Dynamic Earth:
GEO Priorities & Frontiers 2015–2020

FOREWORD

On behalf of the National Science Foundation (NSF) Advisory Committee for Geosciences (AC GEO), I am pleased to share *Dynamic Earth: GEO Priorities & 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.

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.

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 described in this "living" document. Our goal is to both lay out a near-term plan for geosciences research supported by NSF and highlight importance and breadth of the scientific enterprise funded by GEO.

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 turn *this document* into reality.

Dr. George Hornberger
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AC GEO Chair

INTRODUCTION

A Time-Tested Tradition

One of the most important functions of the NSF AC GEO is to provide strategic input into long-range plans and partnership opportunities. Hence, AC GEO—in collaboration with NSF GEO staff—regularly engages in strategic planning exercises to lay out a broad agenda for geoscience research and education opportunities, and direction.

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 the understanding of the planet's integrated systems to benefit the nation.

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. This strategic framework served as an additional foundation for innovation, recognizing that an examination of the underlying and cross-cutting foundational areas for the geosciences was necessary in meeting research challenges and related recommendations. *GEO Vision Report* (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.

Strengthening Our Vision

This newest strategic planning effort, *Dynamic Earth: GEO Priorities and Frontiers 2015–2020*, builds on these previous reports and other strategic planning efforts to fulfill GEO's mission to support research in the atmospheric, earth, geospace, ocean, and polar sciences. Moreover in 2012, the Division of Polar Programs[1] (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 priority ***Imperatives*** and ***Research Frontiers*** that are the life-blood and support structure for GEO activities.

Hence, this document is organized around four strategic priority areas with supporting ***Imperatives*** that must be accomplished in order to fulfill the potential of geoscience to advance knowledge and address critical national needs. These priority areas include: (1) Research, (2) Community Resources and Infrastructure, (3) Data and Cyberinfrastructure and (4) Education and Diversity. In order to advance geoscience research in new directions, this document also identifies five ***Research Frontiers*:**

[1] 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.

Land/Ocean Interface; Ocean Oscillation, Ocean-Atmosphere Interactions, Ice Sheet Dynamics and Related Interactions; Atmosphere and Ocean Processes in the Southern Ocean Region; Urban Geosystem Science; and Early Earth. These emerging frontier areas of scientific opportunity may rise to the level of an Imperative, if GEO and the community collectively agree.

Our Direct Impact

The basic research 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 research that informs practices and policies regarding complex environmental issues such as resource conservation and sustainability, water and energy availability, and species adaptation. Additionally, GEO provides platforms for research in scientific disciplines outside traditional geoscience fields.

An equally important part of the equation, 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 in and awareness of all the science we support, as well as supporting and training the workforce to enable it through extensive partnering with the Directorate for Education and Human Resources (EHR) on the Improving Undergraduate STEM Education (IUSE) effort.

GEO Partnerships

- NSF Directorates
- Academic community
- Professional societies
- Non-profit organizations
- Private foundations
- Private industry
- Federal Agencies [National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration, U.S. Geological Survey (USGS), U.S. Department of Defense (DoD), U.S. Department of Agriculture (USDA)]
- Federal Facility Research and Development Centers (FFRDCs)
- International science agencies

Paramount Connections

The considerable task of supporting and advancing the Imperatives and Frontiers in *Dynamic Earth: GEO Priorities and Frontiers 2015-2020* 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 provide

facilities for a wide array of these and additional science areas and is an important enabler of research. GEO also partners extensively with the Directorate for Education and Human Resources (EHR) on the Improving Undergraduate STEM Education (IUSE) effort and other activities to broaden the participation of underrepresented groups in STEM.

External partnerships are also necessary to bolster GEO goals and 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 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 support 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 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.

These collective efforts reflect and support NSF's strategic goals outlined in the *NSF Strategic Plan for 2014-2018*. Additionally, GEO is committed to transparency and accountability in all its procedures, consistent with administration priorities and policies.

NSF Strategic Goal and Objectives Supported by *Dynamic Earth*
GEO Priorities and Frontiers: 2014-2018

Goal 1: Transform the Frontiers of Science and Engineering.

Objective 1: Invest in fundamental research to ensure significant continuing advances across science, engineering, and education. *This objective is directly supported by the* Dynamic Earth *Research Imperatives.*

Objective 2: Integrate education and research to support development of a diverse STEM workforce with cutting-edge capabilities. *The* Dynamic Earth *Education and Diversity Imperatives promote this objective through engaging topics and activities integrated with geosciences research.*

Objective 3: Provide world-class research infrastructure to enable major scientific advances. *The Community Resources and Data & Cyberinfrastructure Imperatives address maintaining state-of-the-art infrastructure and data sets to enable major scientific advances in the geosciences and related disciplines.*

GEO RESEARCH IMPERATIVES

NSF—one of the largest sources of federal dollars for geoscience research—is the only federal agency that supports the full breadth of the geosciences. NSF-supported geoscience 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.[2]

GEO Research Imperative: Continue Strong Emphasis on and Support for Core Research.

GEO, a principal source of federal funding, advances understanding of our changing, complex planet and the many global processes that affect the Earth's system. Emphasizing and supporting core research in all its forms remains a GEO Imperative. GEO strives to meet this Imperative by supporting established programs and participating in NSF initiatives at the forefront of all geoscience and related disciplines. GEO intends to maintain the culture of excellence in GEO core research programs including disciplinary, interdisciplinary, systems-level, and community-driven science. This includes encouraging and supporting interdisciplinary collaborations and participating in NSF initiatives that advance GEO interests.

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 infrastructure, GEO program officers identified several as current priorities including research across coastal boundaries, high pressure and temperature mineral physics collaboration, characterization of sub-glacial lake environments, and improved space weather specification and forecasting.

GEO Research Imperative: Establish Collaborative Effort to Improve Understanding of and Resilience to Hazards and Disasters.

During the next five years, GEO intends to continue its support for key geohazards research through a new cross-divisional effort. This research 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 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 NOAA and USGS. The program will support research that can enhance resilience and sustainable responses to extreme events and increase understanding of societal and economic impacts associated with hazards and disasters, such as droughts, floods, hypoxic zones, severe storms, space weather events, toxic algal blooms, tsunamis, volcanic eruptions, and wildfires.

Geohazards research will enhance:

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

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

Based on a history of investments in research related to natural hazards and resilience, NSF is well prepared to respond to this issue of critical national and international importance. GEO research priorities in this important area connect with similar efforts at other 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. GEO will bring its unique federal research and education role to bear to complement such activities.

Moreover, the recent addition of PLR to GEO expands the purview within the Directorate's 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).

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 to improve short-time forecasting.**
- **Harness observational technologies to improve understanding of extreme events and natural hazards.**
- **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, 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.**

GEO Research Imperative: 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 resulting in changes in the ways that water, food, and energy cycles interact. 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 water, food, and energy resources as well as a firm scientific footing to underpin important public policy related to water resources.

RESEARCH ON WATER-FOOD-ENERGY NEXUS
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 and agricultural practices will prove most effective in achieving system resiliency and sustainability??**
- **How can integrated modeling efforts inform decision making with respect to seasonal high-risk-of-failure water quantity and quality?**
- **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?**
- **What is the optimal strategy for sustainable biofuel production?**

During the next five years, GEO will coordinate with several NSF Directorates to support efforts that focus on the water, food, and energy nexus. Two goals of this research are to integrate modeling of the Water-Energy-Food system including assimilating information from existing NSF networks such as 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. Under the umbrella of water-food-energy 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.

GEO Community Resources and Infrastructure Imperatives

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.

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. For example, the Research Vessel Sikuliaq, an MREFC project, represents a mechanism to dramatically increase GEO's ability to support Arctic scientific research.

A considerable portion of GEO resources supports community resources and infrastructure such as Antarctic Facilities, Arctic Observing Network, Critical Zone Observatories, CubeSat, Earthscope, IceCube, Incorporated Research Institutions for Seismology, International Ocean Discovery Program, National Center for Atmospheric Research, UNAVCO, and U.S. Academic Research Fleet. Increasingly in this era of constrained resources, challenges have arisen with balancing the need for state-of-the-art infrastructure with the need to maintain strong research programs. GEO investments in facilities must be strategic, such that facility costs do not compromise research programs.

Among the many strategic planning efforts underway at present, prime examples include 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, NSF, other federal agencies, and other countries are doing the same. Private philanthropy, international investments, and university investments are changing the landscape regarding support for facilities. These additional sources of funding represent an opportunity for the geosciences, 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. The challenge for the scientific and engineering community at large is to effectively and efficiently link investments and data to provide an integrated view of the Earth system.

GEO Community Resources and Infrastructure Imperative: 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 cyber-infrastructure that enables concurrent

Ocean Observatories Initiative 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

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 Coastal Ocean Science. GEO's investments in advancement of the ocean sciences on a global scale through OOI are of critical importance.

GEO Community Resources and Infrastructure Imperative: 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. Key examples of the high-caliber resources that GEO must continue to support include:

- The Research Vessel *Sikuliaq*, an MREFC project, 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.
- 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.
- 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) radar 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.
- Regional Class Research Vessels, 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.

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) 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 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,[3] the GEO plan will include programmatic efforts to encourage development of sophisticated tools to collect Earth-observation data. These tools are critical both for advancing understanding of the Earth system as well as to lay an observational foundation for services that protect life, property, and the economy.

GEO Community Resources and Infrastructure Imperative: Implement Strategic Plans for Logistics and Operations for the Polar Regions.

With the addition of the Division of Polar Programs, GEO significantly enlarged its portfolio of facilities, research ships in particular, as well as its expertise and experience in facilities management. GEO facilities management experts, especially those who have experience with midsize infrastructure, are sharing information and best practices. 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. PLR is coordinating with the U.S. Coast Guard and others in these efforts.

PLR remains committed to supporting 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.[4] GEO will follow steps outlined in the recommendations, which includes needs identified by user committees such as researchers, support contractors, DoD and other federal agencies.

GEO Community Resources and Infrastructure Imperative: Begin Conceptualization and Development of Next-Generation Sun-Earth-System Community Models.

Sun-Earth-System models are equally critical GEO community resources as an instrument-based facility. 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.

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. 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.

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[3] 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.

[4] U.S. Antarctic Program Blue Ribbon Panel, More and Better Science in Antarctica through Increased Logistical Effectiveness, July 2012. Available at http://www.nsf.gov/geo/plr/usap_special_review/usap_brp/rpt/antarctica_07232012.pdf

GEO Data and Cyberinfrastructure Imperatives

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.

GEO Data and Cyberinfrastructure Imperative: Develop Community-Driven Cyberinfrastructure in Order to Advance Data/Model-enabled Science and Education.

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. GEO will also facilitate a dialogue regarding the coordination of geoscience data and software facilities.

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 is committed to providing a sustainable, community-based and open cyberinfrastructure for researchers and learners.

GEO will support new, transformative science and education through the effective use of geoscience data enabled by modern software, models, and analytical tools that can simulate and examine complex and interrelated Earth processes. GEO will collaborate with various communities to address issues related to data archiving and reuse, spanning discovery, access, visualization, and integration into a unified cyberinfrastructure framework. 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. This includes increasing and improving access to modeling capabilities for researchers, educators, and students.

GEO Data and Cyberinfrastructure Imperative: Harness the Power of Computing and Computational Infrastructure.

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 increasingly demands high performance computing 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-

Geospatial data, metadata, enabling software and hardware, and training are essential for much of the geosciences community and must be optimized to increase researchers' productivity and capability. Science enabled by data and supporting cyberinfrastructure will be central to furthering our understanding of the Earth System.

enabled science and computing at multiple levels.

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, 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.

GEO Data and Cyberinfrastructure Imperative: 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
- Increase emphasis and capacity for virtual operations, e.g., of field sites

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.

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 is committed to providing a sustainable, community-based and open cyberinfrastructure for researchers and learners.

GEO Data and Cyberinfrastructure Imperative: 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. Among the next generation, we need developers of cutting-edge methods and codes, and all users of widely available codes should have a good 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 Education and Diversity Imperatives

Our future sustainability and prosperity require an interdisciplinary workforce that reflects the nation's diversity and that has the capacity to work collaboratively to develop effective solutions for complex societal issues. Of utmost importance to GEO is promoting community engagement, nurturing the next generation of scientists, enhancing the capabilities of the current workforce, and broadening participation at all levels.

GEO Education and Diversity Imperative: 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 strategy also includes promoting networking of these programs so that their impacts are scalable. Key strategies and specific actions in this area for the next five years include:

- Supplement investment to support 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 and Research Experiences for Undergraduates programs
- Support training programs for those currently in the workforce to enhance their skills

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 cutting-edge geoscience research.

GEO Education and Diversity Imperative: Broaden Participation from 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:

- 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
- Provide research and technical training opportunities for underserved groups at GEO facilities

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. GEO will also work with EHR to support professional development of faculty in areas we support to improve pedagogy and mentoring skills. An important aspect of this approach is to provide

resources and tools for NSF-supported researchers to facilitate meaningful activities to promote broader participation.

GEO Education and Diversity Imperative: 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. GEO has a strong interest in promoting public participation in and awareness of our science. To that end, GEO will:

- Fund supplements for community engagement and to promote 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

A pressing need exists to translate new knowledge into public information and advice to aid decision-makers. GEO will also partner with NSF's Office of Legislative and Public Affairs over the next five years to improve the availability and accessibility of GEO-funded research results. GEO must also work with internal and external partners to enhance understanding of the human implications for Earth system dynamics in order to have a positive impact on natural resources and human populations.

GEO Education and Diversity Imperative: 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 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.

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 means of access to help keep larger numbers of students connected to research and career goals 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 (EarthScope, transportable arrays, radars, and aircraft).

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

GEO RESEARCH FRONTIERS

GEO Research Frontiers are opportunities to enhance current areas of emphasis and to support new interest areas. Frontier areas require resources and capacity beyond current levels (i.e., funding resulting from new money or from sun-setting existing programs). The Frontiers described below were identified and refined through a collaborative process with many sources of input, including an annual science planning retreat of the GEO program officers—one of the Directorate's critical links to the research community. The Frontiers are growing areas of interest within GEO that may evolve in the next five years. Externalities may drive a Frontier to be prioritized up to an Imperative.

GEO Research Frontier: 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 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

GEO Research Frontier: Ocean Oscillations, Ocean-Atmospheric Interactions, Ice Sheet Dynamics, and Related Interactions.

GEO is interested in enhancing research to examine various aspects of ocean circulation and 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 stored in the Beaufort Gyre, or an increased Arctic hydrologic cycle

- Feedbacks 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, i.e., bloom dynamics and impact on carbon dioxide (CO_2) sequestration

An estimated 23% of global ocean's anthropogenic CO_2 inventory is stored in the North Atlantic. GEO could support research on bloom dynamics and impact on CO_2 sequestration.

In the past year, several international workshops have recognized opportunities in the Arctic and North Atlantic and have identified future process studies. International experts are working to prioritize the needs in integrated observations, modeling, and management and decision support. Developing more sophisticated modeling capabilities will improve understanding of process details and allow prediction of the future state of the North Atlantic and Arctic Ocean regional system. There is strong interest from Europe in trans-Atlantic cooperation under the Horizon 2020 framework, starting in 2014. Additionally, a rudimentary observing system is in place in the Arctic, sub-Arctic, and North Atlantic.

GEO Research Frontier: Atmosphere and Ocean Processes in the Southern Ocean Region.

The Southern Ocean is an under-sampled and remote ocean. GEO recognizes the need to increase understanding of oceanic and atmospheric processes in the Southern Ocean region. In particular, increasing understanding of Antarctic climate change and the stability of ice sheets and ice shelves is of global importance. To understand processes, trends, and biogeochemical controls in this part of the world, the scientific community needs support for additional basic measurements and studies.

GEO is interested in supporting Southern Ocean and atmospheric research related to:

- Exchange of CO_2 and heat; carbon cycle sources, and sinks
- Climate change; ocean acidification; community and ecosystem change,
- Better climate models at multiple scales for aerosols, clouds, radiation, and precipitation
- Ice nucleating particles
- Properties of Southern Ocean cloud systems
- Connecting sea-spray and bio-organics to mixed-phase clouds, ice nucleation, and atmospheric radiation balance

GEO Research Frontier: Urban Geo-system Science.

Rapid changes in land use in urban areas 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, 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. 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, 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 Frontier: Early Earth.

GEO would like to accelerate advances in the understanding of fundamental areas of inquiry related to the Early Earth. Key scientific questions worthy of additional exploration include:

- 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

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.