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Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards

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Abstract

Satellite remote sensing is providing a systematic, synoptic framework for advancing scientific knowledge of the Earth as a complex system of geophysical phenomena that, directly and through interacting processes, often lead to natural hazards. Improved and integrated measurements along with numerical modeling are enabling a greater understanding of where and when a particular hazard event is most likely to occur and result in significant socioeconomic impact. Geospatial information products derived from this research increasingly are addressing the operational requirements of decision support systems used by policy makers, emergency managers and responders from international and federal to regional, state and local jurisdictions. This forms the basis for comprehensive risk assessments and better-informed mitigation planning, disaster assessment and response prioritization. Space-based geodetic measurements of the solid Earth with the Global Positioning System, for example, combined with ground-based seismological measurements, are yielding the principal data for modeling lithospheric processes and for accurately estimating the distribution of potentially damaging strong ground motions which is critical for earthquake engineering applications. Moreover, integrated with interferometric synthetic aperture radar, these measurements provide spatially continuous observations of deformation with sub-centimeter accuracy. Seismic and in situ monitoring, geodetic measurements, high-resolution digital elevation models (e.g. from InSAR, Lidar and digital photogrammetry) and imaging spectroscopy (e.g. using ASTER, MODIS and Hyperion) are contributing significantly to volcanic hazard risk assessment, with the potential to aid land use planning in developing countries where the impact of volcanic hazards to populations and lifelines is continually increasing. Remotely sensed data play an integral role in reconstructing the recent history of the land surface and in predicting hazards due to flood and landslide events. Satellite data are addressing diverse observational requirements that are imposed by the need for surface, subsurface and hydrologic characterization, including the delineation of flood and landslide zones for risk assessments. Short- and long-term sea-level change and the impact of ocean-atmosphere processes on the coastal land environment, through flooding, erosion and storm surge for example, define further requirements for hazard monitoring and mitigation planning. The continued development and application of a broad spectrum of satellite remote sensing systems and attendant data management infrastructure will contribute needed baseline and time series data, as part of an integrated global observation strategy that includes airborne and in situ measurements of the solid Earth. Multi-hazard modeling

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capabilities, in turn, will result in more accurate forecasting and visualizations for improving the decision support tools and systems used by the international disaster management community.

Keywords: Satellite remote sensing; Imaging spectroscopy; Interferometric synthetic aperture radar (InSAR); Global positioning system (GPS); risk mitigation; Disaster response; Decision support system (DSS); Natural hazards

1. Introduction

The last two decades have witnessed the increasing use of remote sensing for understanding the geophysical phenomena underlying natural hazards. The scientific knowledge gained along with the ability to disseminate timely geospatial information that can be integrated with demographic and socioeconomic data are contributing to comprehensive risk mitigation planning and improved disaster response. As the discipline of Earth science began to recognize the interactions between the hydrosphere, atmosphere, biosphere and solid Earth as a complex system, satellite remote sensing uniquely has provided the synoptic perspective for in situ measurements on local spatial scales and variable temporal resolution. Observations from Earth orbiting satellites are complementary to local and regional airborne observations, and to traditional in situ field measurements and ground-based sensor networks in seismology, volcanology, geomorphology and hydrology. The contributions of satellite remote sensing to solid Earth science, ranging from high-resolution topography (using e.g. Interferometric SAR, Lidar and digital photogrammetry) and geodesy to passive hyperspectral (such as ASTER, MODIS and Hyperion) and active microwave imaging, have transformed the discipline. This transformation has helped to define a rapidly growing field of applied research that increasingly will provide geospatial information products addressing the operational requirements of multi-hazard decision support tools and systems. Policy makers, emergency managers and responders from international and federal to state, regional and local jurisdictions use these tools and systems to generate scenarios, devise mitigation plans and implement effective response measures.

Satellite remote sensing, in particular, is providing a systematic framework for scientific knowledge of the solid Earth that is the basis for better-informed decision-making. The key to understanding the Earth's dynamics and system complexity is to integrate observations at local, regional and global scales, over a broad portion of the electromagnetic spectrum with increasingly refined spectral resolution, spatial resolution and over time scales that encompass phenomenological lifecycles with requisite sampling frequency. Advances in computational science and numerical simulations are allowing the study of correlated systems, recognition of subtle patterns in large data volumes, and are speeding up the time necessary to study long-term processes using observational data for constraints and validation (Donnellan et al., 2004). Integrating remotely sensed data into predictive models requires measurements at resolutions substantially superior to those made in the past when the observational systems and the discipline of natural hazards research were less mature than they are today. Furthermore, assimilation of data and model outputs into decision support systems must meet operational requirements for accuracy, spatial coverage and timeliness in order to have positive impact on disaster risk management.

In the following sections, satellite remote sensing systems and integrated observational and modeling approaches that are being used to study and assess risks due to earthquakes, volcanoes, floods, landslides and coastal inundation are reviewed briefly. Only hazards manifested through solid Earth processes are the focus herein, although significant advances in the application of satellite remote sensing to severe weather events and wildfires, for example, indeed are being made but left for review elsewhere. This paper is not intended as a comprehensive treatment of the application of remote sensing to the selected natural hazards but rather as a recognition of the contributions of satellite remote sensing to understanding underlying phenomena and providing critical information for decision support by emergency managers and the disaster response community. As such, it is a summary of work reported by the solid Earth science community in natural hazards research and applications (NRC, 2003; SESWG Report, 2002), with reference to the latest results in the literature and to seminal planning documents developed by the Subcommittee on Disaster Reduction (SDR), National Science and Technology Council of the U.S. Committee on the Environment and Natural Resources (CENR) (CENR, 2003), the Geohazards Theme Report of the Integrated Global Observing Strategy (IGOS) international partnership (IGOS Geohazards Theme Report, 2004), and the Disaster Management Support Group (DMSG) Report of the Committee on Earth Observation Satellites (CEOS) within IGOS (CEOS, 2003). The intent is to underscore the view of the Earth as a complex system of forcings and responses, the increasingly recognized potential of satellite remote sensing to assess the consequences of resultant changes, and the need for advanced observation platforms and monitoring systems for sustained measurements of the solid Earth relevant to disaster management.

2. Earthquake hazards

Deformation at the Earth's surface, predominantly adjacent to tectonic plate boundaries, is the manifestation of forces acting deep within its interior. Geodetic and seismological measurements provide the principal data for understanding mantle dynamics, lithospheric processes and crustal response, and for improving numerical modeling for forecasting catastrophic events such as earthquakes and volcanic eruptions. Major advances have been made in earthquake research and risk mitigation. However, the nature of significant seismic events–with greater and more widespread occurrence than volcanic hazards and resultant loss impact that is much higher than that of even more widespread landslide and subsidence hazards (IGOS Geohazards Theme Report, 2004)–presents extant research needs. Research requirements in earthquake science that will contribute to better seismic risk management and forecasting on a global basis include documenting the location, slip rates and earthquake history of dangerous faults; understanding the kinematics and dynamics of active fault systems on interseismic time scales and applying this understanding in constructing probabilities of occurrence; characterizing the three-dimensional material properties of fault systems, their response to deformation and the physics of earthquake nucleation, propagation and arrest; and predicting strong ground motions and non-linear surface layer response, including fault rupture, landsliding and liquefaction (NRC, 2003).

Integrated ground measurements and satellite remote sensing can help meet these various requirements for baseline and time-series data. The Global Positioning System (GPS), for example, used for navigation and positioning in civilian and military applications, provides the millimeter-level differential accuracy that is used by regional ground deformation networks to monitor interseismic ground deformation and co-seismic displacements. GPS monitoring networks are leading to better definition of off-fault surface deformation rates; timely detection of diagnostic changes in the fault environment; and constraints on the extent of surficial fault creep and its significance to potentially significant earthquakes. Accurate estimates of the distribution of potentially damaging ground motions from such earthquakes enable ground motion modeling, structural design planning and risk assessment for loss estimation. Earthquake forecasting efforts are related intimately to generating this increased understanding of the fundamental dynamics of major faults, with fault segment definition leading to a better description of the expected details of earthquake faulting and rupturing. Moreover, GPS and modern digital seismic data can be combined with satellite remote sensing, such as interferometric synthetic aperture radar (InSAR) to provide spatially continuous deformation with sub-centimeter accuracy. Fig. 1 shows a comparison of an InSAR-derived deformation time series with GPS network time series data, providing insight into the spatial and temporal relationship between continuous GPS data and InSAR. The availability of both temporal and spatial deformation data allows for a greater level of understanding of the dynamics of the area. InSAR techniques are an integral component of an Earth observation capability for seismic risk mitigation and response (CEOS, 2003).

Delineation of seismic source zones requires understanding the geology, tectonics, and paleoseismic and neotectonic features of the subject region. Investigations of surface deformation, plate-boundary interactions, frictional properties of faults, and

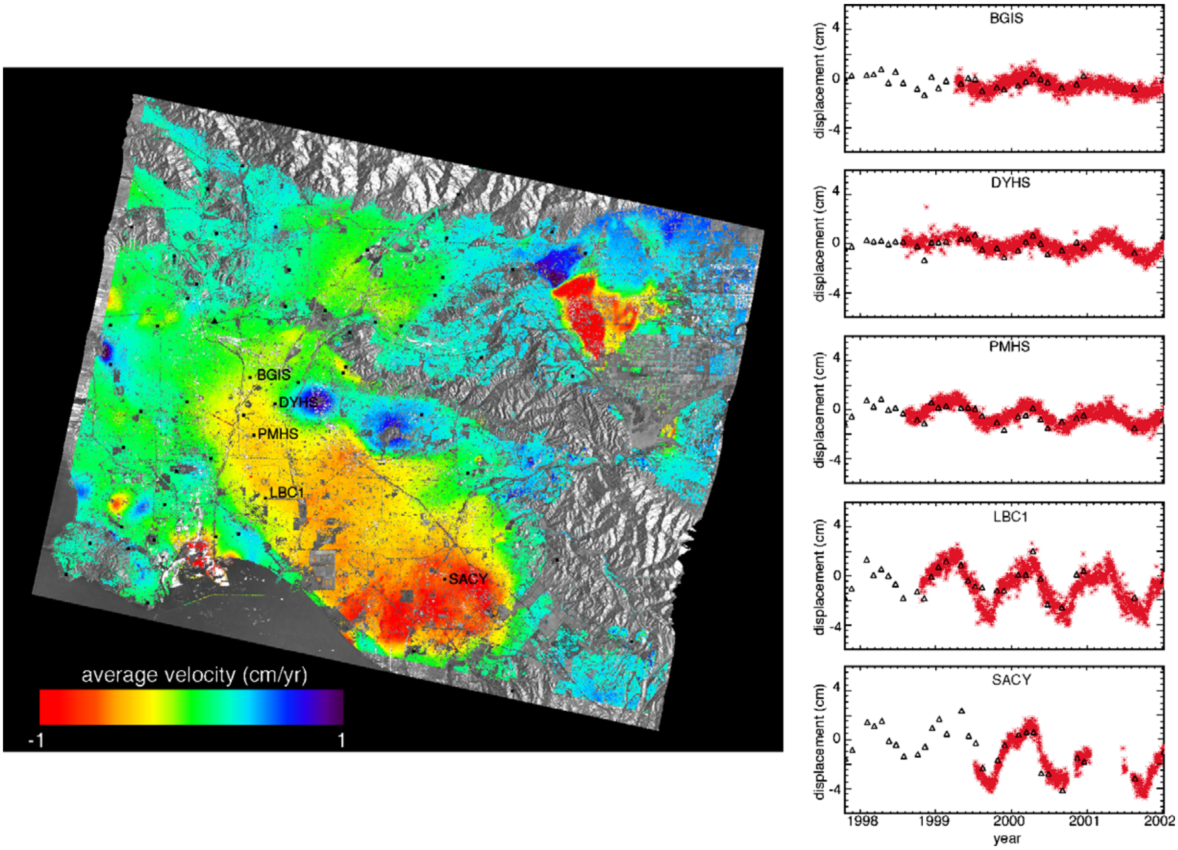

Fig. 1. (Left) InSAR time series inversion map of the radar line-of-sight deformation average velocity, overlying the multi-look SAR amplitude image (gray scale). Small black squares mark Southern California Integrated GPS Network (SCIGN) GPS site locations. (Right) InSAR time series (black triangles) at selected points. Plots compare the InSAR time series to SCIGN GPS (red*) time series for indicated sites (produced from European Space Agency remote sensing data, ERS-1 and ERS-2. Figure courtesy P. Lundgren, NASA/JPL; see also Lanari et al., 2004).

mechanical properties of the Earth's crust and lithosphere help to determine what controls the spatial and temporal characteristics of earthquakes. For example, surface displacements due to the 2003 Bam, Iran, earthquake were mapped using ENVISAT radar data to reveal that over 2 m of slip occurred at depth on a blind strike-slip fault, where no morphological features were present (Talebian et al., 2004). Space-based observations of the entire earthquake cycle, including the aseismic accumulation of strain between events (Fielding et al., 2004) are critical for learning about the phenomenology and for forecasting potentially hazardous earthquakes. Remote and in situ data that support attendant scientific and engineering models are necessary in order to understand the source-rupture process, fault plane geometry and thus infer the resultant patterns of damage (see Lohman et al., 2002). This is critical for effective risk management.

While there are in operation notably successful dense GPS geodetic networks in regions prone to potentially catastrophic seismic and/or volcanic events, such as southern California (Hudnut et al., 2002) and particularly Japan (Shimada and Bock, 1992), economic constraints limit the widespread global deployment of these networks. Furthermore, a lack of standard formats and established archives, plus limited accessibility for the different kinds of deformation data are major challenges for the integration of local GPS data globally, and the integration of GPS data with older, heritage deformation data sets (IGOS Geohazards Theme Report, 2004). The ability of geodetic data to resolve variations in slip patterns also diminishes greatly with slip depth. Prediction of strong motion velocities from geodetic data alone offers limited spectral response, thus being a poor replacement for actual strong motion recordings that are critical to earthquake engineering. In either case, the spectrum of ground displacement signatures measurable by GPS and seismic networks is sampled discretely.

Satellite remote sensing systems not only offer spatially continuous information of the tectonic landscape but also contribute to the understanding of specific fault systems. Combined with ground network data, remote sensing enables a better understanding of displacements, and validation of slip models that are cast in a regional setting of tectonic strain (Cakir et al., 2003) and help constrain source characterization (e.g. Lundgren and Stramondo, 2002). Satellite remote sensing observations are providing insights into how stress is transferred between fault systems from depth and to the surface, how much energy is released by earthquakes and other modes of deformation (Argus et al., in press) and how faults fail mechanically.

In certain cases, earthquakes can produce global gravity perturbations that are detectable through analysis of satellite data from missions dedicated to gravity field determination, such as the Challenging Mini-satellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE) and the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE). Coseismic gravity and geoid changes differ from other, larger and more coherent high-frequency variations such as Earth tides. The coseismic effects of great earthquakes such as the 1960 Chile, 1964 and 2002 Alaska, and 2003 Hokkaido events cause global gravitational field changes that are sufficiently large to be detected by GRACE, for example, based on degree variance analysis using spherical harmonic representation of dislocation theory (Sun and Okubo, 2004) and a normal mode technique comparing the degree amplitude spectra of select earthquakes with GRACE sensitivity (Gross and Chao, 2001). Such gravity data also can provide important constraints on the interpretation of seismological data (Tondi et al., 2003), as for testing the shorter wavelength features of three-dimensional tomographic models based on the inversion of short period seismic waves. Many parts of the lithosphere, where heterogeneity is high, particularly near plate boundaries (Bowin, 1991), are poorly sampled by short period waves and global gravity data from abovementioned satellite systems are spatially continuous and uniquely complementary.

Finally, observations of land cover, land use and of the built environment, structures and lifelines specifically are a critical component of risk management and loss estimation methodologies. Integration of high-resolution satellite remote sensing with InSAR and airborne Light Detection and Ranging (LiDAR) is being researched as a means to image, classify and inventory the built environment through the extraction of land cover and digital terrain models (Gamba and Houshmand, 2002). This contributes to vulnerability assessments and to rapid post-disaster damage assessment (Rejaie and Shinozuka, 2004), through integration with demographic data, infrastructure and building stock databases in a geographic information system (GIS). Rapid damage assessment is critical for effective allocation of disaster response and relief resources, including federal insurance assistance. Available satellite remote sensing systems, from civil space agencies and commercial imaging sources such as IKONOS, OrbView and QuickBird, are witnessing increased utilization in disaster management research and operational domains.

3. Volcanic hazards

Subaerial volcanic eruptions occur often after long intervals of dormancy and thus opportunities for direct geophysical measurements are intermittent and sporadic. While there are numerous indicators of subaerial volcanic activity, in addition to surface deformation and seismicity–such as thermal emissions, and changes in gravity, emission of gasses plus ash and clastic eruptions–little is known about the global levels of these activities and how these phenomena are related. Furthermore, the physical mechanisms that cause surface deformation and those that control the rates and styles of eruptions are poorly understood. The ability to predict or otherwise forecast the timing, magnitude, and style of volcanic eruptions on the Earth's land surface is an important yet generally unmet objective in volcanic hazards assessment and mitigation planning (SESWG Report, 2002).

An observation strategy that incorporates seismic and in situ monitoring, geodetic measurements, high-resolution topography [i.e. Digital Terrain Elevation Data (DTED) Level 1) and hyperspectral imaging can contribute significantly to volcanic hazard risk assessment, mitigation and response. Observational requirements for volcanic hazards include the three-dimensional spatial distribution of seismicity; the characteristic deformation of the volcanic edifice using geodetic and gravimetric techniques that include identification of faults, fractures, landslides and flank instabilities, rift systems and calderas; characterization of gas and ash emissions by species (SO_2, CO_2) and flux; and characterizing and monitoring of thermal features, their nature, location, temperature and possible heat flux (CEOS, 2003).

Fundamental to the understanding of eruptive systems are the identification and characterization of active volcanoes—namely a comprehensive global inventory. This would comprise not only geodetic observations, with InSAR for example (Pritchard and Simons, 2004), but spectroscopic observations of debris flows and land surface, as with Hyperion–the first spaceborne imaging spectrometer–onboard the NASA Earth Observing-1 (EO-1) satellite (Crowley et al., 2003; Wright and Flynn, 2003), and ash and emissions (see Fig. 2), as with the NOAA Geostationary Operational Environmental Satellite (GOES) (Ellrod et al., 2003) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Watanabe and Matsuo, 2003; Pieri and Abrams, 2004). Such measurements and new observational tools are enabling a rapid growth in the understanding of volcanic hazards worldwide.

Geodetic observations of volcanoes with GPS and InSAR are yielding high-resolution digital elevation models (DEMs) (Lu et al., 2003) and full vector deformation rate maps that complement traditional ground-based geodetic techniques. These high-resolution measurements are required in order to reduce ambiguities in inferences of magma chamber geometry from outward structural changes (e.g. Lanari et al., 2003). Computer models of a variety of flows are increasingly being use in volcanic hazard assessment to predict potential areas of devastation (Stevens et al., 2003). Furthermore, DEMs are being used to predict lava flow and lahar paths on remote volcanoes, with a promising level of accuracy over distances of tens of kilometers (Glaze and Baloga, 2003). The accuracy of these models depends on the accuracy of the available topographic data; measurements from the Shuttle Radar Topography Mission (SRTM) provide invaluable data, particularly in remote regions where high-resolution topographic data are unavailable (e.g. Stevens et al., 2003). A monitoring strategy that includes the use of such predictive flow models and risk zonation could support land use planning, particularly in developing countries where the impact of volcanic hazards to populations and lifelines is continually increasing.

Remote sensing indeed is defining a new paradigm for volcanological observations (Pieri and Abrams, 2004). Imaging spectroscopy (or hyperspectral imaging) in both the solar-reflected (0.4–2.5 μm) and thermal portions (3–5 μm and 8–12 μm) of the spectrum, permits the identification, separation, and measurement of subtle variations reflecting the overlapping molecular absorption and constituent scattering signatures of materials present on the Earth's surface. Measurements of surface deposits and composition, surface temperature, topography and surface deformation, SO_2 and ash detection and tracking (Fig. 2), and modeling are needed to better characterize, understand and predict the volcanic hazards environment. Measurements made by the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and by Hyperion have been used to map subtle changes in near-surface rock chemistry and, thereby, identify zones of volcanic-debris-flow susceptibility on the basis of rock strength inferred from specific mineralogical indicators of hydrothermal alteration (Crowley et al., 2003).

Global monitoring, including of remote areas, at weekly time intervals with spaceborne systems would enable the requisite sensitivity to low-level but more nearly continuous processes for assessment of risks in short-term early warning systems. In the event of an eruption, shorter time intervals are desired, with updating several times per day. However, in these cases, only a spotlight view of a targeted area of the globe is needed, for example to provide volumetric estimation of eruptive lava outflow and source modeling (Lundgren and Rosen, 2003), distinguishing between surface deformation caused by magma movement or fluid pressure build-up. A similar rationale holds for the timing of spectroscopic

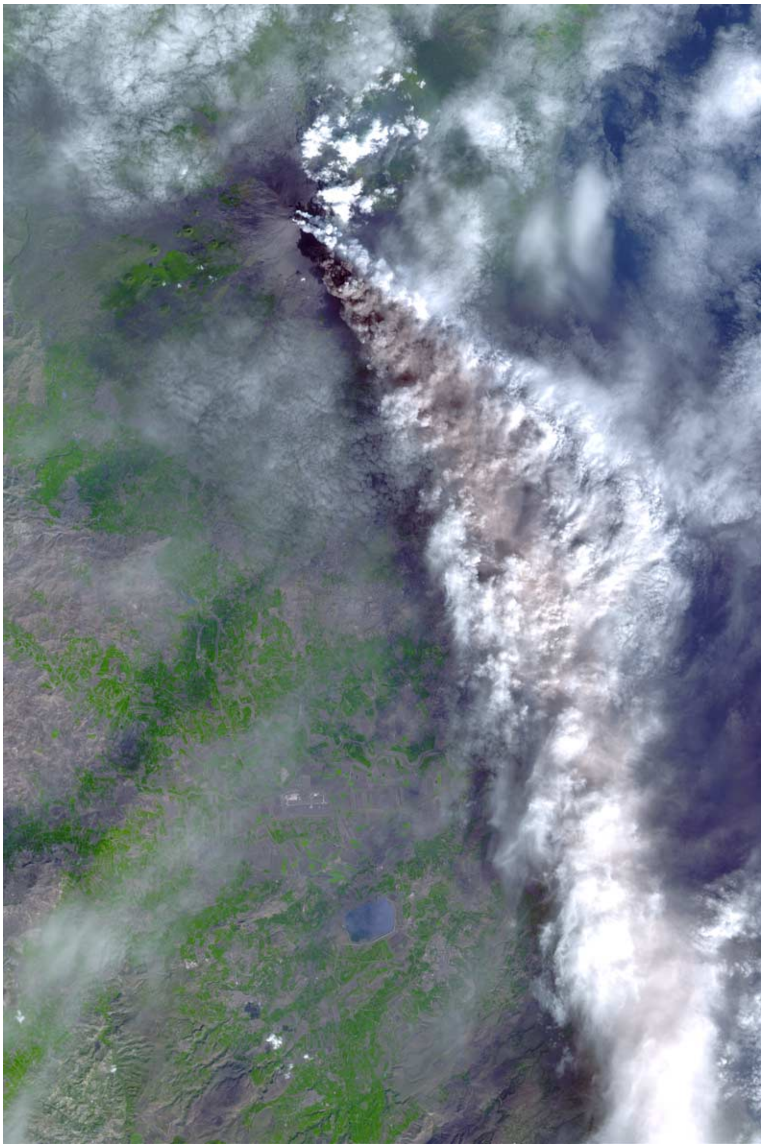

Fig. 2. Mt. Etna is one of the world's most active volcanoes and has been studied for centuries from the ground. On November 3, 2002 Mt. Etna's ash-laden plume was imaged by ASTER. The plume is seen blowing towards the south–southeast, over the city and airport of Catania, Sicily. The previous day, the plume was blowing towards the northwest, and posed no hazard to Catania. The eruption of Mt. Etna, Europe's most active volcano, began on October 27. The image covers an area of 50.8×76.5 km [image courtesy M. Abrams, NASA/JPL].

measurements that provide sensitivity to heat flux and gas emissions (e.g. SO_2 and CO_2) (Prata et al., submitted for publication). Proper temporal resolution, temperature change sensitivity of the order of 0.5 K and accurate measurements of gas emissions, along with surface deformation maps, may allow the forecasting of eruptions. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the NASA Terra and Aura spacecraft are providing imagery of subaerial volcanoes on Earth every 2 days (Watson et al., 2004). There is now an online archive of eruptions going back nearly 5 years, using MODIS data for global monitoring through detection of thermal signatures (Wright et al., 2002, 2004). Retrieval algorithms are able to quantify volcanic ash, ice, sulfates and SO_2 using thermal infrared (8–12 μm). Identification of outgassed species near vents and craters provides information on subsurface activity and processes and may ultimately assist in forecasting eruptions. Thermal measurements of land surface temperature, together with simultaneous measurements of the changing emissivity, provide additional constraints on magmatic processes and volcanic activity. Even the contribution of subaerial active volcanoes to the Earth's energy budget can be estimated (Wright and Flynn, 2004).

4. Flood and landslide hazards

Floods are among the most devastating natural hazards in the world, claiming the largest amount of lives and property damage (CEOS, 2003). Remotely sensed data play an integral role in reconstructing the recent history of the land surface and in predicting hazard events such as floods and landslides, subsidence events and other ground instabilities. Reconstruction of past erosion, deformation, and deposition and quantification of tectonic, climatic, and biologic inputs–including human-induced changes–to the evolving landscape underpin the ability to develop a process-based understanding of the Earth's dynamic surface.

Since land-surface properties change through time, remote sensing of such changes yields critical temporal control on landscape evolution. The need for higher spatial and temporal resolution data is pinpointed by recognizing that destructive floods or landslides can be launched by intense, short-lived storm cells a few kilometers in extent. The height and width of rivers, as well as rainfall intensity and amounts, need to be measured hourly during storms. Hossain and Anagnostou (2004) give an assessment of the current state of passive microwave and infrared-based satellite systems for flood prediction. Few data exist on soil moisture, thickness, and strength, or on vegetation cover, fire history, or detailed topography. Synthetic aperture radar (SAR) and Landsat Thematic Mapper (TM) data have been integrated to provide information on land cover and the geomorphology of slopes, to inventory and characterize landslide potential in high relief areas (Singhroy et al., 1998), and to monitor post-slide motion and characterize debris size and distribution (Singhroy, 1995).

Contributions of spaceborne remote sensing to flood warning, disaster assessment and hazard reduction will rely on a broad-based program of remotely sensed and in situ measurements of rainfall, river heights, soil moisture, with vegetation change providing critical indices for flood and landslide hazards. Integration of remote sensing and in situ measurements is needed, along with hydrologic models benefiting from improvements in multi-scale observations of climate and weather, from global to synoptic and mesoscale to storm scales. For example, the SeaWinds radar aboard QuikSCAT and MODIS optical data are processed and combined with a GIS for monitoring flood propensity and developing weekly surface water anomaly maps (Fig. 3) that emphasize the sustained excess moisture receipts most likely to cause river flooding (see www.dartmouth.edu/~floods). Occasional (5–10 years) quantification of soil composition and thickness would suffice in areas governed by gradual processes, but more frequent measurements will be needed in areas affected by such dynamic events as floods or landslides.

Diverse observational requirements are imposed by the need for surface, subsurface and hydrologic characterization, including the delineation of flood and landslide zones for risk assessments (see Carrasco et al., 2003) and mitigation planning, and zones prone to subsidence due to groundwater interactions (see Buckley et al., 2003). The types of measurements that are needed to quantify, model, and predict flood hazards include 1-m DEMs with 5 cm accuracy for catchment geometry and hill-slope angles used for water routing and landslide threshold assessments; hourly measurements of rainfall intensity and duration with 1–2 mm accuracy; and 12-hourly measurements of soil moisture to assess infiltration and runoff potential. Seasonal measurements of vegetation cover and canopy structure provide for water interception and soil strength assessment, while 5-m resolution geologic mapping provides an overview of rock strength, permeability and erosion potential. In conjunction, multi-channel and multi-sensor data from meteorological satellites are assimilated into numerical weather prediction models to estimate precipitation intensity, amount and coverage, winds and other factors that impact the severity of flood hazards.

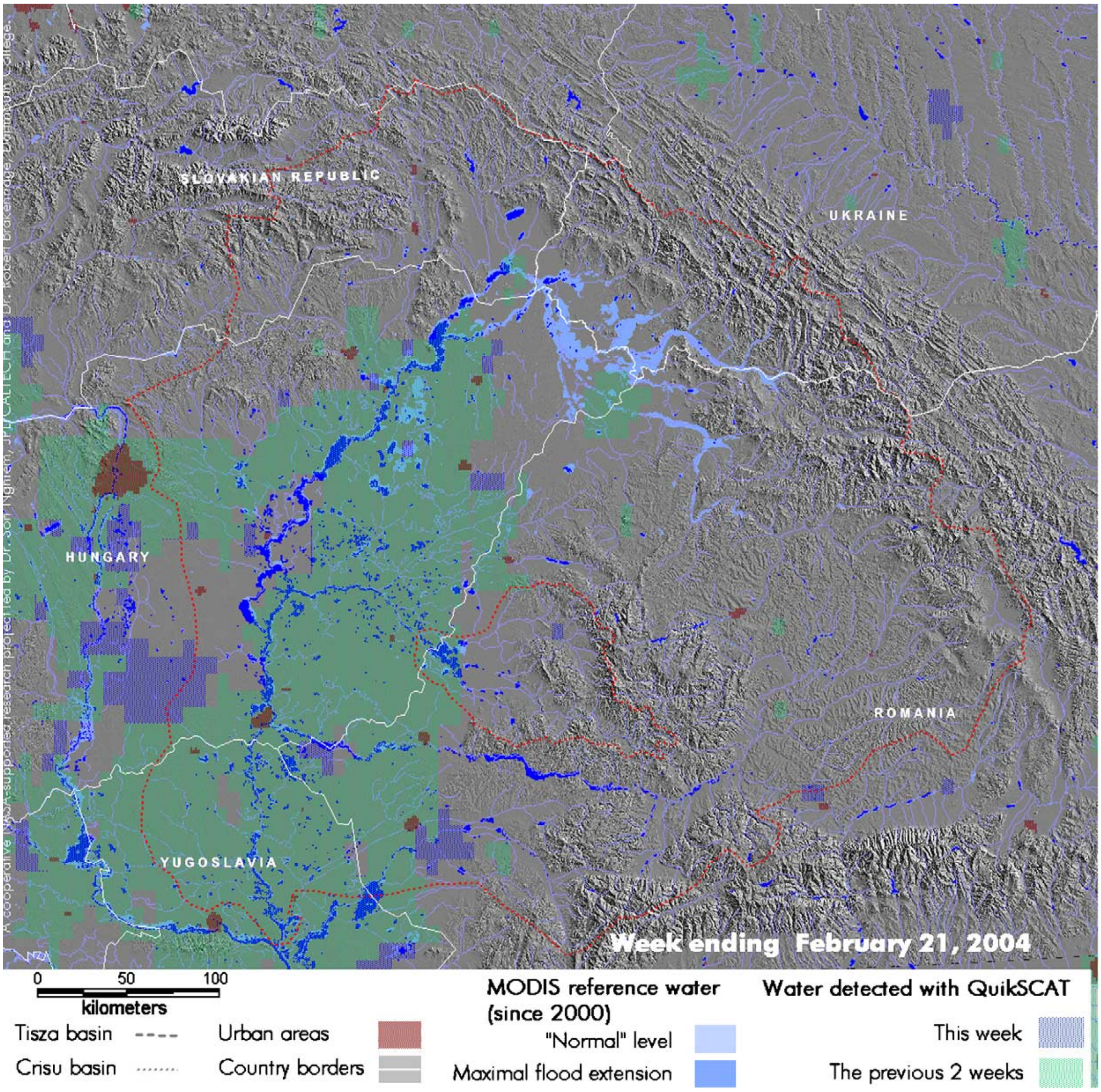

Fig. 3. Wet soil conditions of the Tisza River Basin in Eastern Europe from analysis of QuickScat and MODIS data [image courtesy S.V. Nghiem, NASA/JPL and R. Brakenridge, Dartmouth University].

The principal contribution of Earth observation data is to provide the morphological, land use and geological detail to help determine how a landslide failed and the cause of failure (CEOS, 2003). GIS is being used increasingly for regional risk assessment, including the integration of inventory mapping, location of surface structures and roughness providing information on flow emplacement parameters (i.e. rate, velocity and rheology), and factors such as lithology, location of faults, slope, vegetation and land use. The remote sensors that increasingly will provide flood and landslide hazard monitoring data include InSAR, GPS (Malet et al., 2002; Gili et al., 2000), visible and near infrared/ thermal infrared (VNIR/

TIR) imaging, multi-parameter SAR, laser altimetry, and microwave imaging. SAR data can provide an all-weather flood mapping capability and can be useful for the estimation of hydrological parameters such as soil moisture (soil surface wetness), wet snow mapping, and the monitoring of wetlands and flood extent delineation (CEOS, 2003). InSAR offers the capability for measuring displacements and providing very high accuracy topographic mapping. However, even with the integration of in situ measurements, the ability for a predictive capability for the occurrence and extent of landslide impact falls behind that for mitigation planning (see CEOS, 2003). A thorough evaluation of erosion hazards in the United States related to coastal processes and flooding is provided by the Heinz Center (2000), ranging from risk assessment, economic impact and insurance programs to management and policy. Satellite-based observations will need to be augmented with extensive land-based measurements and data from existing and future, integrated hydrologic and geodetic arrays.

5. Coastal inundation

Atmospheric and oceanic processes have a significant effect on coastal geomorphology. Sea level rise as a consequence of global climate change represents an enormous risk to coastal populations. Eleven of the world's 15 largest cities lie along the coast or on estuaries. About 53% of the US population, for example, lives near the coast (Small et al., 2000). Any short-term or long-term sea-level change relative to vertical ground motion is of great socioeconomic concern, yet no accurate estimate of the vulnerability of coastal communities exists.

The effects of sea level rise are spatially non-uniform due to local coastal variables, such as interactions between lithology, geomorphology, and wave climate, currents and storm frequencies (Gornitz, 1991). Paleo-environmental and historical data clearly have indicated the occurrence of such changes in the past, and the potential impact under enhanced greenhouse conditions (Mcinnes et al., 2003). Sea level rise itself is not globally uniform, as Fig. 4 shows. The TOPEX/POSEIDON altimetric satellite now in its 12th year of operation has established this remarkable record with the most accurate measurements of sea surface topography to date. Its successor Jason-1, and the planned NASA Ocean Surface Topography Mission (each a collaborative mission between the US and French space agencies), as well as ERS-1 and -2, and recently ENVISAT, of the European Space Agency, all contribute to monitoring this crucial quantity.

Sea level rise does not just passively inundate low-lying coastal regions. Sea level rise, as a symptom of climate change, and changes in storm frequency or

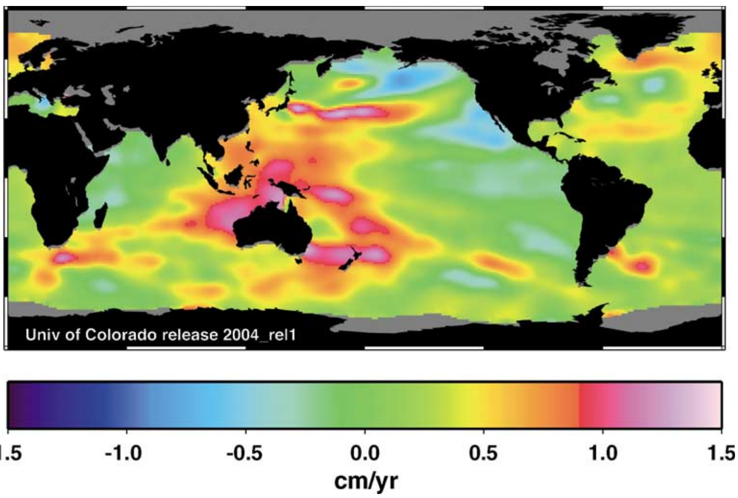

Fig. 4. Trends in sea level derived from TOPEX/POSEIDON data for the period 1993–2003. Inverse barometer (IB) correction applied [see http://www.sealevel.colorado.edu and Leuliette et al. (2004)].

intensity lead to greater erosion of the coasts and accelerate the process whereby the ocean inundates what was previously land surface. The Intergovernmental Panel on Climate Change (IPCC) has outlined major impacts of rising sea level on coastal communities (IPCC, 2001), which include beach erosion, inundation of land and increased flood and storm damage. The IPCC reports that 1 cm rise in sea level erodes beaches about 1 m horizontally; a 50-cm rise in sea level will inundate 8500–19000 km^2 of dry land; and a higher sea level will provide a higher base for storm surges. A 1-m rise in sea level would enable a 15-year storm to flood areas that today are only flooded by 100-year storms (IPCC, 2001). Fig. 5 shows the effect of a 5-m sea level rise on the Florida coast of the US. Flood damages would increase accordingly and contribute to higher sediment deposits at inlets, further exacerbating the inundation hazard risk.

An example of an integrated observation strategy consists of space measurements of ocean vector winds (SeaWinds on QuickSCAT and ADEOS-2; ERS-1 and -2 and now Meteosat) to assess the strength of storms at sea from their surface wind vectors; in addition, Tropical Rainfall Mapping Mission (TRMM) measurements of the precipitation associated with storms, with NASA Atmospheric Infrared Sounder (AIRS), MODIS and other instruments observing the cloud

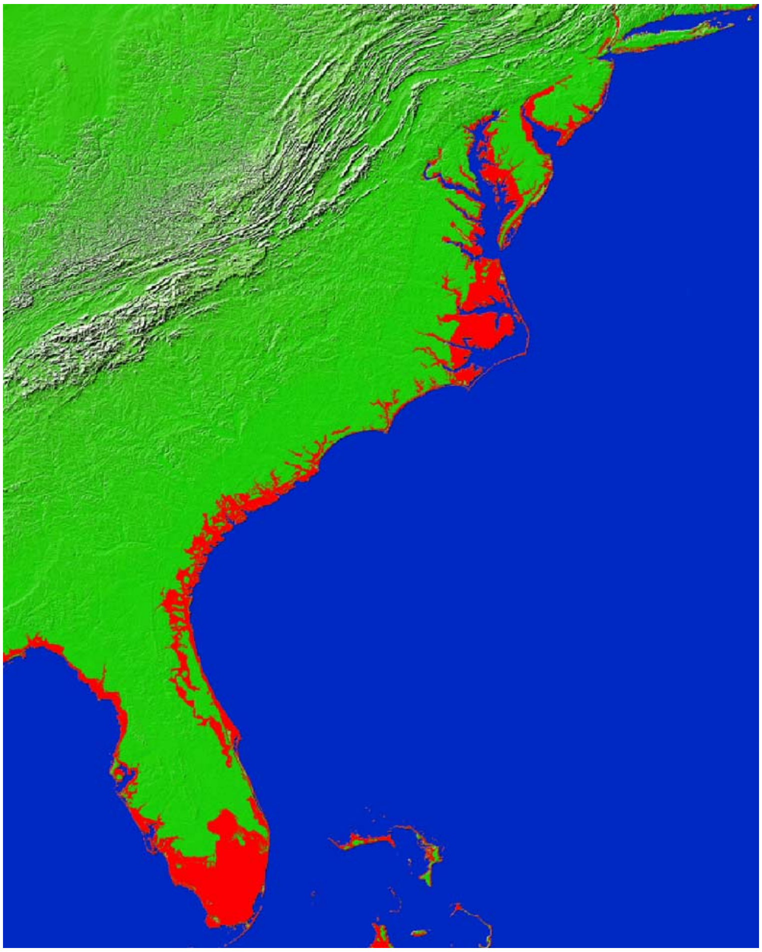

Fig. 5. The potential rise in sea level caused by melting of the Greenland ice sheets seriously jeopardizes low-lying areas such as the Florida coast. Red shows where land would be submerged for an estimated 5-m sea-level rise [image courtesy M. Kobrick, NASA/JPL].

patterns above the storm, and passive radiometers measuring the water vapor around the storm. By studying changes in storm frequency and intensity, for example, better estimates can be made of what future climate change will bring to coastal regions. Integrated SAR and TM imagery have been used to monitor changes in coastal geomorphology and land cover, flood and erosional damage, and to facilitate planning and maintenance of mitigations (Singhroy, 1995). Advances to-date in the science and technology of shoreline change mapping and projection of future shoreline positions are elements of erosion hazard zone identification under the FEMA National Flood Insurance Program (Leatherman, 2003). The U.S. Environmental Protection Agency has studied the environmental impact and economic costs associated with coastal inundation due to the greenhouse effect and sea level rise (Titus et al., 1991). These assessments have direct bearing on coastal land-use planning for risk mitigation.

In addition to the continual effects of atmospheric and oceanic processes on coastal geomorphology, earthquakes underneath or near the ocean (particularly at deep ocean trenches and island arcs) and less commonly submarine landslides and volcanic eruptions can generate tsunamis with the potential to inundate the coast. The magnitude 9.0 Indonesian earthquake of December 26, 2004 off the west coast of northern Sumatra is a recent and indeed historic example of extreme coastal inundation resulting from generation of tsunamis. The devastating losses to life and property from this great event are a reminder of the potential of natural hazards to change the landscape and calls attention to the need for integrated monitoring systems, including in situ and orbiting sensors, real-time communications, extremely fast assessment, and prearranged communication lines to those in the best position to warn populations throughout the globe, where the socioeconomic consequences of catastrophic disaster events are widespread.

6. Conclusions

Integrated satellite-based observations and numerical modeling are leading to new levels of understanding of the complex solid Earth processes that often lead to disasters. Satellite remote sensing data and derived geospatial products increasingly are complementing ground-based network data, and in situ and field observations for disaster assessment and response. Many advances in satellite remote sensing have been and will continue to be made as various resources are secured for technology and infrastructure development, in efforts towards bridging the transition from natural hazards research to enhanced operational capability in disaster management. The Advanced Synthetic Aperture Radar (ASAR) operating at C-band, onboard ENVISAT, launched by the European Space Agency in March 2002, is an enhanced capabilities continuation of the ERS-1/2 that has as one of its mission objectives the monitoring of earthquake and volcanic hazards. The Japanese Advanced Land Observing Satellite (ALOS) includes a panchromatic stereo imager for digital elevation mapping, a visible and near I/R radiometer and phased array L-band SAR (PALSAR). The PALSAR system is designed to provide continuous images of land deformation. Moreover, tools to produce information products through integration, assimilation, modeling and realistic computational simulations must continue to be developed, addressing issues of data access continuity, completeness, interoperability and validation.

The solid Earth science research community must continue to demonstrate the potential of these remote sensing systems and derived products for operational decision-making that impacts the ability to reduce losses to life and property. Assimilation of science, model outputs and satellite data into decision support tools and systems through applications, validation and performance benchmarking is a critical step. Policy- and decision-makers, emergency managers and responders, in turn, will use the enhanced decision support systems, geospatial information products, model-based forecasts and visualizations in long-term planning of emergency services and lifelines, comprehensive disaster assessment and response prioritization. Cost-effective approaches will be necessary, with the participation of the commercial sector in distinct elements of an overall observational architecture, as the resources available are limited. International partnerships and cross-agency relationships can be expected to increasingly enable civil space agencies to develop a broad range of observations and shared data sets that respond to the needs of the operational and policy communities in disaster management while addressing key questions in the solid Earth research community.

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