

Title: Automated detection of anomalous hydrothermal and volcanic activity from space

Summary

The expression of thermal anomalies on the Earth's surface may be used to help predict volcanic eruptions, detect changes in hydrothermal systems, and characterize effects of climate change on natural landscapes. But changes in surface temperature as a function of these dynamic processes are relatively subtle against the background of naturally-occurring diurnal, seasonal and weather-related surface temperature variations. In order for remotely-sensed thermal observations to be used to detect anomalies, surface characteristics such as sediment mechanical composition, soil moisture and vegetation cover need to be accounted for in a model of naturally-occurring temperature variation. The object of this project is the development of a model and method to detect dynamic thermal anomalies using comprehensive thermophysical datasets of climatically, volcanically and hydrothermally-active landscapes derived from satellite and in-situ temperature observations. This project is aimed at mapping representative regions with both a high spatial resolution and high-repeat coverage, resulting in a multidimensional dataset that can be further scaled and utilized by a number of scientific disciplines to better understand volcanic processes and recent climatic history. In addition to applications in hazards prediction, these methods are powerful tools in environmental monitoring and can be applied to additional ecological, geological, and climate studies. In conjunction with the science plan, a major operational objective is to distribute our results as well as the information needed to manipulate these datasets to the science community and general public through growing geoinformatics and visualization portals.

Relevance to the USGS Science Strategy

This project directly addresses two major programs within the USGS, and provides data and monitoring tools for additional strategic goals as outlined in the USGS Science Strategy [USGS, 2007]. Scientific results and datasets resulting from this project will serve to identify natural hazards from active volcanic and hydrothermal systems, identified as key monitoring issues in the National Hazards, Risk, and Resilience Assessment Program. Additionally, results will help develop the characterization and understanding of Earth surface changes due to natural and anthropogenic climatic processes, in line with the USGS Climate Variability and Change program. Specific Geologic Division goals addressed with this proposal include to (#2) provide short-term prediction of geologic disasters and rapidly characterize their effects; and (#4) anticipate the environmental impacts of climate variability. Operational objectives outlined in the Geology Division Science Strategy are to (a) greatly enhance the public's ability to locate, access, and use Geologic Division maps and data; and (b) Promote interdisciplinary research. These are being directly addressed through a focused plan to disseminate thermophysical datasets, maps and models to the geological, ecological, and environmental science communities using established geoinformatics resources.

Research Objectives

1. Map the thermophysical characteristics of geologic surfaces in key volcanic regions in the United States as a function of the diurnal and seasonal thermal response as observed with remote thermal infrared observations
2. Establish the limits of climate, season, precipitation, latitude, and vegetation cover under which the thermophysical modeling can be utilized for thermal anomaly and materials

mapping

3. Quantify the thermal response to natural solar insolation in mapped regions using in-situ surface temperature field observations
4. Generate a thermal model that will aid our interpretation of surface-atmosphere thermal feedback mechanisms, to monitor changes in volcanic and hydrothermal activity, and surface physical changes due to changing radiative/climate environments
5. Integrate the data and results from this research project with community data portals and visualization resources such as the GEON IDV, GoogleEarth, and WorldWind platforms and develop a program for sharing the information needed to apply these derived products to ecological, social, geological, and climate studies

Background

Volcanic systems present danger to the world's population due to the unexpected effects of eruptions. An enormous amount of work has been done to establish the potential for hazards in systems like Yellowstone, and increase the effectiveness of warning systems by looking at a number of signals [Lowenstern et al., 2006]. These programs provide for known hazards, but a more comprehensive, wide-view monitoring system is needed in order to detect and prepare for geologic hazards for which the probability and scale are not well characterized. Remote sensing monitoring is ideally suited for this endeavor given the large areal coverage, high repeat-time observations and multispectral perspectives that can be utilized. The US currently has a suite of remote sensing satellites providing datasets that can be utilized for these purposes. Thermal infrared wavelength observations are ideal for these monitoring efforts, since the wavelengths of energy are most sensitive to the processes that we are interested in studying [Pieri et al., 2004]. This includes the composition of geologic surface materials, the physical properties of ground cover, the temperature of the surface, and the hydrology of soils and sediments. The greatest limitations to thermal infrared monitoring of geologic hazards are the variability in the natural temperature and hydrologic state of surface materials due to diurnal and seasonal solar radiation, and additional effects due to weather. An algorithm and thermal model that takes into account these parameters will allow scientists from a variety of fields to better utilize currently available datasets for monitoring changes in volcanic heat flow, hydrothermal systems, radiative environments, ecosystems, and surface processes related to climate change.

The work proposed here will serve to solve a number of problems within the fields of volcanic monitoring, planetary thermophysics, quantitative geomorphology, and climate modeling. There has been a recognized need for development of monitoring programs and better understanding of the Earth's surface changes to quantify large-scale trends and processes at work focusing on sediment, carbon, water, and energy cycles [USGS, 2007]. Our focus on the thermal flux of hydrothermal and volcanic regions represents a field in which there is a dearth of information due to the complexities of the atmosphere-surface boundary and limits in data. Early studies conducted with the HCMM, TIMS, Landsat and other remote sensing platforms found geological applications of thermal inertia to be challenging due to soil moisture and combination of mineralogy and mechanical composition [Kahle et al., 1976; Price, 1977]. These limitations can be reduced significantly with the application of new techniques in data fusion, thermophysical modeling, and the abundance of calibrated time-variable observations [Wan et al., 2005]. With MODIS low-resolution high-repeat observations and multiple high-resolution ASTER images, the unknowns in composition and surface hydrologic state can be minimized to extract quantitative diurnally-variable temperatures and correlated with field observations.

Technical Approach and Methodology

The three main elements of this project are (1) compilation of remote sensing datasets and field data calibration, (2) development of a thermal model, and (3) implementation and testing of an automated anomaly algorithm. During the two-year project, field campaigns will serve to calibrate remote sensing observations and relate in-situ temperature measurements to known processes and conditions. A majority of the effort will focus on deconvolving existing and new data to isolate thermal variables, and develop a model of natural cycles to quantify observed anomalies. Two major field sites will be studied to develop a comprehensive understanding of the thermal environment. Yellowstone National Park, as a hydrothermally-active region and potential volcanic hazard will be the primary subject of study. A secondary field area which does not experience extended snow cover will act as a control study to quantify normal thermal cycling not related to active volcanism. This second site will be located within the San Francisco Volcanic field, near Flagstaff AZ.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectroradiometer (MODIS) on board NASA Earth Observing System (EOS) satellites have generated large datasets ideally suited for thermophysical mapping on local to global scales. Moderate-resolution (1km) MODIS data with global coverage and a twice-daily repeat cycle, are ideal for observing the natural temperature cycles due to solar insolation and weather. ASTER 90-meter resolution thermal infrared (TIR) and 30-meter visible to near-infrared (VNIR) satellite imagery provide the perspective for mapping surface properties at resolutions that can be directly applied to field observations. The combination of these high temporal resolution MODIS data with high spatial resolution ASTER data can be used to isolate the naturally-cycling thermal flux from anomalous thermal features due to changes in the volcanic-hydrothermal systems. A full daily 7-year, diurnal dataset from MODIS will be compiled to produce a comprehensive thermal curve which will be calibrated with historical weather station observations of local conditions. At 1-km spatial resolution, individual hydrothermal systems are not resolved in MODIS scenes, thus ASTER imagery, with 90-m resolution will be used to further isolate areas of thermal flux. Very high resolution datasets such as MASTER (MODIS/ASTER simulator) flights and hand-held FLIR imagery will be used to distinguish surfaces and fluxes at the meters to centimeter scale. The fusion of high-spatial/low-temporal resolution with low-spatial/high-repeat data allows us to map and isolate features not resolved in uniform datasets.

Mapping Techniques:

Two major kinds of observations will be compiled from both the Yellowstone and Flagstaff field sites. First, a map of surface characteristics and known hydrothermal systems will be generated using a combination of remote sensing and classical geologic/geomorphic mapping techniques. Second, in-situ surface temperatures will be collected and combined with existing field data, to isolate dynamic features.

The term thermal morphology describes a perspective generated from the combination of daytime visible reflectance with nighttime brightness temperature, in which the physical properties controlling the diurnal temperature and visible brightness can be directly interpreted [Nowicki, 2007]. Daytime visible images produce scenes in which the reflectivity, topography, and surface roughness provide the majority of variation within a field of view (Figure 1a). Daytime thermal images are similar to daytime visible, in which the albedo and morphology dominate the temperature variation within a scene (Figure 1b). Nighttime thermal images display information related primarily to the thermal inertia of materials, in which albedo and topographic information is significantly subdued (Figure 1c). Thermal inertia represents the ability of near-surface materials to absorb solar energy during the day, conduct it into the sub-

surface, and then release that energy throughout the night. The combination of two of these datasets (Figure 1d) results in an image where colorized nighttime thermal information is draped over daytime data. This is an ideal dataset for field analysis, since the main thermal perspectives are combined in a single image that may be directly interpreted by the geologist on the ground.

Thermal IR remote sensing data collected by air and spaceborne instruments typically observe at one or two times in the diurnal cycle. This sampling method provides a temporally consistent dataset, which can be readily used to compare different locations, but it is only a limited temporal observation of what may be extremely dynamic processes. By observing fixed locations continuously, large spatial coverage remotely sensed IR imagery can be tied to a detailed well-constrained dataset. Thus, these field observations provide the temporal link between the suite of datasets in a quantitative and interpretable format. Data collected in the field includes surface radiometric temperatures, contact temperatures, solar irradiance, air temperature, wind speed, humidity, and precipitation. All of these datasets are required to constrain the natural solar/atmospheric diurnal temperature curve. Surface temperatures collected by an automated field radiometer station are shown in Figure 2, illustrating the natural cycles and surface characteristics that will likely be observed by a ground sensor.

Thermal Modeling:

A number of models currently exist to describe the surface-atmosphere boundary condition as a function of diurnal and seasonal solar and atmospheric cycling on a planetary scale. In addition, advanced models in dynamic atmospheric radiative transfer such as the Goddard Institute for Space Studies (GISS) GCM have been developed for the use in understanding the thermal interaction of the ocean and land surface with the atmosphere [Schmidt et al., 2006]. For these models, the surface layer is a relatively simple boundary in which the surface properties are only vaguely defined [Zhang et al., 2007], and spatial resolutions are too large to resolve most geologic systems. My efforts will focus on quantifying surface layer characteristics that are most sensitive to changes in atmospheric radiative-transfer, and modeling the processes that control the energy flux across that boundary. With the isolation of thermal properties such as surface roughness and conductivity, we expect to be able to resolve subsurface thermal fluxes due to volcanic and hydrothermal features.

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Research Proposal Estimated Budget:

Year 1

A. Equipment

\$ 2000 ENVI site license

\$ 2795 GIS/RS-capable GPS receiver (Trimble GeoXM)

\$ 300 TerraSync (Trimble) Software

\$ 3000 Field radiometers, weather station, and power supply

Total: \$8095

B. Field Work:

Extensive field work in Yellowstone National Park will occur on extended campaigns during seasons when field areas are accessible, and volcanic surfaces are not covered in snow. Field work in the San Francisco Volcanic Field will occur throughout the year as day trips, and should not require additional travel costs. Additional participant for field work expected.

Year 1: 6-weeks total field time, 2 trips, 2 participants

\$2520 Vehicle rental for round-trip travel from Flagstaff, AZ to Yellowstone National Park (900 miles), and field transport (\$60 /day) x 42

\$5040 Per-diem (food, camping, occasional lodging) for 42 days (\$60/person) x 2

\$1000 Fuel and Miscellaneous

Total: \$8560

C. Conference Travel

AGU meeting, San Francisco

\$390 Registration

\$50 Abstract Fee

\$300 Flight and transport

\$232 Per-Diem and Lodging (4 days)

Total: \$ 1668

Year 1 Total: \$18,323

Year 2:

A. Equipment

\$2000 ENVI site license

B. Field Work

6-weeks total field time, 2 trips, 2 participants

\$2520 Vehicle rental for round-trip travel from Flagstaff, AZ to Yellowstone National
Park (900 miles), and field transport (\$6 /day) x 42
\$5040 Per-diem (food, camping, occasional lodging) for 42 days (\$60/person) x 2
\$1000 Fuel and Miscellaneous

Total: \$8560

C. Conference Travel

AGU meeting, San Francisco

\$390 Registration

\$50 Abstract Fee

\$300 Flight and transport

\$232 Per-Diem and Lodging (4 days)

Total: \$ 1668

Year 2 Total: \$12,228

Project Total: \$30,551