A comparison of the thermal characteristics of active lava flows and forest fires

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Abstract. Landsat TM data of active lava flows from Kilauea Volcano Hawaii (7/23/91) and forest fires within Yellowstone National Park (9/88) are compared to show the differences in the spectral and spatial distribution of radiance. At visible wavelengths, smoke from forest fires obscures terrain features, while active eruptions show little degassing at breakouts (ruptured lava tubes). Lava flows exhibit a gradual increase in infrared radiance (>2 µm) from the edge of an emplaced flow to the central breakout. The hottest parts of the forest fire (which radiate similar amounts of energy to flow breakouts) are located within 90 m of the edge of the burn scar with the interior portions exhibiting sharp decreases in infrared radiance. The radiance measured at 10.4-12.4 µm relative to that at near-infrared wavelengths (2.08-2.35 µm) suggests that the surface cracks exposing molten lava anneal proportionately with the progressive thickening of the flow crust, while burn scars, produced by forest fires, cool to pre-burn background temperatures rapidly with only small areas of high-temperature embers remaining. These differences will be important for the implementation of an automatic thermal-anomaly detection system using satellite data.

Introduction
The identification of thermal anomalies from space has several diverse applications, including the detection of volcanic eruptions [Rothery et al., 1988; Harris et al., 1994] and the analysis of forest fires [Muirhead and Cracknell, 1985; Kaufman et al., 1990]. While these examples may at first appear to be very similar (hot lava flows and burning trees may both have temperatures >1100°C), we report here that the spatial distribution of radiance and the spectral properties of the two surfaces are quite different. We use two Landsat Thematic Mapper (TM) subscenes of high-temperature targets to demonstrate these differences: Kilauea volcano, Hawaii, observed on July 23, 1991, and the Yellowstone National Park forest fires of September 8, 1988. Landsat TM data consist of 7 bands of which the visible to near-infrared bands 1 (0.45-0.52 µm), 2 (0.52-0.60 µm), 3 (0.63-0.68 µm), 4 (0.76-0.90 µm), 5 (1.55-1.75 µm), and 7 (2.08-2.35 µm) have 30 m x 30 m spatial resolution per pixel and the infrared band 6 (10.42-12.42 µm) has 120 m x 120 m spatial resolution per pixel. Because of its spectral range and resolution, unresampled (A-format and nearest neighbor) TM data can be used to estimate temperatures [Rothery et al., 1988] and average flux densities [Flynn et al., 1994]. However, for small, high-intensity thermal anomalies, resampling (cubic convolution) TM data tends to lessen the maximum radiance of the anomaly and spread it to neighboring pixels. For this reason, we will restrict our study to comparing the radiative differences between wildfires and lava flows. An objective of this work is that quantification of radiative differences between lava flows and forest fires may lead to the development of methods for the automatic detection and identification of these natural hazards, using the next generation of spaceborne sensors such as the Moderate Resolution Imaging Spectrometer (MODIS, Salomonson et al., 1989).

Our study uses Landsat TM data obtained over Kilauea volcano, Hawaii (Fig. 1a), and Yellowstone National Park, Wyoming (Fig. 1b) to study the radiative differences of these hot spots. The Kilauea volcanic image (Fig. 2a) shows part of the then 8-year-long eruption of Kilauea's East Rift Zone [Heliker and Wright, 1991]. Several individual lava flow lobes were active at the time the data were collected. A total of ~3500 near-IR pixels (TM band 7) exhibit above-background radiances for the lava flow. The Yellowstone image (Fig. 2b) was taken the day after a major fire storm swept over Old Faithful visitors center [Morrison, 1993], burning 4200 acres (~17 km2) of forest in a period of 19 hours. About 17,500 near IR pixels are above ambient in the Yellowstone image. Several fire lines up to 2 km long can be recognized.

In daytime images, smoke from biomass burning is especially apparent at visible wavelengths. Although there are light areas apparent near the active lava flows (Fig. 2c), this response is due to the reflective character of the glass on fresh pahoehoe lava flows and is not exclusively caused by volcanic emissions. The lava flow image (Fig. 2a) is relatively free of smoke or haze with the exception of the Kupaianaha lava lake area (Fig. 1).

Both anomalies are readily apparent by the effects of their passage on the surrounding terrain. Lava flows appear black in the visible to near-IR wavelengths (Fig. 2a) because of their low reflectivity. However, in the far-infrared (TM band 6) lava flows are anomalously because of their high emissivities relative to the surrounding vegetation. Forest fires leave burn scars in their wake, which appears as a brown streak through the "green" of unaffected forest (Fig. 2b).

Spatial Distribution of Infrared Radiance
The at-satellite detected radiance for any spectral band is a combination of the emitted radiance (both from the surface and atmospheric constituents) and solar reflected radiance from the surface as affected by scattering into and out of the atmospheric column [Rothery et al., 1988; Oppenheimer et al., 1993] and can be expressed by

\[ R_T = \tau (\varepsilon R_E + R_S) + R_A \]  

(1)

where \( R_T \) is the total at-satellite detected radiance, \( R_E \) is the surface emitted radiance which is affected by the atmospheric transmissivity \( \tau \) (here taken to be 0.95 for both images based on MODTRAN atmospheric transmission model [ONTAR Corporation, 1991]), and \( \varepsilon \) is the surface emissivity (for basalt,
Figure 1. The two 11.3 km x 11.3 km study areas were chosen from the island of Hawaii (1a) and Yellowstone National Park (1b). North is indicated by the arrow in each location map. The lava flows (1a) and the burn scar (1b) are outlined in black. Dark blotches mark areas of high thermal radiance, which are active lava flows (1a) or forest fires (1b). Diagonal lines mark lakes in Figure 1b.

0.99 in TM band 7 [Flynn, 1992] and 0.92 in band 6 [J. Salisbury, personal communication, 1992], and an estimate of 0.9 for the fire image). $R_S$ is the reflected solar radiance and $R_A$ is the radiance emitted or scattered by atmospheric constituents upwards to the TM. Both images were subdivided into smaller blocks of pixels having similar characteristics (i.e., location, orientation with respect to Sun, and angle of slope). Background radiance values of non-anomalous pixels for TM bands 6 and 7 were chosen from within each block and used to correct for the effects of reflected solar radiation, atmospheric emittance and scattering, and thermal warming due to solar absorption. Digital numbers (DN) were converted to radiances using Markham and Barker [1986].

The spatial distribution of radiant anomalies for lava flows and forest fires is markedly different and can be illustrated using 2-band (TM infrared bands 6 and 7) radiance-differential maps (Figs. 2a and 2f). The colors represented on the map are derived from the combination of radiances listed in Table 1. The maps show that the hottest parts of the active lava flows (Fig. 2e) are located central to the anomaly, while those of the forest fire (Fig. 2f) are located at or outside the edges of the burn scar. Moving outward from the hottest areas, the lava flows show a gradual

Figure 2. Comparisons of the Kilauea eruption (Figs. 2a, 2c and 2e) and the Yellowstone fires (Figs. 2b, 2d, and 2f) corresponding to Figure 1 locations. The distance scale at the lower right of each image is 3 km. Figures 2a and 2b are TM Band 7, 5, and 3 RGB composites. In Figure 2a, black areas are regions covered by lava flows; vegetation appears green; yellow hotspots denote active flows; and clouds appear white. In Figure 2b, brown areas represent burn scars. Forest fires from another fire line appear at the left edge of Figure 2b. Figures 2c and 2d are TM Band 1 black and white images. Figures 2e and 2f are maps of radiance differentials measured in TM Bands 6 and 7. Table 1 lists the combination of radiances which were used to derive colors for both images.
Table 1. Decision matrix for hot spot emitted radiance-differential map

<table>
<thead>
<tr>
<th>COLOR</th>
<th>band 6 Corrected Radiance*</th>
<th>band 7 Corrected Radiance*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>b &lt; Pixel Rad &lt; 12.50</td>
<td>b &lt; Pixel Rad &lt; 3.840</td>
</tr>
<tr>
<td>Dkblue</td>
<td>12.50 &lt; Pixel Rad &lt; 15.60 (s)</td>
<td>3.840 &lt; Pixel Rad &lt; 11.25</td>
</tr>
<tr>
<td>Dkgreen</td>
<td>b &lt; Pixel Rad &lt; 12.50</td>
<td>3.840 &lt; Pixel Rad &lt; 11.25</td>
</tr>
<tr>
<td>Purple</td>
<td>12.50 &lt; Pixel Rad &lt; 15.60 (s)</td>
<td>3.840 &lt; Pixel Rad &lt; 11.25</td>
</tr>
<tr>
<td>Red</td>
<td>b &lt; Pixel Rad &lt; 12.50</td>
<td>11.25 &lt; Pixel Rad &lt; 14.38 (s)</td>
</tr>
<tr>
<td>Orange</td>
<td>12.50 &lt; Pixel Rad &lt; 15.60 (s)</td>
<td>11.25 &lt; Pixel Rad &lt; 14.38 (s)</td>
</tr>
<tr>
<td>Yellow</td>
<td>Pixel Rad &lt; 15.60 (s)</td>
<td>Pixel Rad = 14.38 (s)</td>
</tr>
<tr>
<td>White</td>
<td>Pixel Rad = 15.60 (s)</td>
<td>Pixel Rad = 14.38 (s)</td>
</tr>
</tbody>
</table>

* All units are in W/m²/μm/sr. “b” denotes background radiance (within block). “(s)” denotes detector saturation

The decrease in emitted radiance at all infrared wavelengths with increasing distance from the breakout. Lava flows which were emplaced several days prior to the TM acquisition are still thermally evident [Flynn et al., 1994]. On the other hand, areas within the burn scar farthest from the active fires exhibit low band 6 radiances, meaning that burn scars cool quickly compared to flows. However, the anomalously high radiance in band 7 means that there was a measurable amount of small hot radiators within the burn scar pixels. This result is more substantial when we consider that the geometric resampling process would tend to minimize the radiance gradient between the anomaly and the background. We suggest that the scenario causing this radiance distribution is that the majority of the burned surface area cools rapidly (< 60°C within hours of the fire), while small residual smoldering and flaming fires account for the high radiance in the near-IR. Typically, this radiance distribution in satellite images is rare for lava flows, except in the case of advancing flow fronts [Flynn et al., 1994], where the presence of active flow toes can result in a high near-IR response (at 30-m resolution), coupled with the majority of the pixel having no active flows giving a low IR result (at 120-m resolution).

These radiative differences between anomalies are also borne out by comparing the overall statistics of both scenes. Scatter plots of band 6 vs. 7 data (Fig. 3) permit discrimination of active flows, fires, and burn scars. The results of this study show that of the 511 pixels which are radiating above 5.49 W/m²/μm/sr in band 7, 241 of these (~47%) are saturated in band 6 (> 15.60 W/m²/μm/sr) and 216 (41%) are saturated in band 7 (~ 14.38 W/m²/μm/sr). The remaining majority of the active and cooling flows (≤ 5.49 W/m²/μm/sr, but > background) saturated TM band 6 in 511 pixels. This is consistent with large surface areas radiating at intermediate temperatures (> 80°C, pixel-integrated band 6 temperature), and small areas at higher temperatures, due again to the low response (relative to forest fires) measured in TM bands 5 and 7. For Yellowstone, of 655 anomalous (> 5.49 W/m²/μm/sr) band 7 pixels, only 116 (~ 18%) pixels are saturated, with only 20 (~ 3%) pixels saturated in band 6. This suggests that the active fire areas were extremely limited in spatial coverage and that burned areas cooled rapidly with residual fires or hot embers emitting radiance in the majority of burn scar pixels.

The transfer of heat from a lava flow or burn scar to the atmosphere is almost exclusively accomplished by radiation and convection [Ozisik, 1985; but specific discussions for flows include Head and Wilson, 1986 and Oppenheimer, 1991]. The conductive component from the thermal anomaly to the ground in both cases is negligible. Head and Wilson [1986] have shown that radiative heat transfer, which depends on the temperature of the object as well as its emissivity, dominates for cooling flows at temperatures ≥ 230°C. While the convective cooling of lava flows and burn scars depends on the thermal conductivity, specific heat, density, and thickness of the material in question, among other parameters, two factors governing the efficient transfer of heat to the atmosphere are critical to the observed differences in cooling rates. The first is the spatial distribution of radiators within a pixel. Lava flows are emplaced as a single relatively large unit, while fires tend to burn brush, leaves, and other kindling of negligible thickness which dissipate heat energy rapidly. The second factor is the location of the “hot zone” within the anomalies. Lava flows have a hot core which typically can remain molten for hours to days after emplacement depending on the flow thickness. The transfer of heat from the core to the atmosphere is greatly inhibited by the formation and growth of the lava flow crust. In contrast, trees burn from the outside with exterior layers of wood charred as the fire progresses. Dissipation of heat from the outer few centimeters of charred wood is relatively rapid.

Figure 3. Anomalous Band 7 vs. Band 6 pixels for Kilauea (3a) and Yellowstone (3b). Axes units are W/m²/μm/sr. Cloud-covered areas were not included in the analysis.
Conclusions

There are three aspects of lava flows and wildfires that enable them to be discriminated from each other at Landsat wavelengths and spectral resolution:

1) Atmospheric opacity at optical wavelengths. The significant amount of smoke generated by burning forest obscures the surface above and adjacent to active fires at visible wavelengths (TM band 1, most noticeably). The particle size of the smoke which reflects incoming sunlight is responsible for this effect [Kaufman et al., 1994]. Except in the instance of a singular intense fire, smoke and eruption plumes may be distinguished by the distribution of source areas. Fire lines will have many associated smoke plumes, while eruption columns will typically be generated from one source vent. We note, however, that anomalous visible radiances cannot uniquely be used to differentiate forest fires from lava flows. Cloud shadows covering smoke plumes can reduce the detected visible radiance at the sensor. Additionally, for obvious reasons, this method would not work for nighttime observations.

2) The spatial distribution of infrared radiance. Lava flows can have large contiguous areas exhibiting anomalous infrared (10.4-12.4 µm) radiances with centrally located near-infrared anomalies (from a vent or break-out). Forest fires can burn in a "patchwork" pattern leaving areas unburned. Typically, the fire line around the burn scar perimeter, even for resampled TM data, is generally only 1-3 band 7 pixels (30-90 m) wide.

3) The rate of cooling. Differential radiance maps (Fig. 2a and f) show that the rates of cooling of the surfaces are strikingly different mainly due to the location and size of the high temperature source within the anomaly. Lava flows form crusts which inhibit the transfer of heat from the molten core to the atmosphere. Fresh burn scars have higher cooling rates because combustibles burn from the outside inward allowing for more efficient dissipation of heat to the atmosphere.

Here, we have introduced the important topic of differentiating between types of thermal anomalies. We have shown that significant results can be obtained using TM data but that more detailed quantitative results have been limited by the dynamic range of the TM channels. For local studies, high temporal resolution images (1 image every few hours) collected with airborne sensors such as the MODIS Airborne Simulator or the Airborne Infrared Disaster Assessment System (operated from NASA Ames) could be used to recognize the patterns of fast-moving perimeter-burning fires as opposed to slowly spreading, centrally hot lava flows. However, only satellite-based systems are available to study thermal anomalies on a global basis.

Noted differences between lava flows and wildfires have significant implications for the future use of high resolution spaceborne sensors for the automatic detection of thermal anomalies, which could incorporate a test of the ratio of near-IR (2.1 µm) to infrared (11 12 µm) flux. The motivation for this work might be to detect the onset of a new volcanic eruption, to determine the extent of a forest fire, or more specifically where to focus relief efforts (either fire fighting or evacuation). In 1998, NASA will launch the first platform of the Earth Observing System, which will carry the MODIS instrument [Salomonson et al., 1989]. MODIS will view most parts of the world at least daily with 36 channels and 1-km spatial resolution or better. Repeat MODIS measurements (3-12 hours apart if one looks at data from the EOS AM-1 vs. PM-1 platforms) may be used to distinguish flows and fires, as flows would remain hot at 11-12 µm while fires would have cooled substantially. Our work with TM data shows that there are significant sub-kilometer-sized variations in the thermal characteristics of fires and eruptions, and demonstrate that "event detection algorithms" using daily 1-km data sets (such as MODIS) could be developed to detect and discriminate between these two phenomena.

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References


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