.g., permafrost thawing, contribution to sea level rise).

Preparing for Thunderstorms

Lightning strikes near the U.S. Capitol building during a thunderstorm in Washington.

Weather warnings with longer lead times will make a big difference in helping people prepare for natural disasters. To better predict where and when spring thunderstorms will strike, researchers are conducting experiments to gain a greater understanding of the genesis and development of severe storms. With high-flying aircraft and fine-grained computer simulations, scientists are enabling earlier warnings thus providing safer skies for air travelers and safer situations on the ground.

Basic Research on Food-Energy-Water System Potential Areas of Inquiry

- Where do water resources face the greatest stress and uncertainty?
- What are the local and global impacts of changes in water cycle dynamics at high-altitude, high-latitude regions?
- What technological innovations in engineering, energy and mineral extraction, and agricultural practices will prove most effective in achieving system resiliency and sustainability?
- Where are water and hydrocarbons hidden beneath the surface?
- What are the impacts of land cover fragmentation on water quantity, water quality, and "quality of life" for humans and ecosystems?
- What impact will a changing climate have on the global and regional precipitation pattern?
- Can biofuels be produced in a sustainable manner, and if so, what is the optimal strategy for sustainable biofuel production?
- What new measurement strategies, integrated modeling efforts, and data and information about the water cycle will enhance forecasting and decision-making at various levels within the system?

[6] ***See NRC report Severe Space Weather Events – Understanding Societal and Economic Impacts: A Workshop Report (2008) (http://www.nap.edu/catalog.php?record_id=12507).***

Establish a Collaborative Effort to Understand the Water Cycle

Water is essential for life in its many forms. Economic growth and human well-being wholly depend on the availability of adequate supplies of water for agriculture, energy use, transportation, ecosystem services, manufacturing and waste management. Climate change, shifting land-use patterns, and alterations in population demographics and needs are impacting the interplay between food availability, energy consumption and water availability. NSF can play a unique role in providing support for enabling a solid scientific understanding of the mechanisms that enable sustainability and resiliency of global food, energy and water resources as well as a firm scientific footing to underpin important public policy related to water resources.

Supporting Sustainable Water Management

Irrigation using pumped groundwater plays a crucial role in sustaining agricultural production.

The High Plains region boasts some of the most productive irrigated agricultural land in the United States, made possible by one of the largest contiguous aquifer systems in the world, the Ogallala-High Plains aquifer complex. However, in the face of the increasing demand for agricultural products, the reserved water is being pumped out faster than natural recharge of rainwater. To develop a plan to sustainably manage this vital resource, researchers are investigating water availability and the interactions of water systems with climate change and human activities.

During the next five years, GEO will coordinate with several NSF Directorates and explore external collaborative options to support basic research efforts that focus on the food, energy and water nexus. Two goals of this research are to integrate modeling of the food-energy-water system including assimilating information from existing NSF networks such as the Critical Zone Observatory (CZO), the National Ecological Observatory Network (NEON) and the Long Term Ecological Research (LTER) Network and to advance science and engineering solutions and technologies that solve component problems and optimize societal benefits. NSF will also partner with agencies and entities that work in agricultural regions and that have supported long-term agronomic research, such as U.S. Geological Survey, the U.S. Department of Agriculture, the Department of Energy, and the Environmental Protection Agency. Under the umbrella of food-energy-water research, GEO will invest in basic water cycle research to foster a better understanding of water as a primary agent for transporting mass and energy throughout the Earth. Research topics to explore include variations in global and regional precipitation rates and patterns, subduction zones and water distribution in the Earth's crust and mantle, shifts in the water cycle due to changes in cloud cover type and location, and water storage in ice, snow, and oceans. Investments will provide foundational research for enhancing societal resilience and decision-making regarding water, given unprecedented perturbations to the water cycle from climate change and increasing demands given a rapidly growing human population.

GEO Imperatives in Community Resources & Infrastructure

Effective science infrastructure satisfies scientific needs, provides broad observational capabilities and is flexible and adaptable to multiple scientific purposes. Facilities, community models and instrumentation are critical to the success of GEO's research investments. Across the geosciences, infrastructure investments range from shared-use instruments with annual operating costs of a few hundred thousand dollars to expansive centers of excellence where annual operations exceed one hundred million dollars. In the case of the United States Antarctic Program (USAP), NSF has special responsibilities to coordinate and manage the program on behalf of the nation. This section highlights the GEO Imperatives related to Community Resources and Infrastructure investments—largely Major Research Equipment and Facilities Construction (MREFC)-level investments—that are critical to meeting GEO and NSF commitments and research imperatives.

NSF's highest priority in achieving community resources and infrastructure imperatives are Major Research Equipment and Facilities Construction (MREFC) projects. NSF's MREFC account supports the acquisition, construction, and commissioning of major research facilities and equipment that provide unique capabilities at the frontiers of science and engineering. A project must represent an exceptional opportunity to enable research and education for NSF to consider it for MREFC funding. The project should be transformative in nature, i.e., with the potential to shift the paradigm in scientific understanding.

A considerable portion of GEO resources supports community resources and infrastructure such as Antarctic Facilities, Arctic Observing Network, Incoherent Scatter Radar (ISR), Toolik Field Station, Critical Zone Observatories, CubeSat, Earthscope, IceCube, Incorporated Research Institutions for Seismology (IRIS), International Ocean Discovery Program (IODP), National Center for Atmospheric Research, UNAVCO, and U.S. Academic Research Fleet. Increasingly in this era of constrained resources, challenges arise in balancing the need for state-of-the-art infrastructure with the need to maintain strong science research programs. GEO investments in facilities must thus be strategic to best support advancement in knowledge. GEO is able to draw on the recommendations of numerous community planning efforts to make these decisions. Some examples are the National Research Council (NRC) Decadal Survey of Ocean Sciences and NRC Study on NSF Science Priorities for Antarctic and Southern Ocean Research, both currently underway and the recently completed NRC Decadal Survey of Solar and Space Physics.

While GEO is making substantial infrastructure investments, other federal agencies, and other countries are doing the same. Private philanthropy, the business community, international investments and university investments are changing the landscape regarding support for facilities. These additional sources of funding represent an opportunity for the geosciences to leverage resources and management and operations expertise, but also a challenge to employ them effectively and appropriately. Fiscal realities require optimization of resources, which may mean changes to the mission, scope and purpose of facilities. An additional challenge for the scientific and engineering community at large is to maintain and modernize singular infrastructure at a level that meets scientific needs and advances scientific knowledge while effectively and efficiently linking infrastructure, investments, and data to provide an integrated view of the Earth system.

Maintain State-of-the-Art Facilities

Observational, computational, sampling and laboratory resources and infrastructure are central to the success of the geosciences and related disciplines. State-of-the-art facilities must be designed to support multiple issues and disciplines and be available as community resources. It is also imperative that GEO sustain its commitment to existing facilities that enable new discoveries. Scheduling and prioritizing access to resources must be transparent in order to ensure the broadest participation. Some examples of the high-caliber resources that GEO must continue to support include:

Research Vessel *Sikuliaq*

Research Vessel *Sikuliaq* is designed to operate in Arctic sea ice and the open water surrounding Alaska. It will support roughly 500 researchers and students annually and spend up to 270 days per year at sea. The vessel is uniquely outfitted with the latest technology for marine research, including a low underwater noise signature, advanced communications, acoustic sensors, and advanced scientific equipment handling systems.

- The US Academic Research Fleet (ARF), as organized through the University-National Oceanographic Laboratory System (UNOLS), constitutes a capable and unique shared-use facility critical for a broad variety of measurements and observations by a diverse community of scientists. The ARF includes the NSF vessel *Sikuliaq,* an MREFC project that dramatically increases the ability to support Arctic scientific research. In addition to its state-of-the-art scientific capabilities, the *Sikuliaq* complies with the Americans with Disabilities Act, allowing increased access to the ship. Regional Class Research Vessels (RCRV), a potential MREFC project, presents an opportunity to optimize the size of the academic research fleet, meet needs across government agencies for research vessels in support of ocean science research and support action items in the National Ocean Policy Implementation Plan.
- EarthScope has enabled exciting discoveries about the dynamics and evolution of the North American continent and the Earth as a whole, including plate boundary process and hazards. EarthScope will continue to catalyze an explosion of new approaches for analyzing and modeling unprecedented volumes of seismic wavefield data across very large arrays. Additionally, geodetic technology supported through Earthscope is transforming our understanding of fault, volcanic, hydrologic and surficial systems and advancing data archiving, data connections and data tools for massive amounts of geodetic, seismic, petrophysical and meteorological information. The success of EarthScope has been enabled by long-term NSF infrastructure investments in seismology through IRIS and geodesy through UNAVCO, both of which support observational networks around the globe.
- McMurdo Station, the largest of the three year-round stations operated by the U.S. Antarctic Program, is a critical hub for U.S. science and logistics. Findings of the U.S. Antarctic Blue Ribbon Panel in 2012 found “no reasonable alternative to McMurdo…that would permit transshipping (sea, air, and land), or that would justify abandoning the investment made in fixed plant at McMurdo.”

- For more than four decades, the NSF-supported Incoherent Scatter Radar (ISR) network has provided critical observations of the ionosphere and upper atmosphere that underpin fundamental research and agency priorities in geospace and space weather science. New ISR technologies offer exciting opportunities to expand global coverage and enable new observational capabilities. Collectively, observations of ISR and other facilities and technologies are essential to inform and guide the development of the next generation Sun-Earth-System Community Models.

GEO must continue to act as a steward of community resources to sustain the infrastructure that will support current and anticipated future scientific research priorities. The NSF-GEO Facilities and Infrastructure Team (GEO-FIT)[7] is developing a GEO-wide approach to infrastructure lifecycle management. The approach will examine and account for all infrastructure phases—from proposal and initial award through construction or acquisition, operation and maintenance, and sun-setting. GEO-FIT will develop a set of standards to assess the efficiency of GEO facility operations and to determine when re-competition of a facility or its management is required and to assess when and how a facility should be discontinued.

Considerable community demand exists for mid-scale infrastructure (approximately $10 million to $60 million). To meet this need, GEO is exploring a process for mid-scale infrastructure support. Consistent with Administration priorities for science and technology in FY 2016,[8] the GEO plan will include programmatic efforts to encourage development of sophisticated tools to collect Earth-observation data. These tools are critical both to advance understanding of the Earth system as well as to lay an observational foundation for services that protect life, property, and the economy.

OOI Priority Areas for Innovation

OOI Technology

- Cabled Technology
- Cyberinfrastructure
- Moorings
- Robotics (Autonomous Underwater Vehicles & Gliders)
- Sensors

OOI Major Science Themes

- Climate Variability, Ocean Circulation, and Ecosystems
- Coastal Ocean Dynamics and Ecosystems
- Fluid-Rock Interactions and the Sub-seafloor Biosphere
- Plate-scale Geodynamics
- Ocean-Atmosphere Exchange
- Turbulent Mixing and Biophysical Interactions

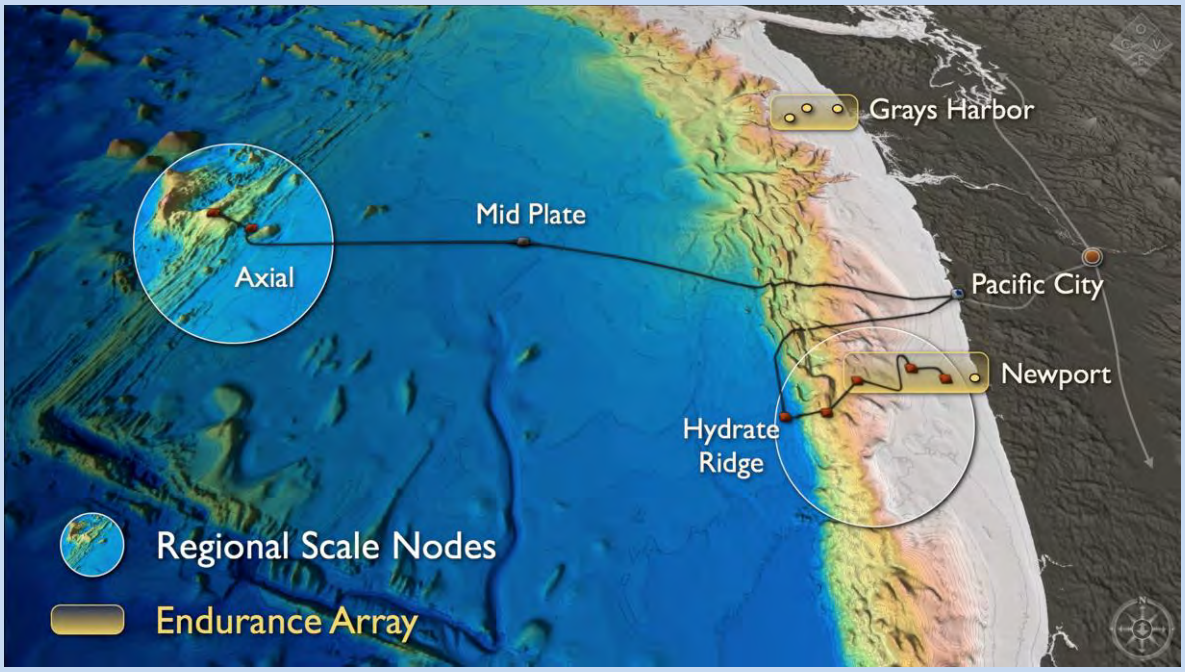
Complete Construction and Begin Full-Scale Operation of the Ocean Observatories Initiative

The Ocean Observatories Initiative (OOI) will enable study of complex, interlinked physical, chemical, biological and geological processes operating throughout the global ocean. This initiative will allow simultaneous, interdisciplinary measurements to investigate a spectrum of ocean phenomena and processes including episodic, short-lived events, and more subtle, long-term changes and emergent phenomena in ocean systems. OOI provides a unifying cyberinfrastructure that enables concurrent control of sampling strategies and response to remote detection of events. OOI contributes to the major goals of both the Integrated Ocean Observing System and the National Ocean Policy. GEO's investments in advancement of the ocean sciences on a global scale through OOI are of critical importance.

[7]The NSF-GEO Facilities and Infrastructure Team is an internal NSF group made up of program officers and other staff who manage infrastructure programs in GEO.

[8]Executive Office of the President of the United States, Office of Science and Technology Policy and Office of Management and Budget, Memorandum for Heads of Departments and Agencies: Science and Technology Priorities for FY 2016 Budget, M-14-11, July 18, 2014.

Ocean Observatories in Operation



Ocean Observatory Initiative (OOI) Regional Scale Nodes program provides high-bandwidth connectivity between land and sea.

OOI is a multi-scale ocean observing system. Planned to be operational for 25 years, it provides sustained, time-series data that enables researchers to study complex, interlinked physical, chemical, biological, and geological processes operating throughout the global ocean. OOI also releases its data to the public and educators, making oceanographic information available to citizens and scholars who might never go to sea.

Implement Strategic Plans for Logistics and Operations for the Polar Regions

GEO remains committed to promoting innovative methods of safe and efficient fieldwork and data gathering in support of the critical research being conducted in the Polar Regions. As part of this commitment, GEO will continue its strategic consideration and implementation of U.S. Antarctic Blue Ribbon Panel recommendations.[9] GEO will follow steps outlined in the recommendations, which includes needs identified by user committees such as researchers and support contractors, as well as the Department of Defense (DoD) and other federal agencies.

With the addition of the Division of Polar Programs (PLR), GEO significantly enlarged its portfolio of facilities, research ships in particular, as well as its expertise and experience in facilities management. GEO continues to sequence major investments, such as vehicle fleet replacement and major maintenance, in order to optimize equipment life-spans and distribution of resources. GEO also pledges to develop a long-term solution to NSF's major ice-breaking needs and is coordinating with the U.S. Coast Guard and others on this effort.

McMurdo, Logistics Hub of the Antarctic

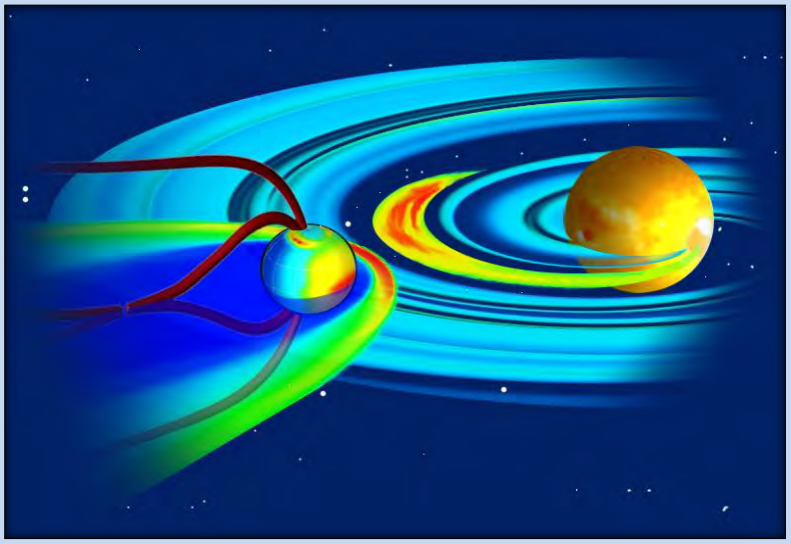
Established in 1955, McMurdo station is the logistics hub of the U.S. Antarctic Program. It is built on the bare volcanic rock of Hut Point Peninsula on Ross Island, the solid ground farthest south that is accessible by ship. The station is equipped with lab facilities, repair facilities, dormitories, administrative buildings, a firehouse, power plant, water distillation plant, wharf, stores, and warehouses.

[9] ***U.S. Antarctic Program Blue Ribbon Panel, More and Better Science in Antarctica through Increased Logistical Effectiveness, July 2012.***

Begin Conceptualization and Development of Next-Generation Sun-Earth-System Community Models

Sun-Earth-System models are equally as critical as an instrument-based facility to GEO community resources. Versions of these models have been downloaded and used by researchers and other professionals throughout the world. The development and maintenance of complex system codes in these models is beyond the capabilities of single researchers and requires strong community collaboration.

Collaborative Space Weather Modeling



A Model of Community Coordinated Modeling Center (CCMC)

NASA NSF Partnership for Collaborative Space Weather Modeling supports large-scale space weather modeling efforts that require collaborative community teamwork. This joint effort has been significantly enhanced by our capabilities in the modeling and prediction of solar eruptions, particle acceleration in the corona and solar wind, small scale physics effects in global magnetosphere models, and upper atmosphere dynamics.

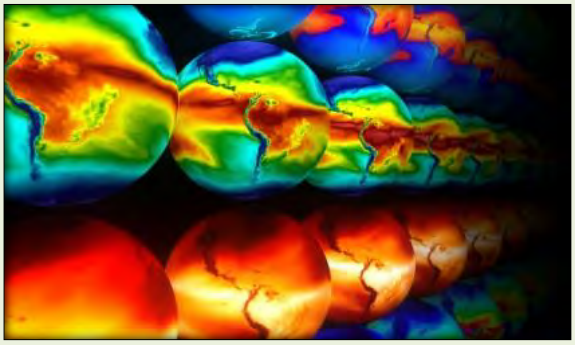
Therefore, GEO will support the development of improved modeling techniques to handle multi-scale phenomena, community access to adaptable, modular, modeling frameworks and improved data assimilation techniques. GEO will work to expand the next generation models to address disciplinary gaps (e.g., ocean sciences, hydrologic sciences, geomorphology). Additional collaboration opportunities may materialize as interest in Sun-Earth System models broadens and scientific working groups in biogeochemistry, land and ocean modeling, land/ice, polar climate, solar and space plasma physics and societal dimensions become engaged. Sun-Earth system models also must incorporate ecological, biogeographic and evolutionary responses to changes in the state of the Earth system if they are to address societal needs by forecasting short and long term environmental change. In addition, integrating ecosystems models into physical Earth system models is one of the great cyber-development challenges facing geoscientists today.

GEO Imperatives in Data & Cyberinfrastructure

Geoscientists are increasingly engaged in data-intensive science and investigation, data management and long-term data access and storage. GEO-supported research endeavors will require significant advances in computational capabilities and data management, including data access and storage issues. GEO seeks transformative concepts and approaches to create integrated data management infrastructures across the geosciences.

Develop Community-Driven Cyberinfrastructure to Advance Data/Model-enabled Science and Education

EarthCube – Geoscience Data for the 21st Century



Advanced computational and data technology is playing an increasing role in geoscience research, powering new knowledge in space, atmospheric, oceanic, and terrestrial systems. However, models and data often exist in disparate and incompatible systems, limiting collaboration and discovery across disciplines. To address this deficiency, GEO is working with NSF's Division of Advanced Cyberinfrastructure (ACI) to develop EarthCube, a community-driven project that aims to grow integrative systems and support data and knowledge management across the geosciences.

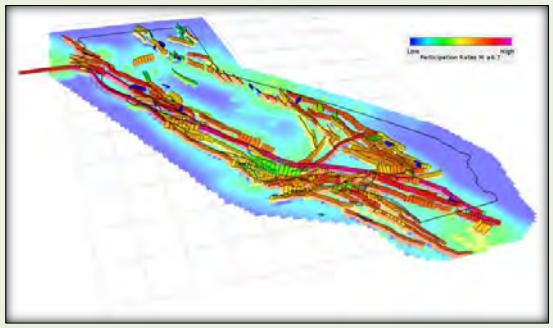
Through its EarthCube project and close collaboration with the NSF Directorate for Computer and Information Science and Engineering (CISE) and other organizations, GEO has entered into a staged, iterative cyberinfrastructure implementation approach that engages various science and information technology communities. GEO will continue to engage the geoscience community in developing a coherent, distributed framework for the open and easy discovery of, and access to, data; software and services; information; and computational resources. Open access to data is critical to promoting scientific innovation and to maintaining a culture that values transparency and reproducible results. GEO will also facilitate a dialogue regarding the coordination of geoscience data and software facilities.

Establishing technology for sharing data and workflows within and across disciplines, as well as for discovery of and access to information across disciplinary boundaries will greatly enhance multidisciplinary research. GEO will support new, transformative science and education through the effective use of geoscience data enabled by modern software, models and analytical tools (e.g., computer vision and machine learning techniques) that can simulate and examine complex and interrelated Earth processes. GEO will collaborate with various communities to develop a unified cyberinfrastructure framework that addresses issues related to data archiving and reuse, discovery, access, visualization and integration. Dark data (data not easily rendered into digital formats) and large volumes of model-generated data pose particular challenges. GEO is well positioned and committed to advancing data and model-enabled science and education including increasing and improving access to modeling capabilities for researchers, educators and students.

Transformative approaches and innovative technologies are needed for heterogeneous data to be integrated, made interoperable, explored, and re-purposed by researchers in disparate fields and for myriad uses across institutional, disciplinary, spatial, and temporal boundaries.

GEO Imperatives in Data & Cyberinfrastructure

Harness the Power of Computing and Computational Infrastructure



Uniform California Earthquake Rupture Forecast v.3 (UCERF3), which forecasts possible damaging earthquakes, produced using TACC supercomputers.

GEO has a long history of cyberinfrastructure investments across scientific domains and now has an opportunity to accelerate the pace of scientific discovery by harnessing the power of computing and computational infrastructure. Cutting-edge geoscience research, involving modeling and the analysis of "big data," increasingly demands high performance computing. Some of these needs must be met at the scale of national computing centers. However, the community of users who require mid-size computing clusters is very rapidly growing, both for certain classes of research problems and for the development of codes that will eventually be implemented on larger platforms. Hence, GEO will support adoption of a robust, widely available computational infrastructure to support data-enabled science and computing at multiple levels.

Science enabled by data and supporting cyberinfrastructure is central to furthering our understanding of the Earth System.

Various modes and methods of support will address resource issues such as:

- Access to and availability of computing resources including the NCAR-Wyoming Supercomputing Center
- Dedicated personnel to support effective use of high-performance computing resources
- Extensible computing solutions and the role of cloud computing
- Improved models/algorithms and sustainable community modeling efforts

Enhancing community-wide frameworks to share and coordinate software development across geoscience fields (e.g., EarthCube and Computational Infrastructure for Geodynamics (CIG)) is key to enhancing geoscience research. As with data, software requires careful stewardship and curation for community use at all stages of its life-cycle, including documentation, distribution, updating, and re-purposing.

Supercomputing out West

Housed at the NCAR-Wyoming Supercomputing Center (NWSC), the Yellowstone high performance computing system is putting U.S. geoscientists at the forefront of their field. The center and its 1.5-petaflops supercomputer are sponsored by the NSF and available for NSF-funded researchers to produce the world's most advanced models, from sophisticated climate simulations to life-saving wildfire prediction systems.

Invest in Infrastructure for Observing Systems and Sensor Arrays

As fully engaged leaders and stakeholders in an unprecedented era of observation and simulation capabilities, GEO must invest in infrastructure for observing systems and sensor arrays. GEO will support connection and integration of observing networks, data streams and systems, and sophisticated analytical and computational resources in order to:

- Enhance availability, effectiveness, quality, and utility of data from sensor, instrumentation, and observing systems;
- Increase speed and transparency of data transfer from the field into data systems and applications; and
- Increase emphasis and capacity for virtual operations, including remote manipulation of equipment at field sites.

Remote Sensing in the Sierra

Remote sensors at work in the Southern Sierra Critical Zone Observatory (CZO).

Wireless sensor networks at the Sierra site and CZO sites across the country are streamlining data collection and enhancing our understanding of climate, hydrology, and biotic systems. These water-balance instrument clusters include over 380 sensors that measure everything from solar irradiation to soil moisture to snow depth, wirelessly transmitting collected data to a central terminal.

Enhanced rates of data transfer from the field and more robust mechanisms for virtual operation of observing systems in the field will improve data quality and research outcomes. Reducing costs of real-time data transfer and virtual operation will make them more accessible to researchers, and eventually could lead to cost savings as necessary person-time in the field is reduced.

Next-Gen Geoscientists

Student outreach is broadening the reach and appeal of the geosciences.

NCAR's Computational & Information Systems Lab (CISL) hosts undergraduate and graduate students from underrepresented backgrounds at the Software Engineering Assembly conference. This experience helps students hone their computational skills.

Use Distributed Instrumentation and Facilities in Support of Research and Education

Cyberinfrastructure has a key role in workforce development as virtual communication can be highly effective in education, mentoring and outreach efforts. GEO's research agenda offers countless opportunities to engage the scientific community in education and outreach activities, as well as provide authentic research opportunities for students, educators and life-long learners. Furthermore, new GEO research directions require greater computing expertise among geoscientists and improved understanding of the geosciences among computer scientists.

GEO Imperatives in Data & Cyberinfrastructure

For the next generation, we need developers of cutting-edge methods and codes as well as users of widely available codes who have a robust understanding of the underlying methods. GEO will leverage its investments in distributed instrumentation and facilities in support of research and education. Bringing data and tools to the classroom will provide invaluable educational experiences and spark interest in pursuing STEM career paths.

GEO Imperatives in Education & Diversity

Our future sustainability and prosperity require an interdisciplinary workforce that reflects the nation's diversity and has the capacity to work collaboratively to develop effective solutions for complex societal issues. GEO is committed to promoting community engagement, nurturing the next generation of scientists, enhancing the capabilities of the current workforce and broadening participation at all levels. GEO will continue to work in partnership with key internal organizations, such as the Directorate for Education and Human Resources (EHR), as well as numerous external organizations, professional societies, scientific communities and private industry.

Two Principal Investigators discuss strategies for GEO Research Experiences for Undergraduate (REU) programs at an REU workshop in San Jose, CA.

Increase Undergraduate Exposure to and Enrollment in the Geosciences

GEO-supported disciplines often differ from other scientific disciplines in the lack of a discrete path from high school to undergraduate studies to graduate studies. Therefore, GEO recognizes and supports the need to recruit and retain undergraduates by exposing them early to the geosciences.

Specific GEO objectives under this Imperative include:

- Increase undergraduate student exposure to the geosciences overall and increase the number of undergraduate students earning Bachelor's degrees in geoscience majors.
- Explore the role and benefits of service learning in geosciences, in terms of workforce development and undergraduate education, engagement and retention, as well as identifying research directions that are relevant to communities and as a bridge between basic research and community-relevant science.
- Increase the number of students enrolling in geoscience graduate programs by ten percent over the next five years.
- Identify graduate-level competencies in the geosciences and other disciplines supported by GEO.

Prepare a Capable Geosciences Workforce

GEO will fund programs that build capacity through education and training experiences for both the current workforce and the workforce of the future. This approach will include promoting networking of programs so that their impacts are scalable. Key strategies and specific actions in this area for the next five years include:

- Identify skills and competencies needed by the GEO workforce and corresponding curricula that provide the undergraduate experiences necessary to gain such skills and competencies.
- Provide supplementary support to well-functioning programs that reach a wider population of undergraduate students, including those at community colleges.
- Expand research opportunities through the established Research Experiences for K-12 Teachers, Advanced Technological Education (ATE) and Research Experiences for Undergraduates (REU) programs.
- Support training programs for those currently in the workforce to enhance their skills.

Student-Built Rover Braves the Antarctic

Two high school seniors work to patch up rover "M'RAJE."

When two high school seniors decided to build a remotely operated vehicle (ROV) for the Marine Advanced Technology Education ROV design competition, they never expected their technology to be used to conduct research in Antarctica. With the help of marine biologist, Gretchen Hoffman from the University of California-Santa Barbara, these students have helped to build an underwater, camera-equipped "rover" that can withstand harsh Antarctic conditions for polar ice observations. Their prototype, referred to as "M'RAJE," completed 10 successful dives during a recent Antarctic research season. Such NSF funded opportunities motivate youth to dream big and invent the seemingly impossible.

Geoscience graduates have numerous employment opportunities.[10] Through partnerships and networks, GEO will help students explore career options for geosciences-related employment in academia, government, and the private sector and also enable established professionals to keep pace with the latest advances in geoscience research.

Broaden Participation of Underrepresented Groups

Broadening participation of scientists and students from underrepresented groups is a priority in all aspects of GEO's business operations—from grant funding to merit review to staff hires. In addition to preparing the future workforce, GEO re-affirms its intention to increase the diversity of students in the geoscience-related fields by pursuing the following objectives and actions over the next five years:

[10] *See the AGI "Current" on "The Industries of Geoscience Graduates' First Job by Degree Field." (AGI Current #90, July 24, 2014) for a graphic depiction of industries that employ newly minted geoscience graduates.*

GEO Imperatives in Education & Diversity

- Increase the diversity of students who participate in internship programs and GEO-funded research.
- Expand access to quality geoscience education and research experiences by partnering with Minority Serving Institutions (MSIs) and community colleges.
- Encourage and support partnerships among geosciences degree-granting institutions, MSIs and community colleges. Adopt methods to sustain partnerships, especially at critical junctures (e.g., times of re-organizations, staff turnover).
- Provide research and technical training opportunities for underserved groups at GEO facilities, including opportunities to enhance participation of persons with disabilities through innovative use of technology.

To meet these objectives, GEO will focus its efforts on those programs that have proven effective and can be scaled, disseminated and sustained. For example, GEO, EHR and other NSF Directorates recently launched the Improving Undergraduate STEM Education (IUSE) program, designed to support research and development leading to and propagating interventions that improve both the quality and quantity of STEM graduates. To be most effective, many of these activities will be developed in partnership with researchers, other agencies, professional societies, and through public-private partnerships. Providing resources and tools for NSF-supported researchers to facilitate meaningful activities for promoting broader participation is an important aspect of this approach. GEO also will work with EHR to support professional development of faculty to improve pedagogy and mentoring skills.

Sailing for Science

Students assist with the management of magnetometers to record the magnetic field during the Jurassic Ocean Crust Magnetic Survey Program (JOCMS) voyage.

First generation college students from Kutztown University of Pennsylvania went on a six-week voyage to study the Pacific seafloor through the Jurassic Ocean Crust Magnetic Survey Program (JOCMS). The purpose of the trip was to study the behavior of the magnetic fields during the middle and late Jurassic period. Alongside real life experience at sea, students participated in data collection and processing and assisted in developing a website for the cruise. The goals of the program are to foster professional development and to provide students with a skillset that will prepare them for advanced programs in marine biology.

Promote Public and Community-based Science to Improve Public STEM Literacy and Decision-making, and to Advance the Geosciences

Another important aspect for GEO's Education and Diversity goals is to promote public and community-based science to improve public STEM literacy, support decision-makers and advance the areas of science that we support. A better-educated public can make informed decisions and choices regarding policies and activities that are beneficial to society and the environment. GEO has a strong interest in promoting public participation in and awareness of our science. To that end, GEO will:

- Fund supplements to promote community engagement and broadening participation.
- Improve the readability of GEO award abstracts and titles so the supported research is more accessible to the general populace.
- Encourage geoscience professionals to communicate clearly with public audiences about the excitement and relevance of their work and to engage in community-based science activities.
- Promote effective communication of geoscience information to stakeholders such as engineers; surveyors; urban planners; emergency managers; resource managers; energy developers; local, regional and federal government officials and related stakeholders in other countries or in international organizations.
- Support development of online and print material and other media to interest the public, particularly students, in the geosciences.

Geoscience for Kids

Online Magazine "Beyond Penguins and Polar Bears" for elementary Geoscience Education.

NSF has funded a free online magazine targeted towards K-5 teachers. Using the natural intrigue of the Arctic and the mystical creatures that live in the wintery tundra of the southernmost part of the world, the magazine covers a broad range of topics from weather and climate to geography, culture and art, and polar science. The magazine also facilitates inquiry-based teaching and scientific discourse. Beyond Penguins and Polar Bears has received Science magazine's Science Prize for Online Resources in Education for its innovative ability to provide free online science education.

A pressing need exists to translate new knowledge into public information and advice to aid decision-makers. GEO will partner with NSF's Office of Legislative and Public Affairs (OLPA) over the next five years to improve the availability and accessibility of GEO-funded research results.

Technology has broken down the barriers between education in formal classrooms and informal learning environments, including museums, science centers, and the home.

Technology-rich environments can help retain students in all parts of the pipeline from K-12 through graduate school. Interactive technology tools can help students learn and retain information better than traditional classroom lectures as they can also be tailored to multiple learning styles and abilities.

Promote Use of Community Resources for Both Research and Educational Purposes

GEO will increase support for projects that harness the power of widely available technology for innovations in GEO-supported science and education (e.g., pressure sensors in smart phones, cars as weather stations, GPS satellite signals).

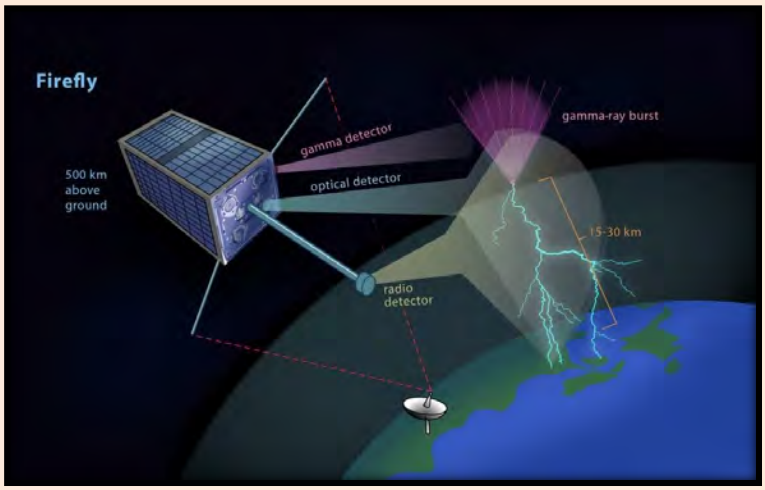
GEO Imperatives in Education & Diversity

GEO will work with partners to explore the possibility of issuing an incentive-based (e.g., prize, challenge) call for proposals in this area. Also key to the GEO-supported research enterprise, particularly in geographic areas such as the Arctic, is support of science that is relevant to local communities. For example, many PLR-supported researchers include Arctic residents as full partners in all aspects of their research projects. These collaborations provide interesting models to engage with community-based science efforts around water, weather and other topics with strong local impacts.

Youth outreach in Critical Zone Observatory, Boulder, CO to explain glacial erosions.

GEO encourages the development of creative, scalable options to expose undergraduates to genuine research experiences and instrumentation. GEO will leverage facility investments for undergraduate research and technical training with a focus on virtual access such as that available through CubeSats, Alvin and OOI to help larger numbers of students connected to real-time research and to facilitate the creation of new networks of researchers. GEO will work with its facilities and researchers to identify viable candidates for instrument deployment and support deployments of instrumentation for the primary purpose of education and outreach (e.g., EarthScope, transportable arrays, radars and aircraft).

Probing Outer Space for Data



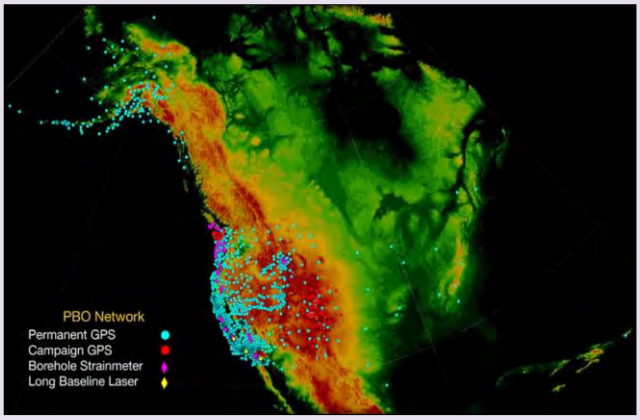
This small satellite known as Firefly will be used to study gamma-ray bursts associated with lightning.

Obtaining observational data from space is essential to understand geospace and atmospheric systems. The CubeSat is a conglomerate of small satellites that are able to provide multi-point information important for comprehensive understanding of the atmospheric sciences. The goal of the CubeSat program is to provide support for the construction, launch and data collection of small microsatellites. Additionally, CubeSat aims to train the future generation of experimental space scientists and aerospace engineers.

GEO Research Frontiers: Dynamic Earth

In addition to GEO Research Imperatives described earlier in this document, GEO has identified examples of emerging research frontier areas that it would like to support in the near future. These Research Frontiers reflect loci of growing interest and activity among GEO researchers that span multiple GEO divisions. GEO Frontiers represent advance planning efforts for areas of investment in the event that new resources become available. The Frontiers described in this document should be viewed as illustrative examples and not as exclusive targets for new funding. GEO will support Frontiers in the interest of advancing scientific knowledge but will not do so at the expense of core research. Supporting fundamental research is GEO's number one priority.

The Frontiers described below were identified and refined through an annual science planning retreat of GEO program officers. These program officers are GEO's critical link to the research community. A crucial part of their job is to keep abreast of trends and issues in geoscience and related fields. They interact daily with researchers, professional societies and Federal partners among many others and keep informed of community reports and national studies such as those of the National Research Council. These are the inputs that they bring to the annual Program Officer Retreat. The annual retreat gathers staff from across GEO to focus on cross-divisional and inter-disciplinary activities, and is in addition to the discipline- and division-specific planning that takes place within GEO's divisions. At the retreat, Program Officers focused on science challenges and opportunities that are forward-looking, scalable and of potential interest across GEO Division boundaries. The forward-looking topics could further develop existing programs by building connections and collaborations only possible through the inclusion of other divisions, directorates, agencies or countries.



NSF EarthScope plate Boundary Observatory GPS network provides precise data for accurate observation and modeling.

As the geosciences continue to advance and investigator-driven research opens up new avenues in basic research, new Frontier areas will emerge and the examples listed below may change in emphasis or importance. Scientific advances and other external forces may cause some Frontiers to be re-categorized as a GEO Imperative. Thus, this document and the priorities described within will be revisited and revised as appropriate.

Earth Systems Processes that Cross the Land/Ocean Interface

Traditional disciplinary examinations of terrestrial processes and ocean processes have yielded significant advances in scientific understanding. GEO is interested in exploring the study of Earth system processes that cross the land-ocean interface to better understand the implications of process interplays on human populations, coastal resources and terrestrial resources. Geologic processes occurring across the land-ocean interface have clear implications for the sustainability of coastal resources, particularly those significantly impacted by concentrated population centers. GEO-supported sea level rise studies and the recent coastal disasters of Hurricanes Katrina and Sandy provide impetus for GEO to lead a strong and productive effort in this area.

GEO anticipates the need for additional basic research support in these areas:

- Response of marine ecosystems to climate change and variability as well as to anthropogenic economic activity, e.g., discharges, fishing pressure, non-renewable resource extraction.
- Surface water-aquifer interactions, submarine groundwater discharge and salt water intrusion into coastal aquifers in response to sea level dynamics that have implications for coastal water resource management, fisheries and aquatic ecology.
- Geodynamics at plate boundaries of active margins and resulting stresses that release energy within fault systems, rearranging topography and initiating high-energy events at the land-ocean interface; altered topography modifies wind and current patterns, sediment and atmospheric moisture transport and renewable marine and terrestrial resources.
- Differentiation between regional and global sea level variability to better understand and predict changes in sea level associated with melting and loss of major ice sheets.
- Atmospheric interactions and effects on the land-ocean-hydrosphere interface.

High Latitude Ocean-Atmosphere-Ice-Ecosystem Interactions and Processes

Inter-agency and inter-governmental partnerships are forming that will enhance research opportunities in the Arctic and North Atlantic as well as in the Southern Ocean. One example is trans-Atlantic cooperation of NSF and NASA programs with Europe's Horizon 2020 framework studies of the Arctic, sub-Arctic, and North Atlantic. In addition, the stability of ice sheets and ice shelves is of global importance, yet the Southern Ocean and Antarctica are especially remote and under-sampled.

GEO is interested in enhancing research that will integrate observations, analysis, modeling and management and decision support for these ocean-atmosphere-ice-eco-systems in the areas of ocean circulation, climate, biogeochemistry, food web dynamics and community structure, and ecosystem health and diversity. Current areas of interest include increasing understanding and predictive capabilities of:

- Variations in fresh water delivery to the surface waters of the North Atlantic and Arctic Oceans via export of sea ice from the Arctic, melting of the Greenland Ice Sheet, periodic releases of fresh water hydrologic cycle.
- Feedback within the non-linear climate system as the atmosphere responds to and drives changes in the ocean, particularly within the Southern Ocean.
- Variations in ecosystem productivity and biodiversity (e.g., bloom dynamics and impact on carbon dioxide (CO_2) sequestration), as productivity is involved in climate regulation and is a primary source of resources that sustain natural ecosystems and human populations.
- Exchange of CO_2 and heat; carbon cycle sources, and sinks.
- Climate change; ocean acidification; community and ecosystem change.
- Better process models at multiple scales for aerosols, clouds, radiation, and precipitation.

Greenland Glacier

Urban Geosystem Science

Scientists will explore interconnectivities between the natural and built environments.

Rapid changes in land use result in complex and poorly understood interactions between air, water, soil and surface characteristics. A need exists for additional research to understand the interactions and feedbacks between urban and climate systems such as the influence of waste heat on regional circulation patterns, urban outflow on ocean systems, urban albedo effects on climate systems on various spatial scales and how sea level rise and storm surge impact coastal cities.

GEO is interested in supporting broad areas of study related to urban geosystem science and other "human system" issues (e.g., suburban sprawl, parklands, recreational and tourism activities). Potential partners with GEO include the NSF BIO, ENG, SBE, and MPS Directorates and other federal agencies with complementary interests such as the Department of Energy, U.S. Environmental Protection Agency, U.S. Army Corps of Engineers, NOAA, the National Institutes of Health and USDA.

NSF is currently supporting two long-term studies of urban ecology in the cities of Phoenix, Arizona and Baltimore, Maryland through the LTER program. Such research will inform GEO-supported research in urban geosystem science. Additionally, GEO and other NSF Directorates issued a solicitation in 2014 for Sustainability Research Networks (SRN) that support multidisciplinary teams of researchers, educators, managers, policymakers and other stakeholders to conduct collaborative research that addresses fundamental challenges in urban sustainability. Networks will be organized around relevant issues such as coastal urbanization, urban heat islands, food systems, energy, biodiversity, essential ecosystem services, transport, or governance.

GEO Research Frontiers: Dynamic Earth

Early Earth

GEO would like to accelerate advances in the understanding of fundamental areas of inquiry related to the Early Earth. The 2008 NAS report entitled "The Origin and Evolution of Earth: Research Questions for a Changing Planet" identified key scientific questions worthy of additional exploration.

Chu Research Group, Chinese Academy of Sciences, dig into a shale exposure North China to explore how early life evolved.

- When and why did Earth's core form and the geo-dynamo originate?
- Why does Earth exhibit plate tectonics while other planets do not?
- How important is a magnetosphere for preservation of atmospheres and oceans?
- What planetary processes could have occurred on a pre-Plate Tectonics Earth?
- How were early Earth's oceans and atmosphere formed and subsequently influenced by biotically mediated and pre-biotic chemistry?
- How was the origin of life constrained by the timing and nature of early Earth's atmosphere, oceans and tectonics? Understanding when and how plate tectonics began and impacts of transition to plate tectonics on ocean chemistry, climate and life evolution.

GEO has a standing Early Earth Discussion Group that has reached out to the academic community and agency partners through discussions, workshops and other mechanisms. GEO could expand its work in partnership with other NSF Directorates and federal agencies to study how early Earth and solar system processes contributed to the development of a habitable environment with ocean, atmosphere and a life-preserving geo-dynamo. This research would provide additional insights and understanding of Earth-core formation processes, geomagnetic field evolution, evolution of the Earth's atmosphere, and emergence of microbial life and diversification.

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