Land Warming as Part of Global Warming

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The recent warming of Earth's surface is well documented in meteorological records. According to the World Meteorological Organization, the Earth's average surface air temperature (SAT) rose about 0.6°C in the twentieth century [*Jones and Moberg*, 2003].

Any global scale variation in SAT is accompanied by variation of the thermal state of all major climate system components including the continental landmasses. Based on worldwide meteorological and borehole temperature records, this study suggests that the twentieth century global warming has deposited a large amount of thermal energy into the continental landmasses, and has resulted in an intensified heating of rocks underground. The feedback to the global climate system and the long-term environmental consequences of the on-going subsurface warming of the land remain to be recognized.

Subsurface Temperature Evidence of Global Warming

Temperatures beneath the Earth's surface comprise two principal components: a steady-state component related to the flow of heat outward from the deeper interior, and a downward-propagating transient component related to the perturbations from temperature changes at the ground surface. In a steady state, subsurface temperature is expected to increase linearly with depth with a geothermal gradient determined by the subsurface thermal conductivity and the terrestrial heat flow.

However, if surface temperature is not steady but changes with time, subsurface temperature will depart from the linear distribution. A progressive cooling at the surface will increase the temperature difference between the colder ground surface and rocks of higher temperature beneath the surface and therefore will increase the temperature gradient at shallow depths. Vice versa, a progressive warming will result in a smaller or even negative gradient at shallow depths.

A ground surface temperature history hence is recorded in a profile of temperature versus depth [*Huang, et al.*, 2000; *Pollack and Huang*, 2000]. Such a temperature-depth profile can be obtained by recording temperature readings while lowering a thermometer into a borehole. There are thousands of boreholes drilled originally for industrial and civil purposes around the world. Many boreholes have been subjected to temperature logging. Shown in Figure 1 are three sample temperature-depth profiles from India. The observed subsurface temperatures at shallower depths are significantly higher than what one would expect for a steady-state regime, which is clear evidence of downward propagation of land surface warming.

The sample temperature profiles are among some thousand borehole temperature profiles residing in the global database of borehole temperatures hosted at the University of Michigan (http://www.geo.lsa.umich/climate). The database has been compiled as an archive of geothermal signatures of climate change, with support from U.S. National Science Foundation and from the international heat flow community.

Calculation of Annual Heat Budget of the Land

The atmosphere and the land are two interrelated major components of the Earth's climate system. Temperature observations from one component are helpful to enhance the understanding of the thermal state of the other component. On one hand, borehole temperatures are complementary to instrumental meteorological records in extending our understanding of the trends of climate changes prior to the existence of meteorological records [*Huang, et al.*, 2000; *Pollack and Huang*, 2000; *Harris and Chapman*, 2001; *Huang*, 2004]. On the other hand, meteorological records are complementary to borehole temperatures in our understanding of the annual heat budget of the continental landmasses over the last one and a half centuries.

This study uses the global database of borehole temperatures to show clear evidence of land warming. However, borehole temperature data do not retain the information to resolve the details of land warming excursions on annual and interannual temporal scales because of the diffusion of thermal signal through the rocks. Preserved in a temperature-depth profile is the information about the heat content change accumulated over a long period. To understand the detailed excursion of the heat content change on an annual timescale, meteorological records from the past one and a half centuries are used in this study.

According to the theory of heat conduction, whenever there is a temperature change at the ground surface, there will be an energy exchange between the atmosphere and the land. Given an annual ground surface temperature anomaly time series (T_i, i = 1, 2,..., n), the time series of the surface heat flux (q_i, i = 1, 2,..., n) across the air-land boundary can be estimated [*Beltrami, et al.*, 2002; *Huang*, 2006] by

$$q_i = \frac{2\lambda}{\sqrt{\pi} \cdot \alpha \cdot \Delta t} \sum_{j=1}^{i} [T_{j-1} - T_j] \cdot [\sqrt{i-(j-1)} - \sqrt{i-j}]$$

where Δt is one year, λ is thermal conductivity of the rocks, and α the thermal diffusivity. In this study, λ and α are respectively taken to be 2.5 watts per meter-kelvin [W/(m·K)] and 1.0×10^{-6} square meters per second (m^2/s), which are typical of the upper layer of the lithosphere [*Clauser and Huenges*, 1995].

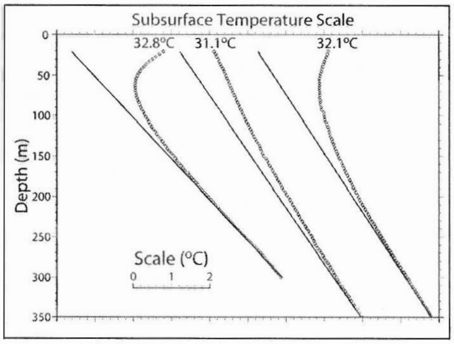

Fig. 1. Sample borehole temperature profiles showing subsurface temperature that is higher than expected steady-state temperature. Temperature measurements are shown in open circles and the steady-state is shown by solid lines. These three profiles (contributed by Sukanta Roy of the National Geophysical Research Institute of India) are shifted to avoid overlap, with the first temperature measurement of each profile marked for reference.

The continental heat content change ΔQ over the period from the mth year to nth year

$$\Delta Q = \sum_{i=m}^{n} q_i \cdot A \cdot \Delta t$$

is described by where A is the total area of Asia, Africa, Australia, Europe, North America, and South America landmasses.

Observational and numerical model studies [*Chapman, et al.*, 2004, and references therein] show that the change in ground surface temperature can be well approximated by the surface air temperature anomaly time series. Although the annual mean temperature of ground is usually warmer than the air above it, and although some degree of air-ground temperature decoupling exists in certain geographical settings [*Pollack and Huang*, 2000; *Majorowicz et al.*, 2005], ground surface temperature generally tracks the surface air temperature variation very well on annual and longer temporal scales.

In this study, a world-wide continental SAT time series assembled from the global database of the land-only meteorological records of the Climate Research Unit of the University of East Anglia [*Jones and Moberg*, 2003] is used to approximate the ground surface temperature variation over the past one and a half centuries. Satellite-derived land surface temperature is another candidate for representation of the ground surface temperature. However, satellite data cover a period much shorter than SAT records.

At the time of this analysis, the Climate Research Unit land-only SAT database spans a 155 year period from 1851 to 2005. The database contains records from meteorological observatories located on mainlands and on

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islands, including some scattered observatories in Antarctica (Figure 2). In this study, Antarctica is excluded from the analysis because of its very limited data coverage and because its wide-cover of glacial ice would skew data. SAT time series from isolated islands far away from a continent are also excluded from the analysis because those island records are more representative of oceanic than continental climate.

Increased Heat Storage in the Ground

Figure 3a shows the ensemble of the selected land-only meteorological data from 722 5° × 5° SAT data boxes. Superimposed on the inter-annual temperature variations are a slight cooling trend over the second half of the nineteenth century and a two-phase warming in the twentieth century. The first phase of warming was moderate and spanned roughly the first four decades of the twentieth century. The second warming phase started at around 1970 and has progressed into the twenty-first century. This ongoing warming phase is much stronger than the earlier one. In between the two warming phases was a slight cooling for about three decades.

Corresponding to the observed surface temperature time series is an annual heat flux, that swings between positive (downward into the ground) and negative (upward to the air) 0.25 watts per square meter at the air-land boundary (Figure 3b). The annual heat flux since the beginning of the twentieth century is mostly positive. Consequentially, by simple arithmetic, there has been a significant amount of thermal energy being stored beneath the worldwide continental landmasses since then (Figure 3c). With respect to the baseline of the mean 1851–1900 temperature, the cumulative continental heat content change for Asia, Africa, Australia, Europe, North America, and South America landmasses over the past 155 years from 1851 to 2005 is 11.6 ZJ (Zetta-Joules, 10^{21} J), over 65% of which was acquired by the land during the warming since 1970. Over 2.1 ZJ of heat was trapped beneath the ground surface of these continents in the last five years from 2001 to 2005 alone.

Impacts of Land Warming

When a large amount of heat comes into or out of the ground, the temperature of the rocks must change accordingly. The thermal state of the continental lithosphere is an important factor controlling various physical, chemical, and biological processes near the ground surface. For example, subsurface temperature increases may mobilize the global stock of soil organic matter and change the carbon cycle in the global climate system.

Furthermore, the climate system of Earth is a dynamic system encompassing interactions among various components including the lithosphere. The annual resolved energy budget of the landmasses can improve the ability to predict future climate as it offers an improved constraint on the energy exchange between the atmosphere and the land in a global climate model. Meteorological analysis overcomes the low-temporal resolution of a typical borehole temperature based analysis, and offers new insights into the excursion of the changing lithosphere thermal regime since the mid eighteenth century.

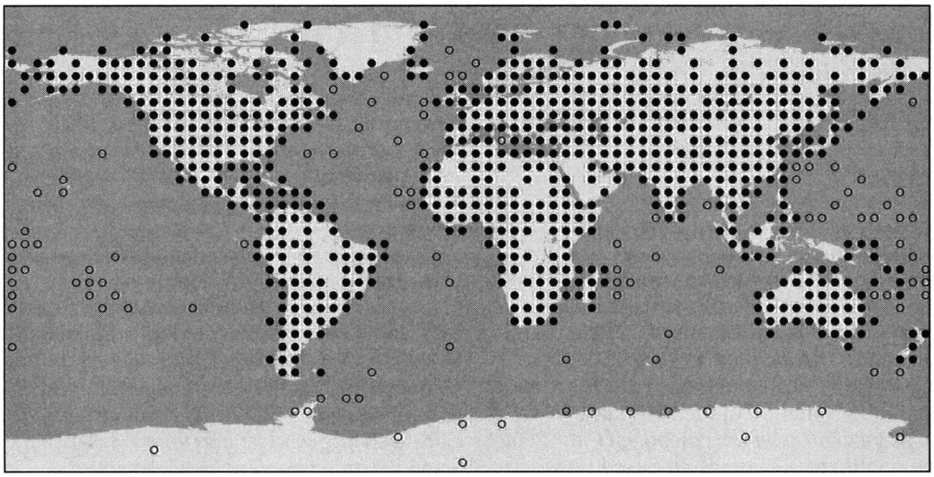

Fig. 2. The spatial coverage of the Climate Research Unit land-based meteorological records in 5° × 5° gridded boxes. Solid circles represent selected data boxes, while open circles are boxes excluded from this analysis.

This study suggests that the recent global climate change has led to an intensified heating of the continental landmasses over the past three decades. Although the land makes up less than thirty percent of the surface of the globe, it is the foundation of life and habitat for humans as well as for numerous plants and animals. It is not known with certainty how such land warming could affect the well-being of various ecosystems. Thus, a good understanding of the changing subsurface thermal state will deepen the understanding of subsurface environmental changes and help to uncover more hidden effects of the recent global warming.

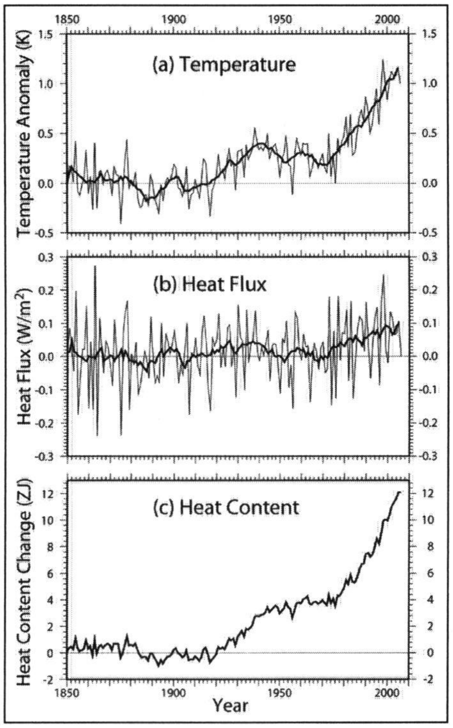

Fig. 3. Annual time series of the area-weighted global (a) land surface air temperature anomaly referred to the mean of 1851–1900, (b) ground surface heat flux, and (c) cumulative heat content change. The bold curves in Figures 3a and 3b are 25-year low-pass smoothed representations of the annual series.

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MEETINGS

Geoinformatics 2006

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Technological advances in Earth observation and science have enabled the collection of vast quantities of data at multiple spatial and temporal scales. Managing the data and making data sets openly accessible to researchers not only can help to reduce redundancy in data collection and ensure the longevity of existing data, but also can lead to new insights as datasets are compared and interwoven.

The U.S. Geological Survey (USGS) and the Geosciences Network (GEON) co-hosted Geoinformatics 2006, a recent meeting that focused on the need for Earth science data management, discovery, integration, and visualization, which is referred to as 'geoinformatics.' This will improve the understanding of the Earth over time and allow more open access to users interested in a wide range of data, explained keynote speaker Linda Gunderson, the USGS acting associate director for geology.

The meeting included oral presentations, posters, and demonstrations related to advanced computational and visualization technologies, application of knowledge engineering for discovery and integration of complex data, and innovative educational methods as they relate to the development of cyberinfrastructure for the geosciences.

Meshing Existing Databases

A. Krishna Sinha (Virginia Tech, Blacksburg) began the meeting with a brief history of geoinformatics. Sinha, who for several decades has been involved with developing strategies for geoinformatics, noted that the first step to implementing Earth science data management was to get scientific communities to agree that such management was necessary.

Data standards and nomenclature that allow for data sets to be easily compared are needed, several speakers noted. For example the usefulness of Geographic Information Systems (GIS) will be limited unless governments, non-profit agencies, academia, and industry agree to spatial data infrastructure (SDI) standards, said Alan Stevens (USGS, Reston, Va.). According to Stevens, whose talk stressed the importance of SDI, maps that are not easily comparable force the user either to convert data to a standard or to recollect the same data at additional time and expense.

Boyan Brodaric (Geological Survey of Canada, Ottawa) discussed standards for sharing geologic map information between states and countries. He said that although the same nomenclature might be used in two different databases, the similar wording might refer to entirely different concepts.

Speakers at the meeting discussed several existing systems that mesh databases as examples of the types of capacity needed for database interoperability. Brodaric highlighted the Geoscience Markup Language system (GeoSciML), an international standard being developed by geologic data providers to share geologic map information. Other presenters described Geospatial One-Stop, a USGS portal with a Google search engine-type interface that merges geographic map data with geophysical, meteorological, hydrological, ecological, agricultural, and demographic spatial data, among other topics.

The USGS is one agency that is paying close attention to how to manage and mesh its thousands of national and regional databases. For example, David Soller (USGS, Reston) informed attendees of ongoing plans to improve the U.S. National Geologic Map Database, which provides databases of nomenclature standards for stratigraphy and other fields. Soller noted that the information found in paper copies of many older pre-computer USGS publications needs to be filed into the Web databases.

Building New Portals

Many breakout sessions revolved around how to build Web-based portals to manage geological data. Key to building new portals will be the creation of metadata, which is data about the data, conference attendees said. Several speakers highlighted the usefulness of data clearinghouses, such as those managed by the U.S. Federal Geographic Data Committee and the USGS. They stressed that Web portals that list clearinghouses and their metadata provide important information to potential users as they browse for datasets.

Once metadata is collected and organized, user interfaces and search tools can be streamlined to ease data access. To organize metadata, Hassan Babaie (Georgia State University, Atlanta) suggested adopting a philosophy whereby everything in the universe is split into two groups: objects and actions performed on the objects, which then creates new objects. Such a philosophy, if used for web portals, could allow users to analyze how geospatial information—such as location, rock type, and chemical composition—relates to the processes that change them, and how these processes across the Earth create different changes depending on the local environment, Babaie explained.

After metadata is organized, scientists and technicians can build virtual observatories, which are "suites of software applications on a set of computers that allows users to uniformly find, access, and use resources and image products from a collection of distributed product repositories and service providers," explained Deborah McGuinness (Stanford University, Stanford, Calif.). During a talk about the development of a virtual solar-terrestrial observatory, McGinnis stressed that such observatories can allow users to discover and create more data from existing information without the user having to perform extended field or telescope observations. Full utilization of such observatories will require a proper description of the parameters and instruments that generated the posted data, so that users can understand assumptions and errors unique to data sets, conference attendees agreed.

The creation of virtual observatories allows data to integrated and cross-referenced at many different levels and in many different disciplines. Sinha, when speaking about multidisciplinary information integration, encouraged the development of systems in which information can be registered at the data level, so that a user can find an individual datum, such as elevation or rock type, in a set that might only be peripherally related to the user's field of inquiry. Other talks focused on how to maximize the effectiveness of data searches.

Some presenters stressed that data management need not occur just within Web portals that aggregate large amounts of data from multiple sources. Christopher Condit (University of Massachusetts, Amherst) introduced the idea of 'dynamic digital maps' for individual geoscientists to collect, process, and share their own geospatial information. By using a template he developed, scientists can create interactive maps of their field areas that allow users to move between, for example, maps of topography, geological units, or paleomagentic signatures, for a given location.

Unique Applications to Specific Fields

Several speakers noted that the integration of data through geoinformatics will be critical to natural hazard assessment and mitigation. Representatives from the Southern California Earthquake Center (Los