Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 112 (2008) 471 – 481
Remote Sensing of Environment
www.elsevier.com/locate/rse

Development and comparison of Landsat radiometric and snowpack model inversion techniques for estimating geothermal heat flux

Fred G.R. Watson [a,*], Ryan E. Lockwood [a], Wendi B. Newman [a], Thor N. Anderson [a], Robert A. Garrott [b]

[a] *Division of Science and Environmental Policy, California State University Monterey Bay, 100 Campus Center, Seaside, CA, 93955-8001, United States*
[b] *Ecology Department, Montana State University Bozeman, United States*

Received 1 July 2005; received in revised form 8 May 2007; accepted 10 May 2007

Abstract

We present the first quantitative representation of the intensity of Yellowstone National Park's surficial geothermal activity mapped continuously in space. A radiative thermal anomaly was remotely sensed throughout a 19,682-km^2 landscape covering Yellowstone National Park in the northern Rocky Mountains, USA. The anomaly is the residual terrestrial emittance measured using the Landsat Enhanced Thematic Mapper after accounting for elevation and solar effects, and was hypothesized to be an estimator of a lower bound for geothermal heat flux (GHF). Continuous variations in the anomaly were measured ranging from 0 W m^{-2} up to a maximum heat flux of at least 94 W m^{-2} (at the 28.5 m pixel scale). An independent method was developed for measuring GHF at smaller scales, based on inversion of a snowpack simulation model, combined with field mapping of snow-free perimeters around selected geothermal features. These perimeters were assumed to be approximately isothermal, with a mean GHF estimated as the minimum heat flux required to ablate the simulated snowpack at that location on the day of field survey. The remotely sensed thermal anomaly correlated well (r=0.82) with the snowpack-inversion measurements, and supported the hypothesis that the anomaly estimates a lower bound for GHF. These methods enable natural resource managers to identify, quantify and predict changes in heat flux over time in geothermally active areas. They also provide a quantitative basis for understanding the degree to which Yellowstone's famous wildlife herds are actually dependent on geothermal activity.

Keywords: Thermal; Geothermal; Remote sensing; Landsat; Snow; Snowpack; Model; Radiative transfer

1. Introduction

Heat flows outward from the Earth's interior through its surface. This flow varies spatially over a wide range of scales. The global average geothermal heat flux (GHF) is about 0.075 W m^{-2}, concentrated mainly around the volcanic spreading zones of the mid-oceanic ridges (Pollack et al., 1991). In the western USA, GHF ranges from less than 0.02 W m^{-2} in the Sierra Nevada, to over 0.1 W m^{-2} in many parts of Oregon, Idaho, Nevada, and Colorado (Blackwell & Richards, 2004). Elevated continental heat flux is associated with active mountain belts, rifts, and hot spots—relatively stationary thermal plumes in the mantle that manifest at the surface of the overlying tectonic plate as moving zone of volcanic activity. One of the best-known hot spots on Earth underlies Yellowstone National Park (YNP) in the northern Rocky Mountains (USA), having originated 17 million years ago (Ma) some 1000 miles to the south-southwest. Here, GHF annually averages above 0.15 W m^{-2} throughout a 50 km radius (Blackwell & Richards, 2004).

The Yellowstone region has been volcanically active for the past 2.2 million years (Christiansen, 2001), including major caldera eruptions 2.0, 1.3, and 0.6 Ma. The most recent caldera spanned most of the present-day western central portion of the National Park. It was largely filled in by rhyolitic lava flows between about 150 and 70 thousand years ago (ka), and subsequently glaciated until as recently as 16 ka (Christiansen, 2001). Magmatic activity continues today, as evidenced by observations of vertical deformation within resurgent domes, lack of seismic focal depths below about 3–4 km, and high heat flow (Fournier, 1989). Many of the modern surface hydrothermal features occur near recent sedimentary low points that are aligned

* Corresponding author.
E-mail address: fred_watson@csumb.edu (F.G.R. Watson).

0034-4257/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2007.05.010

with the main caldera ring fracture, the resurgent domes, and the voids between adjacent lava flows (Christiansen, 2001; Fournier, 1989). The modern climate includes a warm, dry summer with occasional thunderstorms, and a long, cold, continental winter with snow on the ground for about 6 months of the year (e.g. Old Faithful climate station, WRCC, online). The spatial pattern of surface heat energy release is a complex and revealing outcome of these influences.

Much of the heat is advected away from surface features in rivers (Fournier, 1989), while some is radiated and convected into the atmosphere or overlying snowpack. It is this later effect on the snowpack that is the subject of our paper. In particular, we are interested in the extent to which the radiative component can be remotely sensed, giving a lower bound for the total radiative and convective fate of geothermal heat flux. Specifically, we seek to quantify a terrestrial emittance anomaly (TEA), which we define as the residual terrestrial emittance upward from the surface after accounting for non-geothermal effects (see below).

Satellite remote sensing quantification of TEA (in W m^{-2}) of hydrothermal areas does not appear to have been reported in the Journal literature. Many studies report remote sensing of the surface temperature and heat flux of more intense volcanic features, such as active volcanic craters and lava flows (Donegan & Flynn, 2004; Flynn et al., 2001; Kaneko & Wooster, 2005; Lombardo et al., 2004; Oppenheimer, 1997; Pieri & Abrams, 2004; Urai, 2002). Other studies have reported more qualitative characterizations of hydrothermal areas aimed primarily at mapping mineral and geobotanical distribution based on a combination of visible and thermal imagery (Hellman & Ramsey, 2004; Mazzarini et al., 2001; Pickles et al., 2001; Vaughan et al., 2005). Patrick et al. (2004) estimated total heat loss from mud volcanoes (hydrothermal features, smaller than 1 ha), drawing on remotely sensed estimates of thermally active surface area; but they did not use the imagery for direct determination of radiative heat flux. Perhaps due to its subtle magnitude, direct estimation of TEA using remotely sensed data over hydrothermal areas has remained elusive.

Mapping of the spatial pattern of TEA throughout a geothermally active landscape yields several potential benefits. The pattern is a unique measurement of thermal activity, which helps us understand the geologic processes that cause it. Repeated measurement of TEA patterns would allow us to track changes in geothermal processes and potentially, to extrapolate to predict future change. In particular, the remote-sensing technique for measuring TEA presented in this paper provides an important tool for managers of Yellowstone National Park. A significant question for the Park's managers relates to changes in the Park's geothermal system. Simply measuring eruptive intervals of geysers does not adequately define changes in the Park's geothermal system. By analyzing the radiative heat flux using Landsat images, we can quantify temporal changes in the location, intensity, and total radiative heat output. The Park's managers can then use this information to more effectively judge the severity and importance of changes in the geothermal system with respect to visitor safety, volcanic activity, and wildlife management issues. The Park's volcanic activity is one of its major attractions to visitors, but the safety of this experience can be threatened in areas of rapid, intense change. Our interest is chiefly with respect to wildlife. A map of TEA is a key explanatory variable in studies of species that depend on the unique snow-reduced habitat that geothermal areas provide. In particular, geothermal patterns in Yellowstone partially determine the presence, population, and distribution of large mammal species such as elk, bison, and their chief predators, wolves (Craighead et al., 1973; Meagher, 1973).

This paper describes techniques for mapping radiative TEA using satellite remote sensing, and evaluates the extent to which TEA estimates GHF through comparison with GHF estimates derived from inversion of a snowpack simulation model.

2. Remote sensing

2.1. Overall method

Thermal imagery from the Landsat-7 Enhanced Thematic Mapper Plus (ETM+) sensor was used as the primary data source for the TEA map. This sensor responds to thermal infrared radiation emitted upwards from the Earth's surface at a spatial resolution of about 60 m (NASA, online). The data were processed by converting raw sensor data into estimates of terrestrial emittance at the surface, modeling this terrestrial emittance as a simple empirical function of non-geothermal effects, and then computing the TEA as the residual. Below, we discuss why TEA should estimate a lower bound for GHF. A physically based surface energy balance model would, in theory, yield a more direct estimate of GHF, by being able to take account of processes such as diurnal and seasonal heat storage, and an explicit model of convective heat fluxes. However, the effort required to develop and test such a model at the spatial scale of interest is not warranted without first documenting whether there is any evidence that a meaningful proxy for GHF, such as TEA, can be discerned at all over such a large and complex landscape.

2.2. Choice of remote sensing platform

The Landsat platform was chosen because it achieves complete coverage of the Park in a single image. This facilitates consistent radiometric accuracy across the Park, and ease of future application to change detection. Other platforms, such as ASTER, offer higher spatial and spectral resolution, but require at least six images in order to do so. We tested an approach involving a mosaic of ASTER images, but could not satisfactorily remove radiometric differences and georeferencing discontinuities at the image boundaries. ASTER imagery is also only available from arbitrary dates (often differing across the Park) and while the sensor can be tasked to acquire images on specified dates, suitable dates cannot be predicted in advance because of the rarity of appropriate weather conditions.

2.3. Emittance-radiance model

We begin with a model that estimates total emittance of terrestrial origin (M_{terr}, W m^{-2}) from a snow-free, vegetated