Introduction

In terrestrial remote sensing, thermal inertia has been little used because its calculation involves registered albedo, day-night TIR, and DEM images, and its value is sensitive to vegetation, transient cloudiness, and wind. We explore a technique in which $\Delta T = T_{d} - T_{n}$ (the rate of temperature change) is measured and used to estimate thermal inertia. $\delta T$ is proportional to the day-night temperature difference, and hence $P$. It can be measured for short time intervals, reducing the opportunity for cloudiness, wind, or rainfall to distort the experiment. It has a maximum minimum values in the morning or afternoon, instead of noon/midnight for the conventional approach. These characteristics make it a better experimental design.

In the differential approach, however, $\Delta T$ is much smaller than the day-night approach ($\approx 20^\circ K$), and therefore, $\delta T$ is more sensitive to measurement precision (NEAT). NEAT is a more important limit to the ability to recover $P$, therefore. Essentially, $\delta T$ must be large enough that $\Delta T$ < NEAT. For sensors such as MASTER, NEAT = 0.3 K, and common surfaces $\Delta T > 60$ minutes for a signal-to-noise ratio of 10 or more. Although such a low SNR may be acceptable in photometric temperatures, it reduces the reliability of quantitative analysis of $P$, yet increasing $\delta T$ further both reduces the pragmatic advantages of the differential approach and the ability to estimate $\delta T$.

In this study, we use a FLIR System's ThermoCam ST-R TIR camera to evaluate differential thermal inertia relative to daynight algorithms for a playas (Soda Lake) and envos in the Mojave Desert of California.

Background

Thermal Inertia ($P$)

Thermal inertia ($P$) is defined as

$$P = \frac{\Delta T}{\Delta t}$$

where $\Delta T$ = bulk thermal conductivity ($\approx 10^{-7} K m/s$); $\rho$ = bulk density ($g/cm^3$); $C$ = specific heat capacity ($cal/g K$); and $\Delta t$ is a day-night difference in time of day ($\approx 20$ minutes). It is generally estimated by comparing temperature differences during different times of day by values predicted by temperature difference models (Kahle, 1979). Typically, measurements are made near noon and the morning.

A similar approach yields an approximation of $P$, the apparent thermal inertia (ATI), which is determined using two temperature images, one made during the day ($T_d$) and one at night ($T_n$), and the surface albedo (Price, 1977). 

$$ATI = \frac{1}{T_n} - \frac{1}{T_d}$$

where $\Delta T = T_n - T_d$

Thermal-inertia mapping (e.g., Gillespie and Kahle, 1977) is sensitive to conditions (temperature, cloud cover, rainfall, wind). Remote determination of even relative thermal inertia is complicated by: 1) scene components are usually unknown and cannot be measured remotely. The short-term change in surface temperatures of dry and moist subsurface fluctuations, requiring that the ATI also be different, at least at some times of day (Fig. 2). Therefore, $\Delta T$ is inferred from the rate of temperature change as well as from the daily minimum/maximum temperatures, with the notable difference that the optimum times of measurement are out of phase. Differential Thermal Inertia

Materials with different thermal inertias have different diurnal temperature fluctuations, requiring that the ATI also be different, at least at some times of day (Fig. 2). Therefore, $\Delta T$ is inferred from the rate of temperature change as well as from the daily minimum/maximum temperatures, with the notable difference that the optimum times of measurement are out of phase.

Thermal radiance images can now be measured with precision better than when the classic terrestrial thermal-inertia studies were made in the 1970s, and this improvement can be used to shorten $\Delta t$ while maintaining the same number of meaningful gray levels in the output ATI image. We call the ATI calculated with short $\Delta t$ values “differential ATI” or DATI.

Methods

Thermal images were taken every 5 minutes in 10 second time bursts with an FSI FLIR camera from the Zzyzx Research Station located on the western edge of the playa over a diurnal period.

Images were made at an area along the western edge of the playa (viewing toward the center of the playa) that included wet and dry patches. Four of these patches were taken with data loggers that recorded the subsurface temperature using thermocouples imbedded at depths of 20m, 50m, 100m, and 400m (Fig. 4).

Moisture content of the subsurface at these depths was determined by weighing and drying samples collected at the same depths as the imbedded thermocouples at each patch.

These 10 second time bursts were averaged to reduce the effect of atmospheric fluctuations. This is counter to what might be expected from the resolution of these time bursts, we were able to calculate values of $\delta T$ that were relatively insensitive to fluctuating sensible/latent heat due to wind.

The moisture content and subsurface temperatures were used to compare to the FLIR data as well as from theoretical results calculated from heat-diffusion equations.

Results

Subsurface Soil Moisture and Temperature

The surface (close to at least 0.5 cm) of the playa in the analysis is dry (4% moisture by weight).

Soil moisture under this “dry skin” can be as high as 18%, depending on the site and depth (Fig. 5). For the purposes of this study, “wet” and “dry” refer to the moisture content immediately under the surface (1-5 cm). Therefore, C and D are “wet” while A is “dry.” Radiant: on, and subsurface soil temperatures at these sites varied during the heating/cooling cycles and composition (primarily moisture content). This can be seen in Figure 6 which contrasts the effect of wet and dry subsurface soils on the morning heating.

The intensity of the heat wave diminished with depth, such that the effect is only a few degrees at (40 cm) that occurs hours after initial heating.

At the surface, the heating response is more immediate and intense. The increased moisture in the near-subsurface diminishes the rate and intensity of heating. It is the rate of heating at the surfacel-weather surface that is useful for determination of thermal inertia.

Surface Radiant Temperature

The short-term change in surface temperatures of dry and moist subsurface playa soils can be seen in thermal images. Figure 7 shows an effect for the time series shown in Figure 8.

The left column of Figure 8 is a time series of FLIR images taken between 0600 and 0900 during morning sunrises every 20 minutes (the same day as Fig. 7). The difference between the FLIR image in Figure 7 (taken a 0540) and each subsequent time step is shown in the center column of Figure 8.

The band of cooler soil in the lower center of the image (marked by an X) is relatively dry, powder, and humic (relative to the surrounding playa surface). Both the bare soil plus filled with air (as opposed to water). Its thermal inertia is lower and, therefore, gets cooler at night.

Progressive-20 minute temperature differences are shown in the right column of Figure 8. The top image is the difference between the 0540 and 0700 FLIR images and shows little change as the sun has not yet risen over the pockmarks. The center and lower images were taken 20 minutes (0620) after the FLIR surface has reached the whole scene.

Conclusions

Near-subsurface composition affects the response of surface to diurnal heating and cooling.

Ideal measurement times: morning (from sunrise until ~0900) or in the evening (from just before sunset until ~1800). It appears that a minimum of 20 minutes in desert environments is necessary, although closer to 2 hours would be ideal.

Other factors: Surface roughness, less wind, A clouds: can cause fluctuations in the surface temperature. Use multiple images (3-5) averaged over a 1-2 minute period to minimize these fluctuations.

DATI has the potential to be used to map, and ultimately estimate thermal inertia. This approach shows promise in that it allows for relatively quick assessment of apparent thermal inertia and weak effects of changes in climate, diurnal cycles over traditional day-night methods. This makes it more applicable for field analysis as well as use with unmanned airborne vehicles.

The next step is showing how to convert this rate into predicted day/night apparent thermal inertia and then to estimate thermal inertia.

References


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Note that the north, thermally linea (DL) is still learning in a small soil patch in (Fig. 9). This is warming, which might be to reduce. The same effect was observed more warming faster than the wetter patches as has a lower P, hence a smaller apparent thermal heating-cooling cycles. This apparent cooling cycle is not real, but rather a heating/cooling cycle that the image taken looking east, towards the rising sun. The apparent small in early morning cycles shadow in the rough surface of the zone and the depth/depth to the warming zone is not yet apparent in the north. The short-term change in surface temperatures shows promise for this study. This shows an effect for the time series shown in Figure 8.