Generation of the Subsurface Geothermal Climate Signal By Land Surface Processes in the North American Mid-continent

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I. Project Summary

This project addressed the generation of the subsurface geothermal climate signature through the application of a specialized Land Surface Process (LSP) model. The subsurface temperature field to depths of several hundred meters has been utilized extensively by the geothermal community to reconstruct the long-term trends of the temperature history experienced at the Earth’s solid surface. The working hypothesis of the geothermal methodology is that temperature changes in the atmosphere and the solid Earth track each other. In the geothermal analyses the nature of this coupling is formulated simply as a time-dependent temperature boundary condition at the upper surface of a thermally conducting half-space. But the actual physical processes at the surface that achieve the coupling in the real world involve complex energy and moisture fluxes at the land-atmosphere interface over a large range of temporal and spatial scales. We investigated this coupling with an LSP model previously developed to describe the upward-propagating microwave signal seen by satellites. The issues included both the adequacy of this LSP model to generate the downward propagating temperature signal utilized by geothermal scientists for climate reconstructions, and the effects upon the temperature signal induced by changes in precipitation.

Our LSP model is a hi-fidelity, 1-dimensional, coupled heat and moisture transport model that predicts the land-atmosphere fluxes of moisture and energy given boundary forcing by downwelling short- and long-wavelength radiation, air temperature and humidity, wind speed, and precipitation. Its predictions are based upon surface albedo and roughness, vegetation, snow cover, soil moisture and thermophysical properties, subsurface heat and mass transport mechanisms, and freezing and thawing processes. We investigated the generation of the subsurface temperature field in a special setting: the prairie grasslands of the North American mid-continent. The model has already been calibrated for thermophysical characteristics of bare soil and prairie grassland during a year-long experiment in South Dakota.

The model was modified to include the deeper processes of interest in a climate reconstruction. The model was calibrated and validated with data from a series Radiobrightness Energy Balance Experiments in prairie grasslands, wheat stubble, and bare soil that preceded this investigation. Multi-decadal simulations within the parameter space of land cover, mean precipitation, and relative humidity revealed the sensitivity of the deep temperature signal to changes in climate indicators other than air temperature. Emerging from this research is a better
understanding of how hour-by-hour, day-by-day, seasonal, and inter-annual fluctuations in precipitation translate into a downward-propagating temperature signal that comprises the annual, decadal, and century long integrated outcomes of the continuous variability at the surface. In short, this research helps us understanding of the relationship of subsurface temperatures to surface meteorological variables and their temporal trends.

II. ACCOMPLISHMENTS

II.A We have recoded the Michigan LSP (Land Surface Process) model in modular, free form FORTRAN 90 to meet the objectives of this project. The new model is better annotated, more compact, and faster than the model it replaces. A beta version is available to the land surface hydrology community on our server. Scientists in the Hydrology Branch of NASA’s Goddard Space Flight Center find that its performance compares favorably with other Soil Vegetation Atmosphere Transport (SVAT) models (P. O’Neill, NASA/NOAA Hydrology Workshop, Potomac, MD, April 30 through May 3, 2001).

The revised LSP model is based upon a linear state-space representation of the system equation. A state vector consisting of temperatures and moistures for a soil column of N layers (typically 60) of exponentially increasing thickness with depth is defined for each time step. This linearized formulation will enable computation of error covariance matrices of state variables needed to examine the sensitivity of soil temperature and moisture to the constitutive properties and atmospheric forcings. These sensitivity analyses will identify key processes that should be preserved in simplifying parameterizations.

The revised LSP model uses an explicit forward finite-difference scheme to match both an upper boundary at the land-atmosphere interface and a lower boundary at a soil column depth that depends upon the characteristics of the particular experiment. The original LSP model matched boundary conditions only at the soil surface but required soil column depths that were large relative to the propagation distance of thermal transients introduced at the surface. Because lower boundary conditions often become indeterminate once a thermal pulse has traversed the soil column, we may always want a soil column thickness that is large relative to the propagation distance of a thermal transient. However, the two-boundary formulation is more general and its numerical implementation is more computationally efficient.

To further improve computational efficiency, we have adopted a lookup-table approach for the soil constitutive properties. These tables are computed at the beginning of each model run at uniformly spaced, predefined temperatures and moistures for each soil type in the experiment. A local bilinear interpolation is used to estimate the constitutive values at the specific temperatures and moistures incurred during propagation of the model.

The new LSP model is written in FORTRAN 90. The original LSP model, which was written in FORTRAN 77, was developed by a series of Ph.D. students to address narrowly defined research objectives. Each student modified the original code and added unique features. Over time the code became increasingly convoluted, long, and difficult to understand. The new code uses FORTRAN 90 which enables an easily understood modular design without incurring the poor coding practice of universal variables and constants, it is a more compact 1500 lines, and it is well annotated.
In the process of revising the code, we found several minor bugs in the original code and corrected them. We have compiled and tested the new model in both Power PC/Linux and SGI/Unix environments. The revised LSP model is available to the community on the EECS (the Department of Electrical Engineering and Computer Science) FTP server with a detailed README file and all required input files.

II.B Field observations are essential for investigating land-atmosphere interactions and validating the LSP models. Accordingly, during the summer of 2000 a member of our group took a field trip to St. Paul, Minnesota, and Fargo, North Dakota, to visit two sites where long-term (decades) measurements of surface conditions and subsurface temperatures have been archived. The field trip was the beginning of a data acquisition process that, to date, has yielded three significant data sets. The Fargo, North Dakota, site consists of hourly measurements over a twenty-year period including surface conditions and subsurface temperatures at 23 depths over a range of 1 cm to 11.7 m. We do not currently have the St. Paul data, but permission has been granted for acquiring the data from the current data custodian. We have also obtained a seven-year record from Prague, Czech Republic, consisting of multiple daily measurements at twenty different depths ranging from 5 cm to 38.3 m.

Our LSP model requires nearly continuous air-temperature time series so that missing data within the raw observational records are a significant concern. Consequently, data conditioning has been a significant part of our efforts thus far. Data conjecture methods have included linear or average interpolation, and both the Fargo and Prague data sets have been conditioned to yield regularized air-temperature time series aggregated into daily and monthly means. Data analysis has also begun using the Fargo and Prague records. We have investigated subsurface-temperature measurements and their deviations from conductive heat-transport predictions. The predictions have been calculated by forcing a conductive-heat transport model with the air-temperature time series from Fargo and Prague; the deviations have been termed “conductive anomalies”. Using the conductive model, time-resolved conductive anomalies are determined by subtracting model outputs from the actual subsurface measurements. The results are conductive-anomaly time series that illustrate the significant seasonal influences that cause anomalous non-conductive behavior in certain circumstances. Our primary interest lies in the spatial and temporal characteristics of conductive anomalies, as well as their behavior with increasing depth into the subsurface. Such investigations will help mold our thinking as we begin to use the detailed LSP models developed by England’s group, and make quantitative links between the processes in the upper few meters of the soil to processes at depths below 100 m in the subsurface.

III. FINDINGS

Abstract

Temperature changes at the Earth surface propagate into the subsurface and leave a thermal signature in the underlying soil and rock. Measurements of subsurface temperatures have been inverted to yield reconstructions of ground surface temperature (GST) histories that provide regional and global estimates of climatic changes. A principal question remaining in the interpretation of reconstructed GST histories is the extent to which GST changes closely follow changes in surface air temperatures (SATs). While SATs are the principal meteorological component influencing temperatures at the ground surface, a variety of meteorological and
biological conditions also affect temperatures at the interface. Here we use a high-fidelity Soil-Vegetation-Atmosphere-Transfer (SVAT) model to examine the influence of precipitation changes upon shallow subsurface temperature and moisture profiles and mean annual GSTs. We model conditions representative of a prairie region in the southern Great Plains of North America where mean daily temperatures typically remain above freezing. Simulations are forced with meteorological data synthesized from a representative year in the region. A forty-year spin-up period establishes model equilibrium that is then compared to model responses after changes in 1) the total annual precipitation, 2) the temporal concentration of precipitation and 3) the annual phasing of the precipitation pattern. We show that 1) doubling or halving the total annual precipitation cools or warms the mean annual GST by approximately 0.5 K, respectively; 2) increasing the temporal concentration of the precipitation record cools the annual mean GST and 3) when maximum precipitation occurs in the warmest months, it lowers the annual mean GST.

Introduction

Measurements of subsurface temperature perturbations have proved to be valuable indicators of climatic change and have been used extensively for regional and global geothermal climate reconstructions. The basic premise underlying geothermal climate reconstructions is that temperatures at the air-ground interface establish a time-dependent temperature boundary condition, the effects of which propagate downward into the ground by thermal conduction. Thus, reconstructed GST histories are indicative of the integrated changes in surface processes and characteristics that create the thermal surface conditions over time. SATs are undoubtedly the principal meteorological condition controlling the temperature of the ground surface, and agreement between reconstructed GSTs and historical SAT records has been widely documented on decadal and centennial time scales. However, the physical processes that contribute to the thermal regime at or near the Earth surface are driven by a wide variety of changing meteorological and biological conditions on diurnal and sub-diurnal time scales. The extent to which these additional processes influence mean annual GSTs and the thermal signal communicated to greater depths has not been adequately characterized and evaluated over a broad range of temporal and spatial scales. Here we employ a high-fidelity SVAT model developed by the Microwave Geophysics Group at the University of Michigan to explore the effects of land-atmosphere processes upon shallow subsurface temperatures, moisture profiles and mean annual GSTs. Specifically, we examine the effects of precipitation changes on subsurface temperature and moisture fields to 20 m beneath a prairie grassland region with average daily SATs that rarely go below freezing. Our results are presented as an illustration of method and to quantify some of the primary effects that precipitation can have on GSTs. This study is the first in a series of investigations into the connections between microphysical land-atmosphere processes occurring at short intervals over localized spatial scales and the downward propagating geothermal climate signal.

Forcings

All of the forcing data used within this study have been simulated using representative values from Coldwater, Kansas. The daily average temperatures over an annual cycle at Coldwater were determined by approximating observed daily values during 1999, obtained from the National Climatic Data Center, with a sine curve (see Figure 1). Diurnal variation was added to the approximated annual cycle by superimposing a second sine function of daily period. The amplitude of the diurnal oscillation was chosen as the average of the difference between the daily
maximum and minimum temperatures during the 1999 year. The daily precipitation during 1999 at Coldwater was also obtained from the National Climatic Data Center (see Figure 2) and hourly precipitation was approximated by evenly distributing daily averages into each hour of the day.

Model Spin-up

The SVAT model estimates temporal temperature and moisture profiles in the ground. It incorporates surface albedo and roughness, vegetation, soil moisture and thermo-physical properties, subsurface heat and moisture transports, and freezing and thawing processes. The model is one-dimensional, comprising a multi-layered soil with a two-layer vegetative canopy. A zero heat flux boundary condition is assigned at 20 m depth which excludes effects from the outward flux of heat from the Earth interior and confines observations of climatic disturbances to the upper 20 m. The water table is set at 3 m depth. A steady state was established with a forty-year spin-up period comprising identical annual forcing. Steady-state temperature and moisture profiles are shown in figures 3 and 4 respectively.

Experiments

We conducted three experiments, each involving a permanent change in precipitation only; all other forcing, constitutive properties, and model characteristics remained unchanged. These modifications to the original precipitation record were imposed as an abrupt change at the beginning of the forty-first year, and simulations were conducted for forty-years after the occurrence of the changes.

• The scaling experiments. The daily precipitation amounts were scaled by 0.50, 0.75, 1.25, 1.50 and 2.00. The results are shown in Figure 5.

• The “peakiness” experiments. The precipitation record was filtered to either enhance or reduce the temporal concentration of daily precipitation while preserving the seasonal timing of the record (see Figure 6). The results are shown in Figure 7.

• The seasonal timing experiments. The precipitation record was shifted by three, six and nine months (see Figure 8). The results are shown in Figure 9.

Figure 1. Observed and modeled daily average air temperature for Coldwater, KS
Figure 2. Observed daily precipitation for Coldwater, KS

Figure 3. Steady state daily average soil temperatures

Figure 4. Steady State Soil Moistures
Figure 5. Results of the scaling experiments

Figure 6. Precipitation records used in the “peakiness” experiments

Figure 7. Results of the “peakiness” experiments
Figure 8. Precipitation records used in the seasonal timing experiments

Figure 9. Results of the seasonal timing
Conclusions

We present these results as an illustration of a new methodology for investigating the influence of climate on subsurface temperature fields. We have shown that various precipitation changes can affect ground temperatures independent of other meteorological variables. We suggest that continued investigation of land-atmosphere processes by means of the method proposed here will help to elucidate whether or not long-term effects from non-conductive behavior in land-atmosphere coupling plays an important role in the partitioning of heat into the ground.

III. PRODUCTS


Smerdon, J.E., Pollack, H.N. and Huang, S., 2000. Latitudinal trends in northern hemisphere air and ground temperatures. EOS Transactions American Geophysical Union, v. 81


