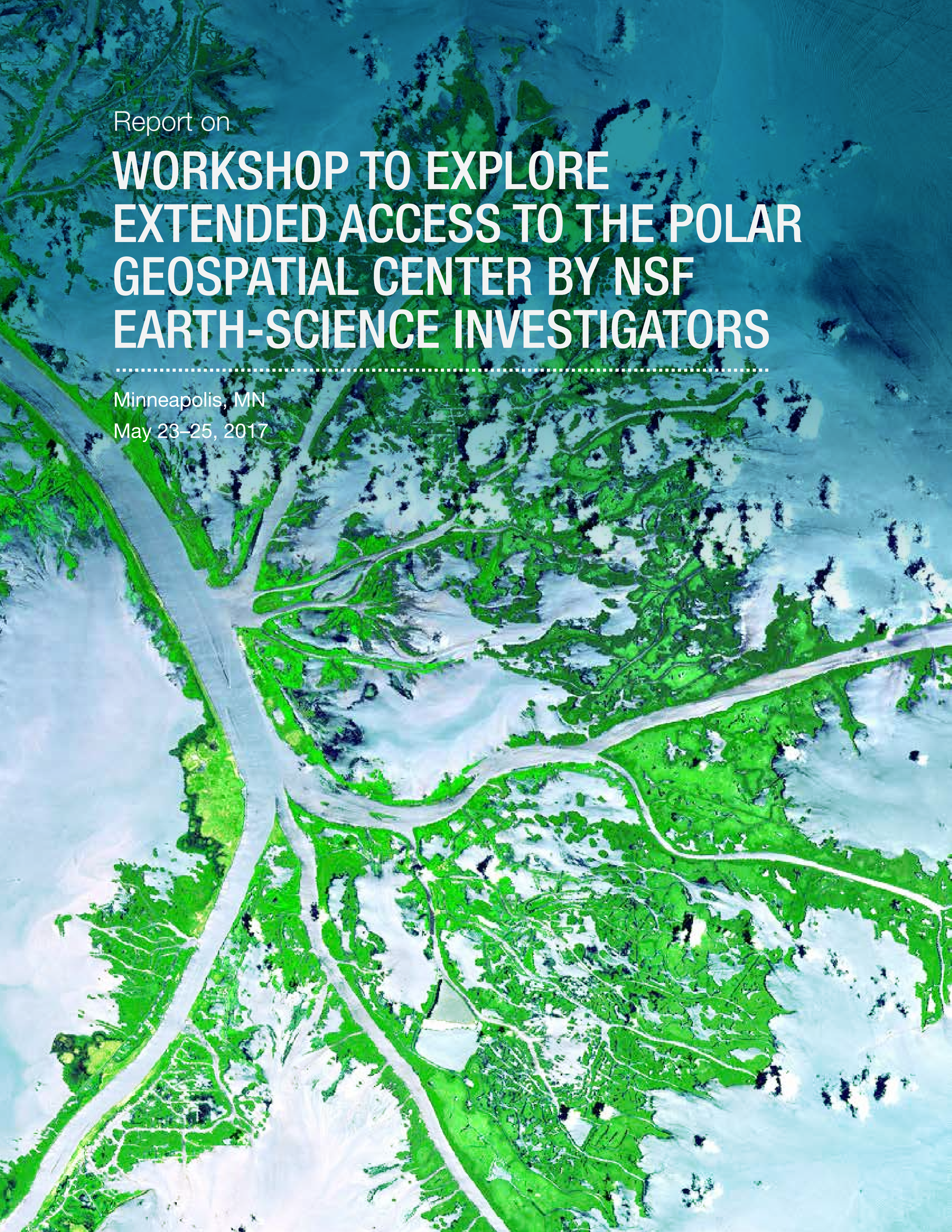
Report on

WORKSHOP TO EXPLORE EXTENDED ACCESS TO THE POLAR GEOSPATIAL CENTER BY NSF EARTH-SCIENCE INVESTIGATORS

Minneapolis, MN

May 23–25, 2017



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INTRODUCTION AND WORKSHOP OBJECTIVES

Workshop Background

The University of Minnesota's Polar Geospatial Center (PGC) and its partners have transformed the poles from one of the least mapped and imaged regions on Earth to one of the most. This change was enabled by the continued support of the National Science Foundation (NSF), the National Geospatial-Intelligence Agency (NGA), and the polar science community. With the help of these collaborators, PGC has developed innovative and dependable services along with products built on capabilities that were not imaginable when PGC began and are not readily available to a significant proportion of the NSF-funded science community. This workshop builds on PGC's successes at the poles, and further explores the possibilities for extending availability to the imagery and associated tools and products to the NSF earth science communities.

It has become clear that there is significant demand outside of NSF's Office of Polar Programs (OPP) for the high-resolution NGA commercial imagery and products that PGC curates and produces. Though it is not practical for PGC to support the use of high-resolution imagery for the rest of the Earth with the one-on-one support it provides to NSF's polar researchers, experience has taught PGC that if data is online and PGC educates the community on how to effectively use the imagery collection then additional science can be supported. The societal implications of PGC's products derived from the NGA commercial imagery has never been more important or relevant. PGC's products could help NSF earth science researchers measure coastline erosion, and change detection associated with other Earth surface processes, in addition to many other societally relevant themes and challenges.

Workshop Goal

The overall goal of the workshop was to produce a report outlining the opportunity that the combination of the commercial imagery and the PGC's services/ infrastructure and technology offers the earth science community. The workshop report will be used by NSF, PGC, and PGC's Science and Operations Committee to help determine the direction of PGC's nonpolar science support.

Workshop Description

The PGC hosted the National Science Foundation-funded Workshop to Explore Extended Access to the Polar Geospatial Center by NSF Earth-Science Investigators on May 23-24, 2017, at the University of Minnesota McNamara Alumni Center. 27 NSF-funded geoscience researchers convened for the two-day workshop to discuss and explore the benefits of expansion of the NSF-OPP arrangement to a broader spectrum of NSF-sponsored geoscience research. A smaller set of the organizing committee members and other participants met for a third day on May 25th to begin outlining and drafting the workshop report. Kip Hodges of Arizona State University was the Co-Chair of the organizing committee, and led efforts for producing the workshop report. The organizing committee was structured to attract key science, terrain generation, HPC, and high resolution imagery experts. Participants came from broad fields, including but not limited to Tectonics, Critical Zones, Natural Disasters, Hydrology, Geomorphology and Land Use Dynamic, focused on science supported by the Geoscience Directorate at NSF. The goal was to have a mix of senior, early career, and students who are all early adopters.

A final outcome of the award is that the workshop participants and the steering committee found great benefit in extending PGC's products and services to support EAR researchers. On the most basic level, high-resolution imagery would be provided anywhere on the Earth. Digital Surface Models can be produced on-demand and at scale. The committee also stated that perhaps the most significant contribution would be the community's access to PGC's User Services staff and consulting capability. In addition, NGA and NSF Polar have funded the establishment of the hardware and software to provide the imagery and derived products to the community. This is a significant investment that could leverage a modest additional outlay by EAR.

MONITORING EARTH SURFACE EVOLUTION FROM SPACE: THE MEASURES INITIATIVE

INTRODUCTION

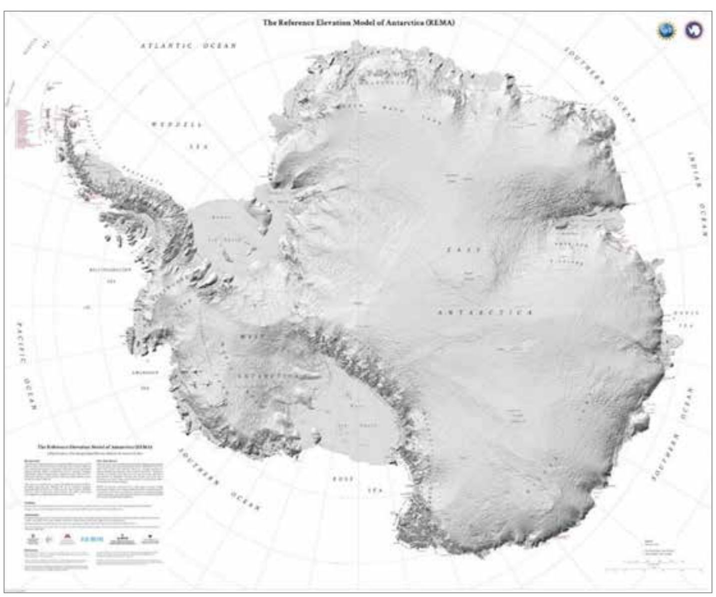
TIME AND SPACE ARE THE WARP AND WEAVE of the fabric of geoscience. Inspired by input from the geosciences community[1], the United States National Science Foundation (NSF) is actively exploring ways to provide systematic, continuing support of an infrastructure to support broad, dependable access for the geosciences community to state-of-the-art geochronologic instrumentation, infrastructure, and expertise. Here we call for a similar initiative that concentrates on increased access to geospatial data as provided through a remarkable interagency collaboration between NSF's Office of Polar Programs (OPP) and the National Geospatial-Intelligence Agency (NGA) and enabled by the Polar Geospatial Center (PGC) at the University of Minnesota. We recommend a global expansion of what is currently a successful partnership that has profoundly improved NSF-sponsored research efforts in polar regions. Doing so would address critical gaps in data availability that frustrate more rapid progress on many of the most pressing research priorities articulated in four National Research Council reports published over the past decade[2-5]. In May 2017, 27 NSF-funded geoscience researchers convened for a wo-day workshop at the University of Minnesota to imagine the benefits of expansion of the NGA–OPP arrangement to a broader spectrum of NSF-sponsored geoscience research. Noting that the surface of the Earth is one of the primary observables for earth system science and is dynamic over multiple timescales, the assembled researchers agreed that an opportunity to repeatedly observe the surface at high resolution over large areas, and preferably at multiple wavelengths, could revolutionize American geoscience research. These capabilities would inspire a research focus on how changes in Earth's surface over short timescales inform our understanding of processes, and would stimulate the design of future strategies for automated change detection that could feed forward into hazard identification and mitigation. Here we briefly review current efforts in the polar regions before discussing new research opportunities that would be enabled by an expanded initiative – referred to here as MEASURES (for "Monitoring EArth SURface Evolution from Space") – and we conclude with specific recommendations for consideration by the Directorate for Geosciences.

THE CURRENT ARRANGEMENT AND THE ROLE OF THE POLAR GEOSPATIAL CENTER

TO SUPPORT ITS NATIONAL SECURITY EFFORT, NGA has entered into long-term contracts with *DigitalGlobe*, and other imagery vendors, for high-resolution (sub-meter), optical Earth imagery. At present, NGA and the United States Government (USG) is the primary client for the multispectral imagery – in the visible and near-infrared spectra – produced by the satellites operated by

DigitalGlobe. The current constellation of these satellites – *GeoEye-1*, *WorldView-1*, *WorldView-2*, *WorldView-3*, and *WorldView-4* – provides images with extraordinary spatial resolution (down to 32 cm/pixel) and repeatability; many scenes can be revisited as frequently as every few days.

In November of 2015, NGA and the National Science Foundation's Office of Polar Programs negotiated a Memorandum of Understanding through which NGA could provide sub-meter imagery to OPP and OPP-funded academic researchers in support of logistical operations and scientific research. In addition, NGA collaborates with OPP and its sponsored researchers to request specific tasking of satellites for image acquisition to meet science and logistics goals. In order to enable these processes, the memorandum established a relationship between NGA and the PGC, with operational funding for the latter coming from OPP. PGC's core service is to archive, synthesize, and provide practical access to the enormous data volumes transferred from *DigitalGlobe* through NGA to OPP. through NGA to OPP. Of particular importance are the varied interactions of PGC personnel with OPP-funded researchers. These scientists have a broad range of expertise with geospatial data, which necessitates personalization of interactions with PGC analysts. The most sophisticated glaciology remote sensing scientists require very little direct help from PGC analysts, but they require massive volumes of imagery and assistance with satellite tasking. On the other end of the spectrum, PGC also supports field geologists who require custom-produced traditional maps. To cope with these varied needs, PGC employs a small, but very effective, "User Services" team to assist scientists, logistics contractors, and NSF staff on a wide range of geospatial problems. Outside of satellite imagery, PGC plays an important role in improving and preserving other polar geospatial data in digital form, including historical maps, aerial photography, and imagery mosaics originally produced from a variety of sources. All told, OPP-funded researchers have access to near-real-time imagery and PGC's collection of more than 5 PB of archive stretching back to 1999. As a consequence of the efficient and effective work of PGC personnel, NGA and OPP can quickly produce large-area, standardized products for the science community. The most notable is the processing of continental-scale stereoscopic imagery into high spatial-resolution (2m/pixel) digital elevation models using open-source software and NSF's Blue Waters and XSEDE high-performance computing (HPC) resources. For example, PGC and collaborators are currently producing publicly available time-dependent elevation models for the entire Arctic and Antarctic. Perhaps most importantly, the operation of PGC as a nexus for Arctic and Antarctic geospatial research contributes to a sense of community among polar researchers and catalyzes new collaborations among OPP-funded researchers.




Shaded relief posters of the Reference Elevation Model of Antarctica (REMA; left) and ArcticDEM (right)

SCIENTIFIC BENEFITS OF AN EXPANSION OF THIS EFFORT

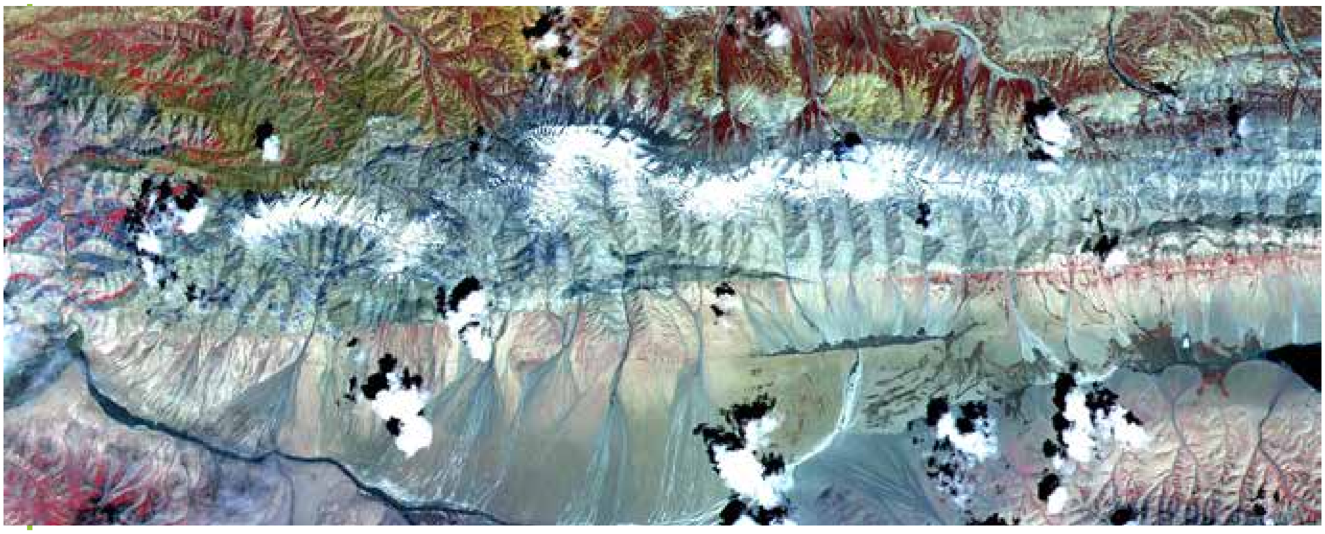
THE *DIGITALGLOBE* AND OTHER HIGH-RESOLUTION commercial imagery procured by NGA and theoretically available to geoscience researchers is global in scope. Thus far, scientific research enabled by the derived products provided by PGC has been limited mainly to the north and south polar regions, but global expansion of this enterprise could begin a new era of geoscience research benefitting continuous monitoring of changes in Earth's surface with unprecedented scope and resolution. Below we imagine just a few of the scientific studies that might be enabled.

TECTONIC AND EARTH SURFACE PROCESSES

Earth's surface is constantly changing in response to tectonic and climatic forcing, and understanding how these changes arise depends on our ability to document these processes in detail, both spatially and temporally. Ensuring community access to high-resolution and high-accuracy imagery and digital elevation models (DEMs) of uniform quality over wide areas would substantially improve the quality, efficiency, and ultimate significance of NSF-sponsored research in both geomorphology and tectonics. Previous datasets have either been of high-resolution, but limited spatial extent, or were available at uniform data quality over wide regions, but at a much lower resolution. The MEASURES initiative would combine the best of these data types into a set of products that will allow the community to perceive the landscape in an entirely new way. Investigators could analyze the landscape as before – albeit with unprecedented ease and accuracy – but they could go further; rapid, repeat coverage by high-resolution imaging assets offers opportunities to document the consequence of significant tectonic and climatic forcing events (e.g., earthquakes, landslides, major storms) and to watch individual events evolve[6]. We imagine that high-resolution imagery provided through the MEASURES initiative will stimulate a wide range of research, including: 1) detailed, near-real time documentation of surface deformation during earthquakes and related phenomena, such as landslides; 2) enhanced, three-dimensional mapping of geologic structures and the distributions of rocks and sediments; 3) monitoring the temporal and spatial evolution of landscapes, including the inter-relationships among hillslope and channel processes; and 4) the development and testing of predictive process models.

1. ACTIVE TECTONICS

Earthquakes are some of the most obvious manifestations of a dynamic Earth. The availability of high resolution imagery and DEMs, together with having an ability to compare before and after images over large spatial scales and through time by repeat observations, facilitates analysis of the surface



Kunlun strike-slip fault in Tibet; Photo by: NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team manifestations of earthquakes in unprecedented detail. Regional coverage would permit geoscientists to accurately, efficiently, and cost-effectively map not only earthquake displacements along fault zones, but also the detailed distribution of deformation off faults, including in remote and challenging environments[7]. Such data also will enable assessment of the relative activity of seismic structures, the best sites for paleoseismic investigations, and the spatial and temporal patterns of displacement in past earthquakes as well as on-going interseismic activity. In turn, these studies will inform our understanding of the seismic behavior of active fault systems. If these behaviors are related to parameters that can documented in advance of future earthquakes (e.g., fault cumulative displacement, local fault structure, types and thicknesses of near-surface materials, etc.), such information potentially could be used to predict the distributions of on-fault and off-fault surface deformation. These, in turn, would have important implications for predictions of strong ground motions, for effects on the built environment, and for the development of next-generation probabilistic seismic hazard models and future strategies for better earthquake-resistant building design[8,9].

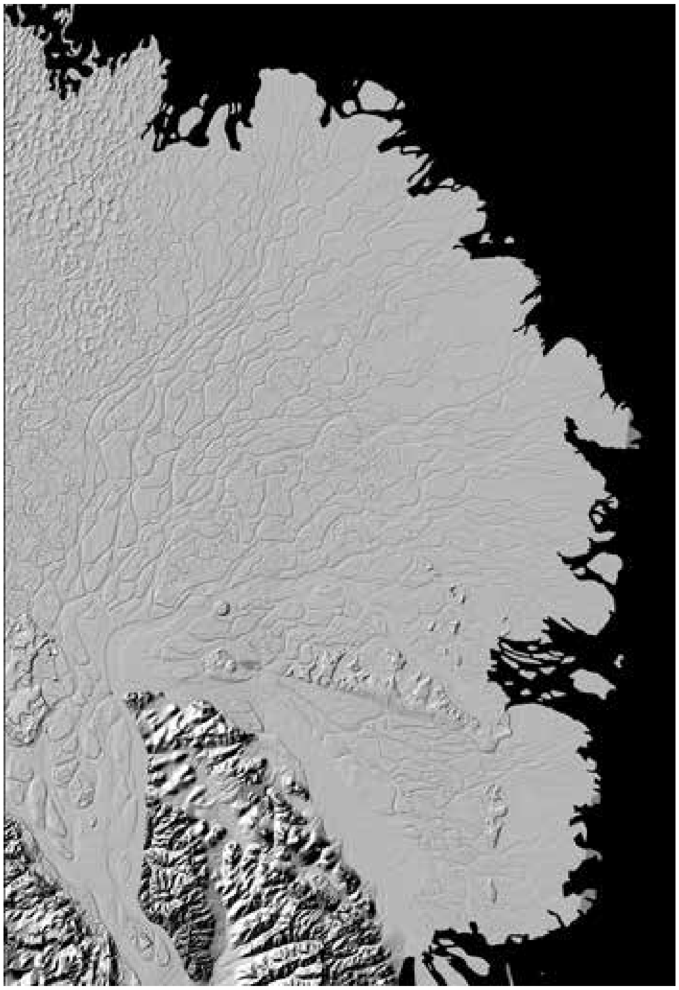
2. Geologic Mapping and Regional Tectonics

While the promise of making extremely high-resolution DEMs on a global scale alone would make the MEASURES initiative attractive to those who make geologic maps or conduct regional tectonics research, high-resolution imagery in both visible and near-infrared wavelengths could have an even greater impact on these disciplines. There are large tracts of the Earth's surface for which detailed geologic maps do not exist due to remoteness or political instability. Taking advantage of remote sensing imagery at multiple wavelengths, the spectral signatures of geologic units seen from orbit can be used to build classification maps that – while not providing the same depth of information as geologic maps made in the field – nevertheless provide opportunities to map geologic units, important contacts, and deformational features where more conventional geologic maps are unavailable or impossible to produce[10,11]. The value of multispectral classification maps for geologic research depends on the spatial resolution and the bandwidth (or spectral coverage) of the sensors available on the satellites. Some remote sensing satellites (e.g., *ASTER* and *Landsat*) have very broad spectral coverage, including thermal infrared bands that can be especially valuable for geologic mapping, but they offer relatively coarse spatial resolution (15-30 m/px). Unfortunately, the classification maps produced from such data are insufficiently detailed to address many important geologic problems. The sensors on *DigitalGlobe* imaging satellites have narrower spectral coverage – visible to near-infrared – which limits the value of derived data somewhat, but the much higher spatial resolution of these sensors makes them highly attractive for detailed classification mapping[12]. For example, each pixel of a *Landsat* multispectral image has the same footprint as 450 *WorldView-3* pixels. Moreover, recent studies using data from the airborne *AVIRIS* platform have documented the benefits of merging broader bandwidth data (including long wavelength infrared) from instruments with lower spatial resolution with higher spatial resolution visible-near infrared data[13]. We can anticipate future MEASURES studies that similarly fuse information from multispectral images captured by the *DigitalGlobe* satellites with longer-wavelength *ASTER* and *Landsat* data for optimal classification mapping.

3. Geomorphology

Characterization of the geomorphologic details of channels, drainage networks, and other fluvial features in unprecedented detail would reap wide-ranging scientific benefits. For example, the conveyance of sediment through fluvial systems can be measured using the sediment budget derived from differential analysis of time series of topographic data[14]. Volumetric changes established in this way provide key inputs to the refinement of geomorphic transport laws[15]. The MEASURES initiative would permit a refined understanding of the three-dimensional architectures of drainage networks, which control the distribution of relief in landscapes and indicate the relative rates of rock uplift and rock resistance to erosion[16]. The initiative also would permit a more precise knowledge of the spatial distribution of organism-scale habitats throughout entire river systems in remote areas, and repeat datasets would document how these distributions change through time. Such information is essential to the application of ecological concepts for understanding river systems[17].

One important research domain that might be productively targeted using *DigitalGlobe* datasets is the hillslope to channel transition. The relative rates of fluvial and hillslope processes establish landscape morphology[18,19], and the inversion of morphometric data (e.g., digital topography) is one of most powerful ways to explore nature of governing process interactions[20]. It is becoming increasingly clear to the process geomorphology community that the quality of such inversion exercises depends critically on the spatial resolution of our topographic data[21]. Pixel resolutions of a few meters or less – such as those that can be derived from *DigitalGlobe* imagery – permit detailed research on the evolution of earth surface process at the hillslope to channel transition, whereas lower resolutions – such as the 30 m/px resolution DEMs derived from NASA's *Shuttle Radar Topography Mission (SRTM)* – do not. At present, the highest quality research of this kind depends on the use of data provided by airborne laser altimetry[22], but such data are only available for a relatively small part of Earth's surface. Finally, we note that the repetitive acquisition and processing of *DigitalGlobe* data obtained through the MEASURES initiative would especially benefit the U.S. geomorphology community by enabling the monitoring of mass movements that transfer materials from hillslopes to fluvial systems.



Lena River Delta from ArcticDEM

HYDROLOGICAL AND COASTAL PROCESSES

The storage and movement of water across Earth's surface are critical processes in the hydrological cycle, and these processes can be quantified most effectively across space and time with high-resolution satellite data such as that which could be available through the MEASURES initiative. Extensive, high-frequency *DigitalGlobe* data would provide new opportunities to characterize the dynamics and distribution of hydrological processes across broad spatial scales. High-resolution satellite imagery and its products would also allow us to determine where water is, where it is not, and where it *could be*.

There is broad recognition that hydrologic processes (at local and regional scales) is non-stationary, that the past is no longer a strong predictor of the future[23]. One solution proposed to overcome this uncertainty as we strive to predict future water resources is to develop more accurate, distributed hydrologic models that can predict streamflow, soil moisture, and groundwater levels. Such models require precise and realistic inputs of important constraints – e.g., landscape topography of landscape and vegetation distribution – to inform the selection of state variables. These models also benefit from the quantification of the range of changes that the models will be required to accommodate. Much of the necessary information could be known at sub-meter resolution through the MEASURES initiative.

Understanding the dynamics of river systems is a fundamental requirement for understanding the hydrologic cycle. Rapid channel changes due to floods, droughts, landslides, and other extra-fluvial incursions require repeated high-resolution imagery to capture transient states and trajectories. Fundamental measurements can be made from such imagery to quantify channel geometry changes, development of knickpoints, channel incision, and planform evolution - all without having to risk personnel in potentially unstable and dangerous field settings. Moreover, the ability to detect and measure change over entire river networks will advance our understanding of how rapid, episodic inputs of large volumes of water, sediment, and organic materials (e.g., wood) promote geomorphic change at the network level and leave downstream legacies.

Coasts lie at the confluence of terrestrial and marine environments, and at this interface, small changes in the extent of one domain or the other can have significant impact on the evolution of a region and the distribution of natural habitats. Building upon previous research experiences[24], the geoscience community could exploit the high-resolution, repeat satellite imagery that would be made available through the MEASURES initiative to observe and detect changes along entire coastlines in unprecedented ways.

BIOGEOCHEMICAL & ECOLOGICAL PROCESSES

Most interactions between Earth's biosphere and geosphere largely occur at meter to sub-meter spatial scales and on brief timescales. The MEASURES initiative offers a unique opportunity for research focused on these interactions because high-resolution commercial satellites offer an optimal combination of spatial, temporal, and spectral resolution for such work. Researchers in these domains already have access to high repeat-frequency, multispectral remote sensing data from *Landsat*, but the spatial resolution is too coarse for many studies. Aerial photographs provide much better spatial resolution, but suboptimal temporal resolution. The comparative ease of repeat image acquisition associated with the MEASURES initiative would open a wide range of research opportunities that are currently impossible to conduct with available datasets.

An important class of geobiological problems revolves around the evolution of microbial mats at the multimeter scale, yet at a smaller scale that than accessible using large-footprint remote sensing data[25]. Targets of opportunity include the dynamics of algal mats in river systems[26,27], and the diversity and distribution of microbiological communities in hot spring environments[28].

While topography alone is a crucial biogeochemical variable – for evaluating connectivity and constraining geochemical fluxes – the combination of high-resolution DEMs with multispectral imagery would provide the most powerful toolkit for biogeochemical and ecological studies in both terrestrial and aquatic ecosystems[29,30]. For example, with that combination, researchers could address questions related to the biochemistry and structure of ecosystems over broad tracts of our planet's surface and how they may relate to soil and bedrock variability[31-38]. Studies of special interest to scientists funded through the Geoscience Directorate include ecological responses, both biochemical and physiological, to transient events (e.g., extreme weather, fire, drought, floods, and landslides)[39,40], as well as the influences of coastal processes on near-shore ecosystems[41]. Using the rapid, repeat scene acquisition capabilities of the *DigitalGlobe* satellites as part of the MEASURES initiative, multidisciplinary teams of researchers could build a more fundamental understanding of the complex interrelationships among climatic, geomorphic, tectonic, *and biological* processes.

Perhaps the most obvious uses of *this new class of sub-meter optical imagery* are for large-area studies of the distribution of biomes and the definition of ecotones with high spatial resolution[42,43]. Closely related applications include mapping of biodiversity patterns[44]. Rapid, repeat data acquisition would be fundamentally important in this regard because biome distributions are rarely (if ever) static, and their dynamics are informative regarding the nature and significance of different forcing factors[45].

Specific examples of long-term, programmatic investments that would benefit from the initiative include Critical Zone Observatories, Long-Term Ecological Research sites, sites of the Marine Biodiversity Observation Network, and the National Ecological Observatory Network. For example, *DigitalGlobe* data would provide powerful ways to "upscale" local-scale observations and mitigate concerns regarding the scale-dependency of research conclusions.

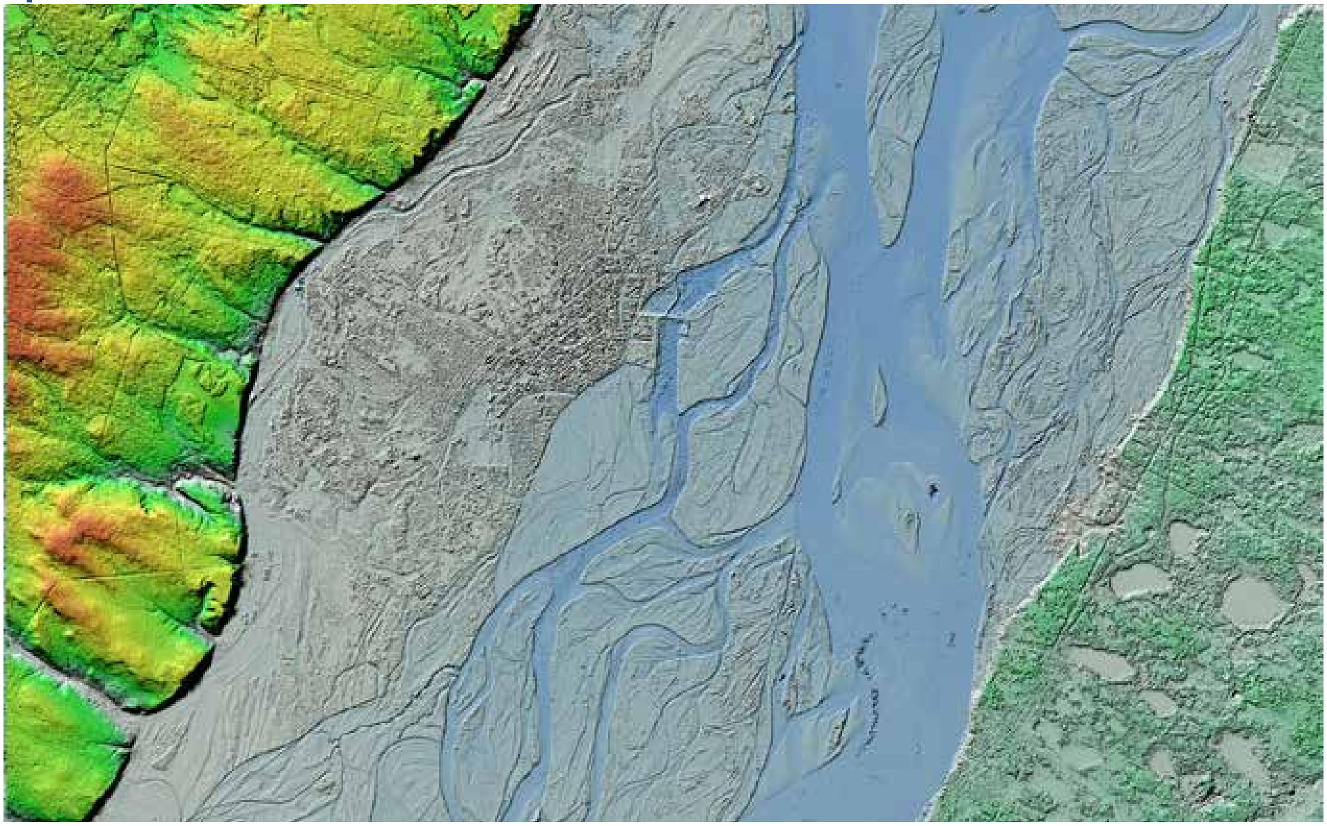
While most of the geobiology applications imagined here pertain to living systems, the MEASURES initiative would likely accelerate paleobiological research as well. For example, correlation of important fossil assemblages with specific time-stratigraphic horizons or lithologies that have diagnostic spectral signatures would permit better informed, and therefore more productive, field research campaigns.

SOCIETAL BENEFITS OF AN EXPANSION OF THIS EFFORT—UNDERSTANDING HAZARDS

UNDERSTANDING THE EVOLUTION OF TOPOGRAPHY over time is critical for deciphering the dynamics of natural hazard processes and the linkages between the natural environment and the built one. We currently have few data collected over the short timescales of many hazardous events because of the prohibitive cost of repeat land and airborne surveys, and often the unpredictability of the location of future events. As a result, existing high-resolution surveys tend to be small in geographic extent, and thus the chance of making observations just before and just after an event is rare and usually limited in scope. As a consequence, we currently lack the ability to quantify the basic physical variables associated with natural hazards, namely the redistribution mass across Earth's surface and the rate at which that redistribution occurs. We aim to rectify this situation through the use of high-resolution, repeat imagery and the production of digital elevation model time series as part of the MEASURES initiative.

The consequent synoptic view of natural hazard events promises to transform our understanding of the dynamic processes behind the events themselves. By quantifying mass and velocity of surface materials, we can evaluate, refine, and develop new dynamic models. Today we are able to describe small portions of events in great detail, and thus can predict what might happen if we have site-specific data, but we are not able to generalize. Event-scale data at high resolution will provide a statistically robust foundation for future models.

There are currently several important research gaps that limit our ability to understand natural hazards (and, often, chains of hazards). We know too little about the initial conditions of a landscape immediately prior to an event. These conditions include both static and dynamic properties that "precondition" the landscape for an event. We also have limited understanding of the interactions among chemical and physical processes triggered by an event, and how these interactions precondition the

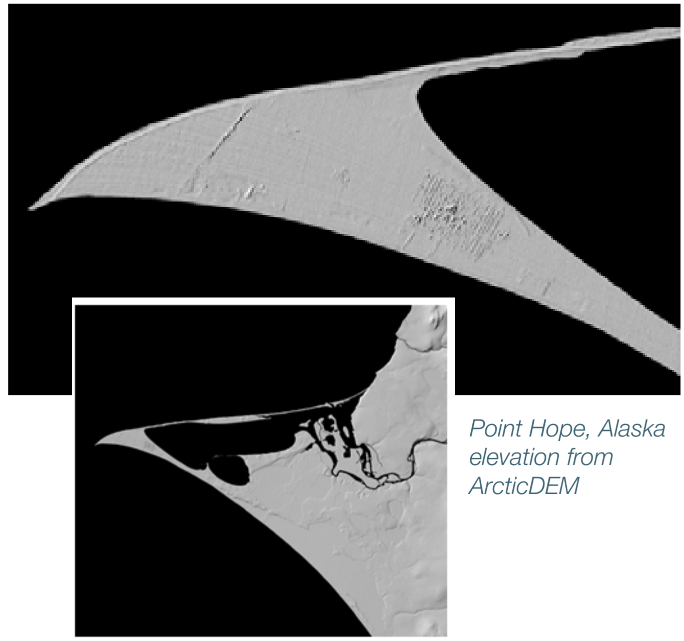


Elevation model of Yakutsk, Russia, from ArcticDEM landscape for subsequent events. For example, what actually happens during an earthquake, how does that influence the development and evolution of consequent landslides, and what role does rainfall infiltration – into both fractured hillsides and landslide deposits – play in extending the chain of episodic landslides into the future? Developing sound, predictive models of natural hazards requires empirical characterization of events as they occur, as well as further observations of affected areas over time to establish long-term impacts. Such work would be uniquely enabled by the MEASURES initiative.

One of the most promising social benefits of MEASURES would be rapid assessment of damage to the built environment caused by natural hazards. The exposure of urbanized populations to natural hazards is exponentially increasing as the global population grows and as more people move to cities. Common hazards to cities and towns include coastal inundation, floods, volcanic and earthquake hazards, and landslide hazards. High-resolution topographic data and damage assessments from satellite methods can economize early reconnaissance efforts and inform scientific studies by capturing perishable data. Data made immediately available to government agencies and non-governmental relief groups is of critical importance to disaster response efforts; it enables a prioritizing of resources for greatest impact, and provides valuable warnings about damaged infrastructure. This requires pre-event characterization of at-risk environments (e.g., having detailed DEMs *before* a disaster that can be distributed soon after an event). Such resources can be compared with specially targeted imagery when an event is unfolding to inform first responses, and after an event to assess continuing hazard. It is critical as part of post-event data collection that time-sensitive (i.e. perishable) observations are documented both in detail and with repeat surveys. In order to capture post-event processes, time-series produced over days to months to years after an event are also needed.

The MEASURES initiative would position us well to prepare for and respond to a wide variety of natural and human-induced hazards.

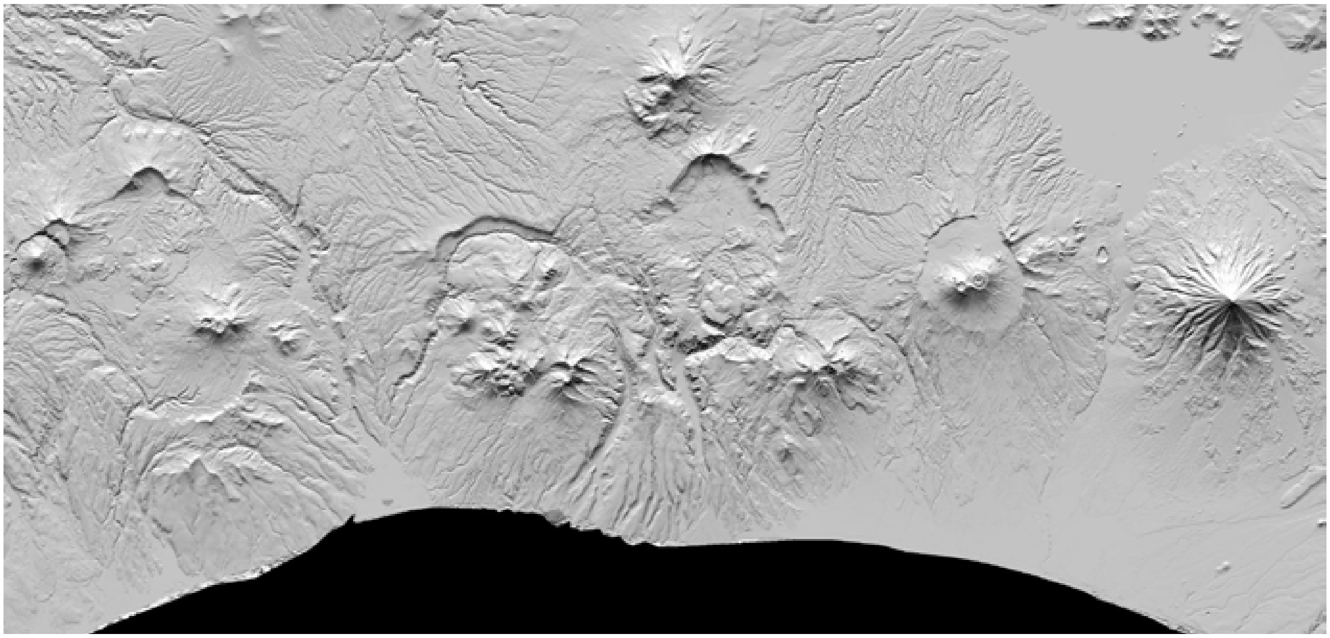
COASTAL INUNDATION. Coastal hazards are tremendously important because approximately 40% of the world's population lives within 100 km of a coastline. Major ports, naval bases, power plants, and many communities with limited access occupy the coastal zones, and we could use the new assets provided by the MEASURES initiative to identify regions of vulnerability worldwide. Repeat, high resolution stereo and cross-track stereo datasets would provide a means to examine subtle coastal topography and topographic changes through time. The extensive data collection capabilities of the multiple constellations of satellites make it possible to derive topography for the entire global coastline. Outside of the G20 countries, inundation maps – critical for predicting the impact of storm surges, tsunamis, and sea level rise – are rare to nonexistent. In Bangladesh, for example, degradation of the mangrove forests that skirt the coastline is driven by the development of shrimp farms and subsidence related to the sediment load accumulating at the Ganges delta. This degradation increases the number of people at risk. Rising sea levels may drive mass migration from such areas, which may, in turn, trigger geo-political crises. For example, Dhaka, the capital of Bangladesh that lies 4 m above sea level on average, has 14 million inhabitants.



Point Hope, Alaska elevation from ArcticDEM

INLAND FLOODING. With high-resolution topography, we can better define flood plains and potential drainage pathways within urban environments, critical information for risk assessment. Repeat acquisition of topographic data allows the effects of flooding on landscape topography and sediment distribution to be examined, while also allowing the effects of urban encroachment into flood plains to be quantified.

VOLCANIC ERUPTIONS. Beyond the fundamental characterization of volcanic phenomena[46], the high-resolution topographic and multispectral data made available through MEASURES would greatly improve our ability to



Volcanoes along the Kamchatka Peninsula from ArcticDEM

assess volcanic hazards. For example, anticipating the direction and extent of lava flows, lahars, and pyroclastic density currents could minimize the human and infrastructure costs of eruptions. Other factors that influence the risks associated with volcanic activity – snow depth, glacial exposure, water availability to trigger phreatomagmatic explosions and lahars – can be better understood by high-resolution, repeat acquisition of satellite imagery. Of special importance is the synergy of the datasets made available through the proposed MEASURES initiative with other characterization datasets. For example, interferometric synthetic-aperture radar (InSAR) deformation mapping is becoming an essential tool for the prediction of volcanic activity, but the quality of the derived information is enhanced substantially when topographic corrections are informed by high-resolution DEMs.

LANDSLIDING. In addition to having incomplete knowledge regarding the pre-conditioning of landscapes for landslide activity, as mentioned previously, we also have imperfect tools for estimating landslide volume, which can influence landslide movement direction, runout distances, and the potential for subsequent mass wasting events[47]. While some recent models partially address this need using simple geometric projections through digital topography[48] or more rigorously defined volumes using numerical approaches[49], none incorporate landslide preconditioning as a control on frequency-area or area-volume distributions for landslide events. We also lack robust, evidence-based models of the compounding effects of slope displacement or strong ground motion (i.e. earthquakes) on near-surface strength, landslide and slope geometry and hydrology as they relate to slope stability. Bedrock fractures produced during seismic events can be numerous and can impact the size and frequency of subsequent landslides[50]. Measurements of such fractures in the field can be onerous, and generalized mapping of them can lead to incorrect assessments of landslide potential. Remote sensing enables characterization of fractured rock volumes over broad areas at fine scales in a systematic manner. While observed increases in rainfall-induced landsliding following earthquakes suggest that an earthquake weakens hillslopes[51], the combined effects of sorting and hydrologic conductivity is poorly known. Integrating mechanical and hydrologic changes into existing hydrologic models of rainfall-induced landslides would allow us to discover tipping-points in this part of the hazards cascade, which may affect earthquake-damaged regions for years to decades following the main event. Although achieving a better understanding of the landslide process will require the integration of multiple modes of inquiry, an essential component of the work ahead is the high resolution characterization of the topography and texture of landscapes before, during, and after major, hazardous landslides.

EARTHQUAKE ACTIVITY. Seismic risk is determined from probabilistic models, which forecast future behavior of faults. Key data inputs include fault slip rate, expected magnitudes, rupture limits, strong ground motion models and building design. These new data are revolutionary because they will facilitate rapid and cost-effective data collection. Moreover, these methods can be applied in remote and challenging environments, where more traditional analyses are difficult or impossible. That said, the quality of probabilistic models is only as good as our understanding of the input parameters, and the observational science made possible by *DigitalGlobe* assets could play an important role in model development and refinement. For example, we have the potential to describe what happened during and immediately following earthquakes, and therefore better predict the relationships among seismic slip at depth, state parameters prior to an earthquake, and ground surface deformation. Unfortunately, people often live in buildings of inferior design in earthquake areas. High-resolution satellite imagery and DEMs – especially when combined with other kinds of remote sensing data – enable the rapid, post-earthquake assessment of damage to the built environment[52], which in turn can inform better construction practices.

SOCIETAL BENEFITS OF AN EXPANSION OF THIS EFFORT — UNDERSTANDING THE ROLE OF HUMANS IN EARTH EVOLUTION

WE HAVE ENTERED THE ANTHROPOCENE – the current geological age in which humans are a dominant influence on the global environment[53]. Humans are moving more sediment than other natural processes[54]. Human activities have interrupted the natural processes that otherwise form and maintain coastal ecosystems[55]. Coastal water quality is threatened by local (and upstream) development, leading to harmful algal blooms and hypoxia. These phenomena are readily visible in high-resolution multispectral imagery such as that which would be provided through the MEASURES Initiative, as are sediment plumes from rivers or other coastal inputs of sediment.

Feedbacks between the built and natural environment strongly influence how urbanization progresses. Thus, measurements of, for example, how the geospatial evolution of megacities influences and is influenced by natural systems is of obvious social value. Time-series of high-resolution imagery would be especially useful in this regard. Synoptic and objective measures of rapid urbanization, human migration, and land-use transformation around the world are valuable economically, politically, and fundamentally as fodder for the study of human-environment interactions. Importantly, these human impacts can exacerbate geohazards.

Measures of geospatial change are also useful for forecasting future alterations in the face of a changing environment and socio-political pressures. These may include the surface area impacted by human migrations, urbanization, other land use transformations. Mass displacements due to human exploitation of Earth materials (e.g., construction and mining) should be monitored as a matter of practice. In addition, the MEASURES initiative would enable monitoring of the development of reclaimed land, floodplains, and permafrost, allowing us to realistically evaluate human impacts. Repeat multispectral imaging would permit tracking of chemical weathering of urban materials under conditions of elevated atmospheric CO_2, with consequences for structural integrity and water quality in the built environment.

The use of groundwater and surface water to support human societies has a strong impact on the distribution and volume of this important resources, in many cases disrupting the natural hydrologic cycle with largely unpredictable consequences. In conjunction with other satellite-based methods such as differential InSAR, the repetitive collection of high-resolution elevation data and multispectral imagery provides a means to monitor these effects.

EDUCATIONAL BENEFITS

FINALLY, WE NOTE THAT THE MEASURES INITIATIVE could have a substantive educational component that would ensure the broader impacts of consequent NSF-sponsored research. Geospatial tools such as *Google Earth* are proven educational resources for preschool through college students[56,57], and products derived from even higher quality imagery could expand the value of geospatial resources in Science, Technology, Engineering, and Mathematics (STEM) education.

At the collegiate and post-baccalaureate levels, a broader opportunity to use such data in the classroom would help expand geoscience education into the realm of planetary science because the quality and quantity of panchromatic, multispectral, and hyperspectral datasets for planetary bodies like the Moon and Mars are actually, in many cases, superior to those widely available for Earth. Numerous opportunities exist to compare and contrast the *DigitalGlobe* datasets with those developed using NASA orbital assets, thereby encouraging students to explore what is sometimes called comparative planetology. Greater use of this mode of inquiry could reap benefits in the form of a better understanding of how our home world came to be, and how (and why) other worlds evolved very differently.

RECOMMENDATIONS

ENCOURAGED BY OUR REVIEW OF THE PAST SUCCESSES of the current NGA–OPP Memorandum of Understanding and our extensive discussions of how high-resolution optical imagery data could benefit geoscience research outside the polar regions, we propose to launch MEASURES as a grassroots, community-based initiative. However, such an initiative will not be possible without broader data access and enabling NSF sponsorship. **First, we strongly recommend that the NSF Geoscience Directorate explore broadening the current arrangement with NGA to provide the entire NSF-funded geoscience research community with comparable access to data products derived from high-resolution imagery.** Past experiences of the polar science research community with the arrangement already in place make it clear that the current staff of the PGC has been essential to the success of this program. Unfortunately, this staff and the present infrastructure of the PGC are inadequate to support an expansion of services to a broader community. Thus, **our second recommendation is that the Directorate explore funding mechanisms that would permit the growth of this unique organization into an effective geospatial facility to support our community.** One effective model may be that used by the Instrumentation and Facilities Program of the Division of Earth Sciences to support multi-user facilities, but there may be others that are, at present, more attractive to the Directorate. For example, just as polar research is an exemplar of transdisciplinary convergence and PGC has thus far functioned as a key enabling strategy for polar research, we might consider a broad, transdisciplinary "collaboratory" to study earth surface evolution with an expanded PGC playing a central role.

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