Numerical modeling of lava flow cooling applied to the 1997 Okmok eruption: Comparison with advanced very high resolution radiometer thermal imagery

M. R. Patrick, J. Dehn, and K. Dean
Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA

Received 11 April 2003; revised 6 October 2004; accepted 5 November 2004; published 24 February 2005.

1. Introduction

[2] The modeling of active lava flow cooling has advanced recently to a high level of sophistication [e.g., Kesthelyi and Denlinger, 1996; Neri, 1998; Harris and Rowland, 2001], yet the modeling of long-term flow cooling has not been commensurate. Perhaps one reason for this disparity is the difficulty in obtaining reliable temperature data throughout the flow’s cooling history, which may last years. This is especially true at remote volcanoes. A partial remedy to this problem is to concentrate on surface temperature, which can be measured routinely with satellite remote sensing instruments. The benefits of satellite data for this purpose include the high temporal resolution and relatively inexpensive procurement, even for the most remote volcanoes.

[3] In this second part of the study, the numerical model described by Patrick et al. [2004] was applied to the 1997 Okmok lava flow and the predicted lava surface temperatures were compared with surface temperature measurements made by advanced very high resolution radiometer (AVHRR) thermal imagery throughout the course of the cooling period. Several techniques, including the dual-band approach and pixel merging, were compared for extracting reliable measurements of the lava surface temperature from the infrared imagery.

2. Background

[4] The National Oceanographic and Atmospheric Administration (NOAA) AVHRR data used in this study originated from the image archive at the Geophysical Institute of the University of Alaska Fairbanks (UAF). Data are recorded by up to three polar-orbiting satellites (NOAA 12, 14, and 15) and are received directly at the Institute in near real time. The Alaska Volcano Observatory Remote Sensing group at UAF analyzes these AVHRR data on a daily basis over Alaska, Kamchatka, the Cascades and the Kurile Islands for...
remote monitoring of the North Pacific region’s numerous active volcanoes [Dean et al., 1998; Dehn et al., 2000].

AVHRR collects data in five spectral bands (Table 1), all having a nadir (vertically down looking) pixel size of about 1.1 km [Kidwell, 1991]. The repeat period for each satellite over the equator is approximately 12 hours, but owing to multiple satellites and the convergent orbits over high latitudes, Okmok (Figure 1) and the rest of the Aleutian volcanoes can have up to eight passes a day. Analysis of volcanism using AVHRR data is typically performed with bands 3 (3.55–3.93 μm) and 4 (10.3–11.4 μm). Band 3 (B3) data are especially useful as this band’s wavelengths approach the peak emittance wave-lengths of erupting lava while the band 4 (B4) wavelengths more closely match those of normal ground. Converting the at-satellite radiance to actual ground radiance requires correcting for the effects of surface emissivity, atmospheric transmissivity, upwelling radiance, and reflected radiance, described in detail by Harris et al. [1997b]. The emissivities of numerous substances have been measured using spectroradiometry [Salisbury and D’Aria, 1994], and transmissivity can be estimated with an atmospheric modeling program such as MODTRAN4 [Berk et al., 1999]. Upwelling radiance in band 4 can also be calculated with MODTRAN4, while its contribution in band 3 is often assumed to be negligible [Harris et al., 1997b]. Reflected radiance in band 3 is often estimated from nearby pixels in daytime scenes [Wooster and Kaneko, 2001], or taken as insignificant in nighttime scenes, and it is assumed to be negligible in band 4 in general [Harris et al., 1997b]. Ground radiance in these bandwidths can then be converted to ground temperature using the inverse Planck function. It is especially important to appreciate that this temperature value is a composite of the actual range of temperatures within the pixel footprint, as a function of the fractional area and temperature of the various thermal components as well as the wavelength of the channel.

3. Model Comparison With AVHRR Imagery

3.1. AVHRR Measurements of the 1997 Okmok Eruption

In order to measure lava surface temperature, the UAF AVHRR archive was scanned by eye for anomalies over Okmok in the period February-December 1997. From this set, nighttime, cloud-free images with low scan angles (<40°) were selected and, fortuitously, all of these nighttime images were in the ideal predawn hours, when solar heating of the surface is at a minimum. Only those images which saw the caldera completely cloud free were used, and this stringent criterion reduced the total number of usable AVHRR scenes acquired throughout 1997 to 65. Of these, 47 were acquired during the eruption and 18 were from the post-eruption cooling stage. To provide a rough representation of the vigor of the eruption the highest AVHRR B3 pixel value and the highest B4 pixel value (not necessarily spatially coincident) from each image have been plotted (Figure 2). These values are uncorrected pixel temperatures, and are meant only for a qualitative synopsis. A more rigorous extraction of surface temperatures, suitable for...
comparison with the model results, is discussed in the following sections.

[7] Figure 2 shows a sudden increase in B3 temperature around 13 February, a plateau of saturated values for a period after this date, then a sudden decrease toward background temperatures. The rise in B3 temperature corresponds to the first observed thermal anomaly in satellite imagery (13 February, 1305 UTC), which was small (1–2 pixels) and located at cone A, and is interpreted to correspond to initial lava effusion. The first pilot report of activity was received the next day [Dean et al., 1998]. The plateau of sensor-saturated pixel values reflects continued effusion and emplacement of the lava flow. The end of this saturated period and the subsequent decrease in temperatures reflects cooling of the lava after effusion has ceased. Thermal anomalies were observed in AVHRR imagery until mid-October 1997.

3.2. Progressive Versus Instantaneous Cooling

[8] The simplest way to apply the cooling model is to assume that the entire flow was erupted en masse and began to cool immediately. The results shown in Figure 6 of Patrick et al. [2004] essentially operate on this assumption. In actuality, the lava was erupted over a period of about 5 weeks, from 13 February to approximately 20 March [Patrick et al., 2003], and this progressive eruption and cooling introduces a potentially serious complication. Ameliorating this concern to some degree, the AVHRR results from Patrick et al. [2003] indicate that a large outflux of lava occurred between 11 March and 15 March and largely represents the eruption of the second lobe, which comprises 40% of the total flow area. Visual analysis of the imagery suggests that much of the lava on the first lobe was also active during this phase. Therefore it appears that in this period of time the majority of the lava flow surface was active. Because our comparison effectively analyzes only the upper portion of the flow (over 200 days surface cooling only penetrates a few meters), the effective time range of eruption for most of the flow area is narrowed from 5 weeks to 5 days, reducing the influence of prior cooling in the AVHRR-derived lava surface temperature data.

[9] Nevertheless, there may still be significant effects from differential cooling of the flow surface, and we used a simple model to characterize this. The aerial extent of each lobe was divided into small packets, which were erupted out in an even temporal distribution from the emergence of the lobe to its effusive cessation, based upon the observations of lobe eruption times of Patrick et al. [2003]. In actuality, as mentioned the flow surface likely overran older portions of the flow thereby limiting the actual surface cooling time prior to the effusive cessation, so this simulation assumes a worst-case scenario. The surface temperature was assigned to each packet based on its age at each time step during the eruption phase and subsequent cooling period, from the model results of Patrick et al. [2004], allowing us to create a simple lava flow that is concurrently cooling and erupting. Because it is unrealistic that a packet begins static cooling as soon as it is erupted we assigned an arbitrary ‘active lava’ temperature distribution to the packet if its age is less than an assumed emplacement time. We modeled this as being spatially 1% hot cracks (1000°C), and 99% crust (200–500°C). Once the packet age is older than the emplacement time, say 1 or 2 days, it begins cooling (i.e., assigned temperatures from the cooling model).

[10] In this way, we can compare how closely a more realistic composite cooling curve (i.e., more thermal components of different ages as a result of graduated eruption and cooling) compares with a simple, single-component (i.e., uniform temperature, instantaneous eruption and cooling) version. Figure 3 shows results for average lava surface temperature from the progressive eruption model as well as the standard model results assuming instantaneous eruption and cooling. Differences between the progressive and instantaneous models are limited to the first
The dual-band method was pioneered by Dozier [1981] and Matson and Dozier [1981], first applied to volcanic targets by Rothery et al. [1988], and subsequently modified for AVHRR measurements of volcanic phenomena by Harris et al. [1997a]. Both two-component (used in method 1 here) and three-component (method 2) dual-band approaches are used here. A two-component approach models the pixel-integrated temperature as resulting from two-component approaches are used here. A two-component approach models the pixel-integrated temperature as resulting from the combined thermal signature of warm lava at a temperature \(T_h\), occupying a fraction of the pixel area denoted by \(p_h\), and cold ground at ambient temperature \(T_c\), occupying an area \(1-p\). In this case, the dual-band equations are

\[
\begin{align*}
R_3 &= p_h L_3(T_h) + (1-p_h)L_3(T_b) \\
R_4 &= p_h L_4(T_h) + (1-p_h)L_4(T_b)
\end{align*}
\]

where \(R_3\) and \(R_4\) are the total radiance values measured by the satellite in bands 3 and 4, respectively, \(L_3(T_b)\) and \(L_4(T_b)\) are the radiance contributions from the hot component in each band, and \(L_3(T_h)\) and \(L_4(T_h)\) are the radiance contributions from the background component in each band. \(L_3(T)\) and \(L_4(T)\) are determined using the Planck function values for a blackbody at temperature \(T\) at the B3 and B4 central wavelengths. Background temperature \(T_b\) can be estimated from adjacent nonanomalous pixels, and the remaining two unknowns \((T_h\) and \(p\)) can be calculated simultaneously.

For a three-component model, the pixel area is assumed to be composed of small, hot areas \((T_h)\) on the flow occupying a pixel fractional area of \(p_h\), areas of moderately warm, cooling lava \((T_c)\) occupying a fractional area of \(p_c\), and areas at background temperature \((T_b)\) occupying the remainder of the pixel area \((1-p_h-p_c)\). The dual-band equations are

\[
\begin{align*}
R_3 &= p_h L_3(T_h) + p_c L_3(T_c) + (1-p_h-p_c) L_3(T_b) \\
R_4 &= p_h L_4(T_h) + p_c L_4(T_c) + (1-p_h-p_c) L_4(T_b)
\end{align*}
\]

With five unknowns \((T_h, T_c, T_b, p_h\) and \(p_c\)) at least three must be assumed to reduce the unknowns to two. Unfortunately, for emplaced, extended cooling only background temperature is known with some certainty (from adjacent pixels), so \(T_b\) and \(p_h\) need to be assumed in order to solve for \(T_c\) and \(p_c\). The hot component temperature and area are not well known as little field work has been done to constrain them, and they likely change dramatically as the available underlying heat diminishes. On a pixel-by-pixel basis, therefore the ignorance of both the hot component temperature and area renders the three-component model ineffective for providing additional information.

### 3.3.2. Pixel Merging

In order to reduce the number of unknowns in the radiance equations for the three-component model, the pixel merging method performed by Harris et al. [1999] is adapted for AVHRR imagery. In this approach, the radiance values for each pixel in the anomaly are essentially averaged to produce a larger pixel. This technique has the benefit of encompassing the entire hot source, so that when the total area of the volcanic target is known (as in the case of a lava lake or an emplaced lava flow) this area can be used to constrain the other unknowns.

A complication is introduced by this method, however, as a result of pixel overlap. Because the ground sample distance (GSD) of AVHRR is less than the IFOV [Cahoon et al., 1992], substantial overlap of pixel footprints will result [Breaker, 1990], leading to repeated incorporation of the hot target radiance with the merging approach. Calculation of IFOV size versus scan angle was done using the simple geometric approach of Cahoon et al. [1992] for a curved Earth surface, using the assumptions in Table 2. Along- and cross-track GSDs were taken from Cahoon et al. [1992] and B3 and B4 IFOVs were taken from Harris et al. [1997b]. To account for the oversampling, the merged area of pixel coverage was calculated taking into consideration the GSD and IFOV as a function of scan angle (Figure 4), as opposed to simply summing the total

### Table 2. Values for IFOV/GSD Calculations

<table>
<thead>
<tr>
<th></th>
<th>Value, mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-track GSD</td>
<td>0.95</td>
</tr>
<tr>
<td>Along-track GSD</td>
<td>1.05</td>
</tr>
<tr>
<td>Band 3 IFOV</td>
<td>1.51</td>
</tr>
<tr>
<td>Band 4 IFOV</td>
<td>1.41</td>
</tr>
</tbody>
</table>

*aFrom Cahoon et al. [1992] and Harris et al. [1997b].

month after cooling ensues, after which the results converge to nearly identical values. This similarity indicates that the instantaneous eruption and cooling scenario is a reasonable assumption for long-term cooling.

### 3.3. Tools for Comparison

#### 3.3.1. Dual-Band Method

[11] The dual-band method was pioneered by Dozier [1981] and Matson and Dozier [1981], first applied to volcanic targets by Rothery et al. [1988], and subsequently modified for AVHRR measurements of volcanic phenomena by Harris et al. [1997a]. Both two-component (used in method 1 here) and three-component (method 2) dual-band approaches are used here. A two-component approach models the pixel-integrated temperature as resulting from the combined thermal signature of warm lava at a temperature \(T_h\), occupying a fraction of the pixel area denoted by \(p_h\), and cold ground at ambient temperature \(T_c\), occupying an area \(1-p\). In this case, the dual-band equations are

\[
\begin{align*}
R_3 &= p L_3(T_h) + (1-p) L_3(T_b) \\
R_4 &= p L_4(T_h) + (1-p) L_4(T_b)
\end{align*}
\]

where \(R_3\) and \(R_4\) are the total radiance values measured by the satellite in bands 3 and 4, respectively, \(L_3(T_b)\) and \(L_4(T_b)\) are the radiance contributions from the hot component in each band, and \(L_3(T_h)\) and \(L_4(T_h)\) are the radiance contributions from the background component in each band. \(L_3(T)\) and \(L_4(T)\) are determined using the Planck function values for a blackbody at temperature \(T\) at the B3 and B4 central wavelengths. Background temperature \(T_b\) can be estimated from adjacent nonanomalous pixels, and the remaining two unknowns \((T_h\) and \(p\)) can be calculated simultaneously.

[12] For a three-component model, the pixel area is assumed to be composed of small, hot areas \((T_h)\) on the flow occupying a pixel fractional area of \(p_h\), areas of moderately warm, cooling lava \((T_c)\) occupying a fractional area of \(p_c\), and areas at background temperature \((T_b)\) occupying the remainder of the pixel area \((1-p_h-p_c)\). The dual-band equations are

\[
\begin{align*}
R_3 &= p_h L_3(T_h) + p_c L_3(T_c) + (1-p_h-p_c) L_3(T_b) \\
R_4 &= p_h L_4(T_h) + p_c L_4(T_c) + (1-p_h-p_c) L_4(T_b)
\end{align*}
\]

With five unknowns \((T_h, T_c, T_b, p_h\) and \(p_c\)) at least three must be assumed to reduce the unknowns to two. Unfortunately, for emplaced, extended cooling only background temperature is known with some certainty (from adjacent pixels), so \(T_b\) and \(p_h\) need to be assumed in order to solve for \(T_c\) and \(p_c\). The hot component temperature and area are not well known as little field work has been done to constrain them, and they likely change dramatically as the available underlying heat diminishes. On a pixel-by-pixel basis, therefore the ignorance of both the hot component temperature and area renders the three-component model ineffective for providing additional information.

#### 3.3.2. Pixel Merging

[13] In order to reduce the number of unknowns in the radiance equations for the three-component model, the pixel merging method performed by Harris et al. [1999] is adapted for AVHRR imagery. In this approach, the radiance values for each pixel in the anomaly are essentially averaged to produce a larger pixel. This technique has the benefit of encompassing the entire hot source, so that when the total area of the volcanic target is known (as in the case of a lava lake or an emplaced lava flow) this area can be used to constrain the other unknowns.

[14] A complication is introduced by this method, however, as a result of pixel overlap. Because the ground sample distance (GSD) of AVHRR is less than the IFOV [Cahoon et al., 1992], substantial overlap of pixel footprints will result [Breaker, 1990], leading to repeated incorporation of the hot target radiance with the merging approach. Calculation of IFOV size versus scan angle was done using the simple geometric approach of Cahoon et al. [1992] for a curved Earth surface, using the assumptions in Table 2. Along- and cross-track GSDs were taken from Cahoon et al. [1992] and B3 and B4 IFOVs were taken from Harris et al. [1997b]. To account for the oversampling, the merged area of pixel coverage was calculated taking into consideration the GSD and IFOV as a function of scan angle (Figure 4), as opposed to simply summing the total

### Figure 4. Graphical representation of the pixel-merging method. The pixel merging area is that of the black box, whose dimensions are calculated from the number of pixels in the cross- and along-track dimensions, and their IFOV and GSD.
area of the individual pixels which would produce an overestimate of the actual ground footprint. The total area of the lava flow (8.9 km²) was then divided into this total merged pixel area to calculate lava fraction (\( p \)).

The merged area was chosen manually in each image based upon visually elevated pixels, making sure to encompass the entire flow. Attempts to isolate the anomalous areas using automated band-differential thresholding [Harris et al., 1995; Higgins and Harris, 1997] were not consistently successful, most likely because this method was developed for active lava in which band 3 is more reliably raised above background.

### 3.4. Comparing Modeled Cooling to AVHRR Data

The model results were compared to AVHRR data collected over the flow throughout its initial cooling period using the selected images, covering a period from 24 March to 2 September. In order to extract the lava temperature from the AVHRR pixel-integrated temperature (a composite of lava and background temperature) two basic approaches were used. First, the dual-band approach to calculate lava surface temperature is attempted (in methods 1 and 2). Second, the pixel merging method of Harris et al. [1999] is used (methods 2 and 3).

#### 3.4.1. Method 1: Dual-Band, Pixel-by-Pixel Method, Two-Component Model

For each cooling image the two-component dual-band approach was applied to each pixel in the thermal anomaly (Figure 5). Band 3 and 4 transmissivity values and B4 upwelling radiance were estimated using the MODTRAN4 atmospheric model [Berk et al., 1999]. B3 reflected radiance was negligible in these nighttime images, and background temperature (\( T_b \)) was taken from the average of nonanomalous adjacent pixels. The mean hot component temperature (\( T_h \)) solution for the anomalous pixels in each image is shown in Figure 5b, with the standard deviation to indicate the range of values in each image. The plot shows an exponential-like drop and leveling similar to that exhibited by modeled temperatures (Figure 5a), but in a much higher temperature regime.

Whereas modeled temperatures are 5–10°C above background throughout the majority of the 200-day cooling period, the hot component temperatures we measured average around 50–100°C above background for the period. Summing the hot component area of the anomalous pixels in each image results in a total area (<4 km²) that is considerably less than the actual total lava flow area (8.9 km²). Clearly, this two-component dual-band approach fails to characterize the temperature of the cooling crust, and likely reflects influence from small, anomalously hot areas on the flow surface (an unaccounted third component).

In dual-band calculations of active flows [e.g., Harris et al., 1997a] these anomalously hot areas are attributed to cracks in the nascent crust which expose incandescent lava. For extended cooling of an emplaced flow a similar model can be applied with the small, high-temperature areas representing areas of active fumaroles, as were observed on the Omok flow in 2001, as well as on other flows (A. Harris, personal communication, 2002). In the two-component pixel approach, however, the flow is modeled as a single component, resulting in the extracted lava temperature being an unconstrained composite of the hot steaming areas and cooling crust.

#### 3.4.2. Method 2: Dual-Band, Pixel-Merging Method, Three-Component Model

To resolve this problem a three-component model was applied to the dual-band equation to solve for the temperature of the cooling lava. By merging the pixels over the flow the number of unknowns in a three-component model can be sufficiently reduced to make the dual-band method viable. Here \( p_h + p_c \) accounts for the area of the entire lava flow (8.9 km²) divided into the merged pixel area, letting us solve for \( p_h \). This leaves essentially three unknowns: \( T_h \), \( T_c \) (for which a solution is sought) and \( p_c \). Background temperature was determined by pixels near the flow, as in the previous method. If a range of possible values for \( T_b \) is assumed the range of values for \( T_c \), \( p_c \) and \( p_h \) can be solved for. On the basis of field observations at Omok in 2001 (K. Papp, personal communication, 2002) and Etna in 1991–1993 (A. Harris, personal communication, 2002) typical hot component temperatures could range from 50°C to 300°C. Solution for the crust temperature using this range of hot component temperatures is shown in Figure 6. Temperature values are generally consistent with modeled predictions, in that crust temperature drops to within 10°C of background within 1 month and hovers at ~5–10°C above background for the remainder of the 200-day study period. The size of the hot component (Figure 6b) is inversely related to hot component temperature and generally decreases with time, with total sizes for \( T_h = 300°C \) ranging from 3 × 10⁻⁴ to 0.1 km².
(for 24 March to 2 September) and for $T_h = 100^\circ$C ranging from 0.02 to 0.48 km$^2$ (for 11 April to 2 September). The method yielded no solution for $T_h = 100^\circ$C for the period before 11 April, probably because such a low assumed hot component temperature is unable to account for the actual hot component radiance in this early part of the cooling.

### 3.4.3. Method 3: Single-Band, Pixel-Merging Method, Two-Component Model

[21] Finally, we attempt extracting lava surface temperature from band 4 alone. Band 4 was chosen over band 3 because of its reduced sensitivity to the small, anomalously hot portions of the flow which are essentially ignored in this method. The impact of this assumption has been estimated and incorporated into the error discussion in section 3.5.2. The pixel-integrated radiance can then be assumed to be the sum of the background radiance ($L_4(T_b)$) covering an area $1-p$ and the cooling lava flow radiance ($L_4(T_h)$) covering an area of $p$:

$$R_4 = pL_4(T_h) + (1-p)L_4(T_b)$$

Background temperature is computed from the average of pixels surrounding the hot area. In order to avoid errors introduced by assumptions for transmissivity and emissivity inherent in any calculation of absolute temperatures, uncorrected band 4 temperatures were used and a relative calculation of lava surface temperature over local background was performed (Figure 7). The band 4 measurements of the flow are mostly consistent with the range of modeled temperatures. Rapid exponential cooling ensues for approximately the first 50 days, and is followed by a very steady decrease in temperatures hovering at $\sim$5–10°C.

![Figure 6](image_url)

**Figure 6.** Results from method 2 AVHRR lava surface extraction approach (dual-band, three-component, pixel-merging). (a) Surface temperature results agree well model results (Figure 5a) using heat transfer coefficients between 50 and 100 W m$^{-2}$ K$^{-1}$. (b) Hot component areas for various assumed hot component temperatures.

![Figure 7](image_url)

**Figure 7.** Results from the method 3 AVHRR lava surface extraction approach (single-band, two-component) compared to modeled results using varying convective heat transfer coefficient values. The AVHRR-extracted values are most consistent with convective heat transfer coefficients between 50 and 100 W m$^{-2}$ K$^{-1}$ and are generally above 25 W m$^{-2}$ K$^{-1}$. This range is in agreement with measured convective heat transfer coefficients over lava surfaces by Keszthelyi and Denlinger [1996] of 65–75 W m$^{-2}$ K$^{-1}$. 

---

6 of 9
3.5. Error Analysis

[22] The radiant signature of the lava flow is relatively subtle compared to that of the background, and this study attempts to extract a signal that is significantly weaker than what has been studied with active lavas [e.g., Harris et al., 1997a, 1997b], compelling an estimate of the scale of error in our extraction methods. For each method, the total error was calculated by the square root of the sum of the squares of the individual error sources. It should be noted that errors in MODTRAN-estimated upwelling radiance and assumed emissivity were estimated to be negligible.

3.5.1. Method 2 Errors

3.5.1.1. Error Source 1

[23] Uncertainty in the MODTRAN-estimated transmissivity values for bands 3 and 4 can have a significant impact on extracted lava surface temperature. The crust temperature solution was observed to be more sensitive to the difference between band 3 and 4 transmissivity values than to their absolute values, and therefore we varied the difference by ±0.03 which slightly exceeds the variation in summer/winter transmissivity difference between B3 and B4. This produced crust temperatures that varied by 0.1–2.0°C (mean = 0.7°C).

3.5.1.2. Error Source 2

[24] The background temperature may vary among the background portions of the pixel merged area, and this may present a problem as a single background temperature was assumed. On the basis of visual inspection of the variance in background around the thermal anomalies, the maximum range in background temperature was estimated at ±1°C. The effect of this uncertainty was addressed easily by simply varying the background by that amount and rerunning the method. This produced an effect of 3.2–6.7°C (mean of 4.5°C).

3.5.1.3. Error Source 3

[25] In the pixel-merging method the spatial extent, or footprint, of the pixel on the ground was estimated using an effective IFOV, as described earlier. An effective IFOV assumes a perfect response function, that is, the response of the sensor within the IFOV is 1 and 0 anywhere outside. In actuality, the detector response (or point spread function, PSF) is a relatively smooth function, and the IFOV simply approximates this as best as possible. In order to estimate the error introduced by this, the AVHRR PSFs were placed at nadir ground sample distances above the flow to replicate the actual AVHRR response, and the pixel merging approach was performed using the effective IFOV values described earlier. For method 2, this produced errors in the crust temperature from 1.7 to 5.4°C for the range of scan angles and hot component temperatures (100–300°C). The simulations always produced higher values for crust temperature than the actual value, which likely reflects the pixel overlap producing repeated incorporation of radiance into the merged value.

3.5.2. Method 3 Errors

3.5.2.1. Error Source 1

[26] This method also suffers from uncertainties arising from the pixel-merging method, and the pixel-merging simulation was performed in the context of this method, as well. The error in extracted lava temperature was within 12% (again, always producing an overestimate) of the difference between lava and background temperature, and for numerous randomly chosen PSF positions over the flow, indicating that the method has an inherent error at that level.

3.5.2.2. Error Source 2

[27] To address background temperature uncertainty, we reran the method with background temperature deliberately altered by ±1°C. This produced errors in extracted lava temperature ranging from ±1.3 to 4.5°C, depending on the lava temperature and fractional area of background in each image.

3.5.2.3. Error Source 3

[28] Band 4 will have a much reduced sensitivity to the anomalous hot components on the flow, compared to band 3, but there may still be a significant impact. The hot component temperatures and calculated areas from method 2 were used to estimate the impact on the pixel merged temperature, and the method was rerun with altered values to examine the effect on the extracted lava surface temper-
the two-component nature of the lava surface and produced reasonable results in rough agreement with the model predictions (Figure 6). The single-band, two-component approach (method 3, Figure 7) assumed that the radiant contribution of the anomalously hot areas (those areas not conducive to conductive modeling) was insignificant in long-wave band 4 due to their very small size. In this case, the calculation is relatively simple and the combined errors in this method were slightly lower than those in method 2. Because of the simplicity in the approach and lower errors, method 3 is taken here as the favored method for model comparison, but it should be noted that there is nevertheless a good overlap between the method 2 and method 3 solutions.

30 These AVHRR data were originally meant for a formal validation of the model, but the degree to which this was successful is arguable. In one sense, the AVHRR data indeed show a similarity with the modeled predictions: an exponential-like drop and leveling of surface temperature in a similar temperature range. On the other hand, the sensitivity tests of Patrick et al. [2004] indicate that the 200-day model predictions for lava surface temperature are highly dependent upon the convective heat transfer coefficient \( h_c \), which could not be established with much confidence because of the paucity of knowledge on its behavior over lava flows. This uncertainty therefore precludes a definitive validation, and only a range of predicted lava surface temperatures (Figure 7) can be compared to the AVHRR-derived values.

31 If we accept the validity of the model, however, the AVHRR-derived lava surface temperatures can be used to ascertain reasonable convective heat transfer coefficients for the flow throughout its cooling. This is possible because the modeled lava surface temperatures are relatively insensitive to all input parameters except the convective heat transfer coefficient [Patrick et al., 2004, Table 2a]. Varying any of the other input parameters within a plausible range will produce a temperature difference of up to only 3°C. The modeled Ogmok lava surface temperatures were plotted for a range of plausible convective heat transfer coefficients, spanning both natural (\(~5–20\) W m\(^{-2}\) K\(^{-1}\)) and forced convective (\(~20 \div \) W m\(^{-2}\) K\(^{-1}\)) regimes (Figure 7). As Figures 6 and 7 show, the AVHRR-derived lava temperatures from methods 2 and 3 are consistent with a convective heat transfer coefficient in the realm of \(50–100\) W m\(^{-2}\) K\(^{-1}\), and generally above \(25\) W m\(^{-2}\) K\(^{-1}\). These results are in agreement with the field measurements of Keszthelyi and Denlinger [1996] for forced convection over lava surfaces, in which values of \(65–75\) W m\(^{-2}\) K\(^{-1}\) were observed for winds of \(3–4\) m s\(^{-1}\). Keszthelyi et al. [2003] found values for \(h_c\) between 45 and \(50\) W m\(^{-2}\) K\(^{-1}\). These two studies measured \(h_c\) in conditions somewhat different than in this study (recently erupted pahoehoe vs. the emplaced ‘a’a studied here), suggesting that \(h_c\) values of \(50–100\) W m\(^{-2}\) K\(^{-1}\) may be generally relevant for rough lava surfaces with moderate winds. Nevertheless, all of these results suggest that previous approaches for calculating the convective heat transfer coefficient [Head and Wilson, 1986; Oppenheimer, 1991; Harris et al., 1997a; Wooster et al., 1997], which produce values around \(10\) W m\(^{-2}\) K\(^{-1}\), may be prone to underestimating the convective heat loss. It seems clear, however, that more
work is needed to establish definitive relations for convective heat transfer in a lava cooling context.

[32] Finally, the modeled lava surface temperature exhibited a secondary rise in the summer months due to higher background temperatures which result in a decrease in cooling rate affecting the lava surface (Figure 9a). When shown in absolute values (i.e., without the background temperature subtracted), the AVHRR-derived lava surface temperatures (Figure 9b) appear to show the same phenomenon. This is only meant to be a relative comparison, however, since a direct comparison of temperatures is not possible due to discrepancies introduced by atmospheric correction and background temperature differences.

5. Conclusions

[33] The numerical model described by Patrick et al. [2004] was applied to the 1997 Omok lava flow and the model predictions for lava surface temperature over a 200-day cooling period were compared to lava surface temperatures measured by AVHRR imagery. To extract the subpixel lava component from the pixel-integrated radiance, three methods were compared: (1) a dual-band, pixel-by-pixel approach with a two-component pixel model, (2) a dual-band, pixel-merging approach with a three-component pixel model, and (3) a single-band, pixel-merging approach with a two-component pixel model. Of these, methods 2 and 3 produced results consistent with the range of model predictions, suggesting a convective heat transfer coefficient for the flow most commonly between 50 and 100 W m⁻² K⁻¹, and generally above 25 W m⁻² K⁻¹, which agrees with values measured elsewhere. Finally, the model prediction of a secondary rise in lava surface temperatures due to seasonal warming was corroborated by the AVHRR time trend of lava surface temperature.

Acknowledgments. Considerable assistance was provided by V. Sharpston (UAF), and K. Engle (UAF) must be thanked for his competent administering of the AVHRR receiving station at the Geophysical Institute. Comments and shared field data from A. Harris (University of Hawaii at Manoa) very much improved the paper. K. Papp (UAF) provided valuable comments and shared field data from A. Harris (University of Hawaii at Manoa) very much improved the paper. K. Papp (UAF) provided valuable comments and shared field data from A. Harris (University of Hawaii at Manoa). K. Papp (UAF) provided valuable comments and shared field data from A. Harris (University of Hawaii at Manoa). Comments and shared field data from A. Harris (University of Hawaii at Manoa). Comments and shared field data from A. Harris (University of Hawaii at Manoa). Comments and shared field data from A. Harris (University of Hawaii at Manoa).

References


