Earth Science System of the Future: Observing, Processing, and Delivering Data Products Directly to Users

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Abstract: Advances in our understanding and ability to predict changes in our environment will require more comprehensive and coordinated measurements, data delivery systems, and modeling tools. The advanced Earth observing system will incorporate an integrated web of sensors deployed on the surface, in the air, and in space. The space-based assets will include both active and passive sensors in low Earth orbit, large aperture sensors in geostationary orbits, and sentinel satellites at L1 and L2. Data collected by these platforms will be coordinated by an advanced, semi-autonomous, network that links these systems each other and provides a seamless interface with data processing centers. There, advanced numerical modeling tools will be used to rapidly assimilate, evaluate, and disseminate this information directly to users. To illustrate utility of this system architecture, we describe its application to studies of rapidly evolving natural hazards.

I. INTRODUCTION

Recent advances in measuring systems and modeling tools have dramatically improved our understanding of many aspects of the physical, chemical, and biological systems that constitute the Earth's environment. For example, the data collected by the ground and space based operational meteorological networks are now routinely processed by state-of-the-art data assimilation models to yield weather forecasts that are reliable for 3 to 5 days over much of the globe. Similarly, measurements collected by advanced remote sensing instruments like those on NASA's Earth Observing System (EOS) satellites are expected to improve our understanding of many aspects of the Earth's climate on global and regional scales. However, even with this progress, a much more comprehensive and coordinated series of measurements and theoretical models will be needed to understand and predict the evolution of our environment on local, regional, and global scales. These advances are needed to facilitate the reliable prediction of the local, regional, and global effects of rapidly evolving environmental conditions that constitute natural hazards. They are also needed to predict the long-term evolution of environmental systems whose forcing and response are characterized by strongly coupled physical, chemical, and biological processes acting on a range of spatial and temporal scales. Examples of these systems include the Earth radiation budget, the global carbon and hydrological cycles and the role of the oceans in the climate system. Here, we have attempted to outline some of the primary features of a coordinated Earth observation, modeling, and data delivery system. In this system, observations will be acquired on a range of spatial and temporal scales by an integrated web of sensors deployed in the oceans, on the ground, in the air, and in space. These observations will be coordinated and transmitted to the data processing centers by a semi-autonomous, fault tolerant communications network. There, advanced modeling tools will be used to rapidly validate, assimilate, and distribute both raw data and high-level data products directly to users. To illustrate the scope and utility of this approach, the following sections describe how it might be used to monitor and predict rapidly evolving natural hazards.

To minimize the impact of severe storms, forest fires, flash floods, volcanic eruptions and other rapidly evolving natural disasters, an improved, global observing network must be deployed to provide continuous, real-time coverage over a range of spatial and temporal scales. This network should incorporate a broad range of existing and new environmental instruments. It will also require an advanced, semi-autonomous, fault-tolerant communications architecture that links these systems together, and to their data processing centers. Finally, to predict the evolution of these natural phenomena, and their impact on lives and property, advanced numerical modeling tools are needed to rapidly assimilate, evaluate, and disseminate this information to users.

II. THE OBSERVING SYSTEM

The natural hazards observing system will incorporate components on the ground, and in the air, as well as in space (Figure 1). In-situ measurement systems deployed at the surface and on aircraft are needed to characterize small-scale processes that cannot be adequately resolved from space-based platforms. These resources might include an enhanced, automated global network of fully autonomous surface weather stations (on land and on buoys), Doppler radars, cloud and aerosol radars and lidars, and instruments on both commercial and research aircraft. Because the in-situ sensors in the surface network measure only their local environment, large numbers of autonomous stations will be needed to resolve the spatial and temporal structure of passing events. For greatest value, these stations should be linked into a true sensorweb by an intelligent network that can adapt to rapidly evolving conditions by exchanging information among the nodes to optimize the scheduling of their observations [1,2]. The network could also include communication nodes designed to provide a fault-tolerant, near-real-time approach for delivering data collected the web to the appropriate processing center.

In low Earth orbit (LEO), sophisticated active instruments (radars and lidars) will soon augment advanced passive sensors (atmospheric temperature and water vapor sounders, and surface hyperspectral imagers). These LEO instruments will provide a detailed, altitude-dependent description of the winds, temperatures, rainfall rates, clouds, and aerosol amounts, and other properties throughout the troposphere along their orbital tracks. Observations acquired by high-resolution passive imagers and imaging spectrometers deployed in geosynchronous orbit (GEO) and at the libration points, L1 and L2, will complement this suite of observations by providing global synoptic scale observations at high temporal resolution. These data will be of particular value for establishing the spatial and temporal context for the phenomena observed at higher spatial resolution by surface, airborne, and LEO instruments. For example, future observations by high-spectral-resolution imaging instruments, such as the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), can be used to track winds in both clear and cloudy regions by measuring water vapor advection as well the motions of clouds. High spatial/spectral resolution O_2 A-Band spectrometers deployed in GEO or at L1 could monitor storm intensification by measuring the rate of change of cloud top heights, as well as the evolution of volcanic plumes or dust storms. The L1 perspective is of particular value for studies of cloud properties at solar wavelengths, since there are no shadows from this vantage point. Views of the nigh-time hemisphere from L2 would be of value for monitoring lightening.

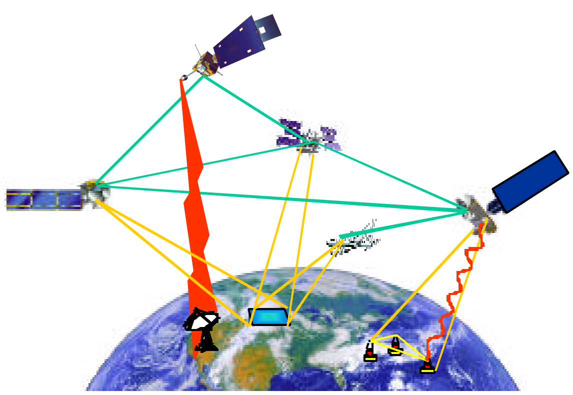

Figure 1: Coordinated observations acquired by surface, aircraft, and space-based platforms. The spacecraft are linked by optical communication, while the communication to the surface is through a high-rate microwave links.

III. System Architecture

The second component of the proposed natural hazard network is an advanced system architecture that integrates these resources into a coordinated, fault tolerant, observing system, that provides near real time access to the data being collected from all vantage points. To insure near-real-time access to the data collected by observing systems deployed on the ground or in the air, these systems should continuously transmit their data through ground and space based commercial communications facilities, or directly to dedicated UHF transponders on satellites in LEO or GEO.

An enhanced space-based communications architecture is also needed to enable reliable, timely access to observations of rapidly-evolving natural hazards observed by advanced active and passive instruments on satellites in LEO orbits. For example, if a radar on a LEO satellite detects a tornado or tidal wave, but cannot report that observation until it flies over its ground station 50 minutes, this observation may of much less use for protecting lives or property. To address this issue, the communications system should enable near real time access to a centralized ground processing facility. High communications bandwidth is also highly desirable for the foreseeable future because the advanced software and computing facilities needed to rapidly recognize, analyze, and disseminate information about hazards will be much easier to implement using state-of-the-art ground based computers.

One such architecture might include high-rate optical communication (comm) links between spacecraft in LEO, GEO, and L1/L2, combined with high rate microwave links between GEO and a dedicated ground station. Compact, low-power optical comm systems are needed to enable high-rate LEO to GEO data transmission from low-cost, small-to-moderate-sized LEO spacecraft. High-rate optical comm would also provide an efficient means to link the assets at L1 and/or L2 to other parts of the system. However, a high-rate microwave link would provide the most reliable approach for transmitting data to a dedicated ground station, because this link would be much less susceptible to disruption by clouds. This combination of optical and microwave communications should provide both the bandwidth needed to handle large downlink data volumes, and a robust, fault tolerant communications infrastructure for coordinating LEO, GEO, and L1/L2 assets for coordinated operations.

Even though the onboard processing hardware and software needed to recognize and coordinate a multi-spacecraft observing strategy for severe storms and other natural hazards may not be available within the next decade, significant advances in spacecraft autonomy are still needed to detect and track natural hazards. Specifically, observing network operations could be simplified substantially if individual components of the observing system could react autonomously in response to simple, goal-oriented command, precluding the need to generate and uplink complicated command scripts from the ground. The algorithms needed to enable these capabilities are currently under development.

IV. Advanced Modeling Tools

A new generation of data assimilation/prediction models are needed to rapidly incorporate data from these diverse sources and produce improved medium to long term predictions that could be used for hazard mitigation. In addition to the ongoing improvements in spatial and temporal resolution, both improvements in the model physics, and more efficient approaches for accommodating diverse, spatially and temporally varying data types are needed.

Currently, large-scale models for atmospheric data assimilation and weather prediction include static, spatially invariant parameterizations for small-scale physical processes that can have a significant impact on regional climate and weather. The observing network described above will provide the near-real-time data needed to accurately constrain these processes over a much larger range of spatial and temporal scales. The model algorithms must be updated such that they can accommodate and learn from this information.

The types of data provided by this network will vary with time as the coverage by various components of the observing system changes. For example, a cloud radar on a LEO satellite can provide a detailed snapshot of the vertical structure and rain rates within a hurricane or severe storm as it flies over, but it can monitor the storm only intermittently. At other times, the storm might be monitored only by GEO satellites, passive instruments on other LEO satellites, and/or ground- and aircraft-based assets. Existing meteorological assimilation and prediction models cannot incorporate these diverse, temporally varying data sources on a routine basis to improve their forecasts. Over the next decade, NASA should pursue a vigorous model-development effort into its hazards monitoring and prediction infrastructure to address this need.

V. Delivery of Data to Users

The products produced by the proposed integrated natural hazards network must meet the needs of a broad range of customers. For example, organizations responsible for public safety need only high level products (alerts of environmental hazards and predictions of their evolution), but these products must be reliable, and they must be delivered in a timely fashion, and in a convenient format. The National Weather Service's existing system for severe storm warnings addresses these needs for weather hazards throughout much of the United States (particularly the mid west). However, systems for monitoring, forecasting, and distributing information about other rapidly evolving, large-scale, natural hazards (e.g. fires, flash floods, tsunamis, and volcanic eruptions, etc.) are much less well developed. A global, hazards warning system, similar to the U.S. severe storm warning system, would be of great value for protecting lives and property from these often-devastating events.

At the opposite end of the user spectrum, researches will employ the detailed observations of natural hazards to develop an improved mechanistic understanding of their processes and environmental consequences. This information will be incorporated into more reliable models for predicting these events in the future. For this application, timeliness is less important, but a comprehensive, calibrated data set that characterizes all aspects of the phenomenon is essential. In principle, this information can be accessed from one or more conventional, Distributed Active Archive Centers (DAACs). However, the existing data archiving system still requires a significant amount of effort by individual researchers to locate and download all measurements relevant to a specific event if these measurements were acquired by different elements of the observing network. This system would be of much greater use for these applications if all of the relevant measurements could be accessed from a distributed archive in a similar format, by sophisticated, automated search tools. These tools should therefore be a high priority in the future development of the Earth Science information systems.

VI. Conclusions

The approach described above provides a rough outline of a future system for observing, analyzing, and distributing information about natural hazards. This approach, which employs coordinated observations, analysis, and data delivery from a distributed sensor web, would also be of great value for studying other aspects of Earth system science. For example, a coordinated, distributed observing system would be ideal for studying the spatially and temporally varying processes that control the Earth's solar and thermal radiation budgets. The limited application of this approach in radiative "closure" experiments has already provided a great deal of insight into the effects of clouds and aerosols on the atmospheric solar and thermal radiation fields. An approach that incorporates in-situ measurements as well as remote sensing observations from the sub-surface, surface, airborne platforms, and from space is also needed to enable a comprehensive investigation of the carbon and hydrological cycles. Similarly, systems for integrating sub-surface and surface measurements acquired by moored and drifting buoys, with global satellite measurements of sea surface temperatures and winds are needed for more detailed investigations of the role of the oceans in the climate system. In each of these applications, advanced modeling tools will be needed to validate, assimilate, and analyze the data from diverse range of sources. Finally, advanced data delivery and archiving methods will be needed to insure that these products are available to their intended users.

Acknowledgements

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