Constraints on the partitioning of Kīlauea’s lavas between surface and tube flows, estimated from infrared satellite data, sulfur dioxide emission rates, and field observations

W. C. Koeppen · M. Patrick · T. Orr · A. J. Sutton · D. Dow · R. Wright

Abstract This paper describes how observations of sulfur dioxide (SO₂) degassing rates (obtained in situ), thermal emission rates (obtained from infrared satellite data), and semiquantitative flow field observations can be used to elucidate the partitioning of lava between the surface and tube systems at Kīlauea volcano, Hawaiʻi, over a decadal timescale. For most of our study period, 2000 to 2009, we found that the infrared spectral radiance measured by Moderate Resolution Imaging Spectroradiometer from the flow field under clear-sky conditions is controlled by the lava effusion rate and the amount of flow accommodated by the subsurface tube system. At Kīlauea, the degree of tubing is estimated qualitatively using field observations, and we show that the satellite data and in situ gas data can be used to estimate the percentage of lava on the surface relative to the total amount erupted. This empirical relationship works to describe many cases in the past decade at Kīlauea but breaks down when there is a lack of concurrent clear-sky radiance and SO₂ data or when magma is being stored and degassed prior to eruption. Our observations provide a simple way to estimate the partitioning of Kīlauea’s total lava supply between surface and tube-fed flows using a long-term dataset. This is important because the transition between periods when lava is distributed primarily by surface flows to periods where tubes dominate has been suggested to indicate significant changes in the character of decadal-scale eruptions at Kīlauea (Heliker et al., Bull Volcanol 59:381–393, 1998). In addition, it is during those times when surface flows predominate that the flow field does most of its lateral expansion and the hazards associated with the lava effusion become more pronounced.

Keywords Sulfur dioxide degassing rates · Thermal emission rates · Semiquantitative flow field observations · Kīlauea volcano · Surface and tube flows

Introduction

Kīlauea volcano is one of the most active and best studied volcanoes on Earth, and its current eruption centered on the east rift zone (ERZ) has been ongoing for over 29 years (Fig. 1; Heliker and Mattox 2003; Kauahikaua 2007). The eruption has been characterized by persistent emplacement of lava flows for most of its history, and tracking the rate of this discharge has been fundamental to monitoring activity levels of the volcano (Sutton et al. 2003). During typical flow field activity, magma supplied at the vent is distributed between surface flows and lava tubes (Kauahikaua et al. 2003). The transition between periods when lava is distributed primarily by surface flows to a regime where most lava is confined to the tube system has been suggested as being indicative of significant changes in the character of such long term (i.e., decadal timescale) eruptions (Heliker et al. 2003).
In their study, Heliker et al. (1998) define periods when lava is distributed predominantly by long-lived tubes as periods of stability during which lava is delivered from the vent to the ocean entry with few surface breakouts. Periods of instability are caused by variations in effusion rate, which result in pauses and surges in the amount of lava available for flow field transmission (Cervelli and Miklius 2003). Surges in lava effusion can overwhelm the carrying capacity of the lava tube, resulting in surface breakouts, particularly at points predisposed to formation of hydraulic jumps (Orr 2011). It is during these phases of instability when surface flows dominate that the Kīlauea flow field does most of its lateral expansion. As such, recognizing the transition between the stable and unstable phases has implications for evaluating lava flow hazards in this geographic area (Heliker et al. 1998). Although sulfur dioxide (SO₂) emission measurements provide a reliable way to estimate the total amount of magma available to be erupted (Sutton et al. 2003), characterizing the proportion of this which is emplaced as surface flows or via lava tubes, which may be the ultimate expression of the shift between stable and unstable regimes, is typically subjective and qualitative.

Here, we present data that describe how thermal flux from Kīlauea’s ERZ (obtained from infrared remote sensing data acquired by the National Aeronautics and Space Administration [NASA] Terra and Aqua Moderate Resolution Imaging Spectroradiometer [MODIS] sensors) and SO₂ emission rates (determined in situ via solar occultation methods) have varied between 2000 and 2009. We then compare these datasets with field observations that describe the relative importance of tube-fed flows and surface flows to determine the extent to which the partitioning of lava between the surface and tube systems can be quantified using information extracted from these two routinely acquired datasets. Infrared satellite radiance data have been shown to provide reasonable estimates of time-averaged effusion rate (Wright et al. 2001; Harris et al. 2007), but the satellite sensor will only “see” active lava on the surface of the flow field (lava transmitted by tubes being hidden from the sensor). By comparing the satellite radiance (indicative of surface flows) to the SO₂ emission (indicative of the total amount of lava degassed at shallow levels), we can gauge the relative supply of lava to the tube system and surface flows. Our work shows that the SO₂ emission rates scale relatively well with emitted radiance.
during periods dominated by surface flows, but these parameters decouple during periods when lava is predominantly carried by tubes, confirming that at-sensor radiance is controlled both by effusion rate and flow style (tube vs. surface) in a sensible manner. Overall, the combined analysis of thermal remote sensing data and field-based SO₂ fluxes provides semiquantitative constraints on the emplacement styles at Kilauea volcano, with these variables being coupled during periods when surface flows are predominant, but decoupled when they are not.

**Overview of activity at Kilauea volcano for the period 2000–2009**

**Eruption summary**

The Pu‘u ‘Ō‘ō–Kupaianaha eruption, in Kilauea’s ERZ, began in January 1983 (Fig. 1). The first 3 years of the eruption were characterized by a series of episodic fountaining events that constructed the Pu‘u ‘Ō‘ō cone and fed short-lived, high-volume channelized flows that buried the surrounding terrain (Wolfé et al. 1988; Heliker et al. 2003). In 1986, eruptive activity shifted 3 km downrift, and episodic lava fountaining was replaced by relatively steady, sustained effusion that built the Kupaianaha lava shield (Kauahikaua et al. 1996; Heliker and Mattox 2003). The nearly continuous effusion led to the formation of a broad tube-fed pāhoehoe flow field that reached the ocean and destroyed the village of Kalapana in 1990 (Fig. 1; Mattox et al. 1993; Hon et al. 1994). The Kupaianaha vent was abandoned in 1992 as activity shifted back to Pu‘u ‘Ō‘ō (Kauahikaua et al. 1996), and relatively steady effusion from vents on the west and southwest flanks of the cone (Heliker et al. 1998; Heliker and Mattox 2003) persisted until 2007. The nearly continuous activity was interrupted several times by intrusions, such as those in 1993 and 1997 (Heliker et al. 1998; Thormber et al. 2003), which briefly robbed magma from the Pu‘u ‘Ō‘ō reservoir, causing the crater floor to collapse. Following another intrusion and crater collapse in June 2007, new fissures opened up between Pu‘u ‘Ō‘ō and Kupaianaha (Poland et al. 2008) in July 2007, eventually focusing on the easternmost fissure. After sending flows northeast initially, the Fissure D vent, as it was called, stabilized in late 2007 with a switch in flow direction toward the south (Fig. 1). These flows reached the ocean in March 2008, adding to the already vast tube-fed flow field and remaining active for the rest of the study period.

**2000–2009: detailed eruption chronology**

Now, we examine the 2000–2009 period in detail. The year 2000 began with ongoing steady effusion from flank vents on the west side of Pu‘u ‘Ō‘ō cone. Lava feed directly into tubes and was transported downslope to feed widespread surface flows and intermittent ocean entries. This activity was the continuation of the reorganization of the lava tube system following an intrusion and eruptive pause in September 1999. On several occasions, breakouts from the tube system above the steep slope of the Pūlama Pali led to an increase in surface activity, particularly during a surge in effusion in late September 2000. Surface activity slowed during October–early December, but was rejuvenated in mid-December with new breakouts that continued into 2001. With the prevalence of surface flows, ocean entry activity was subdued during the first 5 months of 2001, with lava tubes reaching the sea only intermittently. After a brief surge in output in May, surface activity declined during June–August 2001 but picked up slightly by September and remained widespread through November.

In December 2001, activity shifted to the upper flow field, above the Pūlama Pali, and began the construction of a series of rootless shields in a process that lasted through April 2002. A large breakout—the Mother’s Day flow—began on May 12, 2002 on the west flank of Pu‘u ‘Ō‘ō and widened the west margin of the flow field as lava made its way quickly downslope to the ocean (Fig. 2a). After the initial downslope push, surface activity related to the Mother’s Day flow declined in volume but remained present into 2003. This relatively steady, moderate level of surface activity was interrupted by two surges in eruptive output in 2003, on January 21 and August 9. Both events led to large breakouts on the Mother’s Day flow field above the Pūlama Pali that increased the level of surface activity temporarily. The August increase began to fade in late 2003, and the distal portion of the Mother’s Day tube system was abandoned as breakouts began to occur farther upslope. Rootless shields began to grow over the upper part of the tube system in a pattern much like that seen in late 2001–early 2002.

The dominance of the Mother’s Day tube system was usurped in early 2004 by the Martin Luther King (MLK; started January 18) and the Prince Kūhiō Kalaianaa’ole (PKK; started March 20) breakouts on the southwest flank of Pu‘u ‘Ō‘ō (Fig. 2b). During this period, all activities were confined to the surface, and a branch of the Mother’s Day flow began to creep downslope, reaching the ocean eventually in late May. By August, the ocean entry had stopped and surface activity related to the Mother’s Day flow began to diminish. As it did so, the PKK flow began to ramp up, peregased by a surge in effusion in late July, and progressively hosted a greater level of surface activity. By late September, the PKK flow had captured the full effusion from Pu‘u ‘Ō‘ō, and a new tube system carrying lava from the PKK vent to the ocean was established by early November. The PKK flow was bolstered again in February 2005 by another surge in output, resulting in an increase in
surface activity that had begun to taper off by the end of March. The level of surface activity declined slowly but steadily through the remainder of 2005 as the PKK tube system became well established, and the first several months of 2006 were characterized by relatively steady flow through the tube to the ocean (Fig. 2b). Short-lived increases in effusion built a series of shatter rings along the PKK tube (Orr 2011) eventually leading to the formation of a new branch of the PKK tube system in May 2006. This new breakout resulted in an increase in the level of surface activity over the following several months as lava advanced slowly to the ocean. Comparatively benign surface activity continued on the flow field into the first half of 2007, with a moderate number of surface flows and several persistent ocean entries.

Effusion from Pu‘u ‘Ō‘ō was terminated by the Father’s Day intrusion on June 17–19, 2007. The intrusion culminated in a tiny, brief eruption on Kāne Nui O Hamo shield, about 6 km west of Pu‘u ‘Ō‘ō (off map), and was accompanied by the collapse of the floor of the Pu‘u ‘Ō‘ō crater due to magma withdrawal (Poland et al. 2008). This was followed by an eruptive pause that lasted until July 1, when lava began to refill the Pu‘u ‘Ō‘ō crater. On July 21, 2007, fissures opened on the east flank of Pu‘u ‘Ō‘ō (Poland et al. 2008) and propagated to the western base of Kupaianaha (Fig. 2c). Effusion soon centered on the easternmost fissure, Fissure D, and from late July to November, lava flows were directed north of the rift zone (Kauahikaua 2007), building a perched lava channel (Patrick et al. 2011). On November 21, 2007, a breakout (informally called the Thanksgiving Eve Breakout [TEB]) from directly above the buried trace of Fissure D diverted lava toward the south away from the perched lava channel. From December 2007 to February 2008, the bulk of the TEB lava had accumulated within about 2.5 km of the Fissure D vent, building more than a dozen rootless (i.e., tube-fed) lava shields (Fig. 2c), each 20–30 m high and 200–400 m wide (Patrick and Orr 2011). In late February, lava began to advance more rapidly, cutting a swath through the Royal Gardens subdivision (Fig. 1) and reaching the ocean on March 5. Surface flows diminished over the next months as a stable tube was established, though a brief surge in activity in late June–early July fed vigorous surface flows for several days. Thereafter, the TEB tube and associated ocean entry were active almost continuously through the end of 2009.

In addition to the lava merging at Pu‘u ‘Ō‘ō, a new vent at Kīlauea’s summit (not shown) opened in March 2008 in Halema‘uma‘u Crater (Wilson et al. 2008). A lava lake resided deep within the vent cavity, which enlarged from 35 m across at the beginning of the eruption to 130 m across by the end of 2009 (Orr and Patrick 2009). SO2 emission was generally 600–1,000 t day−1, which is lower than typical values on the ERZ during 2000 to 2008. The steady
degassing and lava lake activity were punctuated by a handful of small explosive events that ejected juvenile and lithic tephra (Orr et al. 2008; Houghton et al. 2011). Notably, intermittent minor to moderate surface breakouts from the TEB tube system onto the ERZ flow field were commonly associated with cycles of deflation and inflation (DI events) at Kīlauea’s summit.

Methods

Estimating the total lava supply rate using SO2 emission rates

SO2 gas emitted by Kīlauea has been measured regularly since 1979 (Elias et al. 1998). For this study, we used SO2 data collected between 2000 and 2009 by three vehicle-based instruments: the Correlation Spectrometer (COSPEC IV) from January 2000 to March 2001, COSPEC V from March 2001 to September 2004, and FLYSPEC from September 2004 until the present. Each instrument changeover included a transition period during which both the old and new instruments were run concurrently (Elias and Sutton 2002, 2007).

Kīlauea’s summit region and ERZ are generally treated as distinct and independent sources of SO2, and they have been measured and recorded separately since 1984 (Elias et al. 1998). At Kīlauea, ERZ SO2 emission rates were routinely used to estimate the volume of lava erupted from ERZ vents. However, in late 2008, ERZ SO2 release began to be affected by preeruptive summit degassing, so that SO2 measured from the ERZ beyond July was no longer clearly linked to the ERZ effusion rate (Sutton et al. 2009). Therefore, for this study, we used vehicle-based SO2 measurements from the ERZ from January to July 2008, and we excluded SO2 data from July 2008 to December 2009.

SO2 emission rates, reported in metric tons per day, can be converted to dense rock equivalent lava effusion rates via the equation:

\[ V_m = E_{SO2} \times K_d \]  

where \( V_m \) is the derived effusion rate (cubic meters per day), \( E_{SO2} \) is the measured SO2 flux (metric tons per day), and \( K_d \) is a degassing constant based on the weight percentage of SO2 present in typical Kīlauea basalts and the void-free lava density measured from Kīlauea’s submarine basalts (a full derivation of Eq. 1 can be found in Sutton et al. 2003). Previous estimates of \( K_d \) have ranged from 207 (Sutton et al. 2001) to 233±80 m³ of lava erupted per metric ton of SO2 (Sutton et al. 2003). For this work, we use a \( K_d \) of 239 m³/ton SO2, a value calculated by USGS Hawaiian Volcano Observatory (HVO) staff using the methods of Sutton et al. (2001) that more accurately reflects the CO2/SO2 ratio of the east rift eruptive gases during our period of our study. For comparison with the radiance data, we present the derived effusion rate (\( V_m \)) in cubic meters per second.

Estimating the relative abundance of surface flows using infrared satellite data

Spectral radiance data from two MODIS currently in orbit were used in this study. The first MODIS instrument was launched on board NASA’s Terra satellite and began returning data in February 2000; a second instrument was launched on board NASA’s Aqua platform and began returning data in June 2002. Individually, the two polar orbiting satellites achieve global coverage of the earth approximately twice per day. However, for this study, we used only nighttime passes, which avoided complications due to reflected sunlight in the thermal images. Nighttime images over Hawai‘i are collected nearly daily between 9:40 and 11:30 p.m. Hawaiian Standard Time (HST) by Terra and between 1:10 and 3:00 a.m. HST by Aqua. This provided approximately one image each night between February 2000 and June 2002 and approximately two MODIS images each night from July 2002 to December 2009. There were days where neither satellite orbit track included Kīlauea in its field of view; however, this occurred in <5 % of days that we analyzed in this study.

MODIS collects data in 36 wavebands, 10 of which are suitable for monitoring thermal behavior on the Earth’s surface. For this work, we used MODIS bands 21 (3.930–3.989 μm), 22 (3.930–3.989 μm), and 32 (11.770–12.270 μm), which have spatial resolutions of ~1 km pixel⁻¹. Bands 21 and 22 cover the same wavelength region; however, band 21 has a higher saturation temperature (~500 K) than band 22 (~330 K) as well as more noise (Barnes et al. 1998; Kaufman et al. 1998).

We used a hybrid time series algorithm (Koeppen et al. 2010) that combines two previous algorithms, MODVOLC (Wright et al. 2002) and a time series approach (e.g., Pergola et al. 2004, 2009), to process the nighttime MODIS data between February 2000 and December 2009. The algorithm detects thermal anomalies (i.e., volcanic surface activity) and calculates the excess 4-μm radiance, which is the radiance emitted by the active lava corrected for background radiance emitted by the surrounding inactive lava/substrate. It uses bands 21, 22, and 32 of each MODIS MOD021KM radiance file, along with its companion MOD03 geolocation file, to generate oversampled (0.5 km pixel⁻¹), time-ordered, georeferenced image cubes for the 4- and 12-μm wavelength data. The 4-μm cubes are composed of band 22 data, unless the band 22 values are saturated by high-temperature thermal anomalies (e.g., active volcanic eruptions or fires) whereby those pixel values are replaced with band 21 values. The hybrid time series algorithm (1) uses the 4- and 12-μm image cubes to calculate the normalized thermal index, identifying and removing major thermal anomalies from the cube (Wright et al. 2002, 2004), (2) derives 4-μm reference (mean) and variability (standard deviation) images.
for the region for each calendar month, (3) compares the original 4-μm data to the reference images, normalized by their variability, and (4) adds any pixels that fall outside of the envelope of normal thermal behavior to the pixels detected in step 1. A mask cube of thermally anomalous pixels is returned, with one mask image for each input image in the cube. We calculated the excess 4-μm radiance emitted by Kīlauea’s ERZ flow field in each image by subtracting the reference radiance from the measured radiance for each anomalous pixel and then summing the excess radiances across the region.

Using both Terra and Aqua instruments, MODIS provided excess 4-μm thermal radiance measurements on 8,008 discrete occasions over Kīlauea volcano between February 2000 and December 2009. However, many of these images showed the presence of clouds that can either partially or fully obscure the volcano, leading to observed radiance values lower than what was present on the surface. Unfortunately, the MODIS cloud mask could not be used to automatically identify cloudy images as it consistently misidentified cloudy vs. clear conditions over Hawai’i (Koeppen et al. 2010). Therefore, for this test case, we manually inspected all of the MODIS images and classified the area over the ERZ as “clear” (747 images), “partly clear” (1,599 images), or “cloudy/unknown” (5,662 images). Images with the clear classification showed no identifiable clouds over the flow field, and satellite-measured thermal radiances are expected to be indicative of the lava present on the surface of the flow field. Images with the partly clear classification showed some clouds present over the flow field, some of which may partially obscure the excess radiance emitted by the surface lava. In these cases, the excess radiance may be indicative of the lava on the surface or may be slightly depressed and underestimate that emitted by surface flows. Images with the cloudy/unknown classification show individual clouds obscuring the ERZ flow field, moderate to heavy cloud cover over the entire image, or they show missing values in the region of interest (a product of being on the edge of the MODIS field of view). Excess radiance values derived from these images almost certainly underestimate the excess radiance emitted by Kīlauea’s surface flows.

To form a complete radiance time series, we used all of the data classified as clear and added some measurements from partly cloudy and cloudy images when those values exceeded what could otherwise be interpolated between temporally adjacent clear-sky observations (Fig. 3). For example, between February and November 2000, there are only ten clear images of the ERZ flow field, and there were no clear images identified in February, April, May, or October. During this time, there are an additional 47 cloudy or partly cloudy images that show radiance values exceeding those that would be obtained by interpolating between the few available clear-sky observations. As another

![Fig. 3 Time series of excess radiance values over the ERZ flow field of Kīlauea volcano. The solid line connects values that were used for this study, which mostly consist of clear-sky data (blue squares), but include partly cloudy (green squares) and cloudy data (red squares) that displayed a higher excess radiance than that which would be interpolated from the clear-sky values alone](image-url)
example, the peak of the excess 4-μm radiance in July 2008 would be estimated at ~260 W m$^{-2}$ μm$^{-1}$ sr$^{-1}$, occurring on July 5, if only clear-sky radiance data were used to form the time series. However, a cloudy image shows an excess radiance of at least ~410 W m$^{-2}$ μm$^{-1}$ sr$^{-1}$ on July 4. Because the thermal radiance values associated with partly cloudy and cloudy images cannot overestimate the excess radiance, we used these values to fill in gaps and achieve better estimates of the excess radiance during this time period. Unfortunately, it is impossible to algorithmically identify periods where the partly cloudy and/or cloudy data can be used when it is lower than the values interpolated between clear data. For example, there is a paucity of clear data between March and May 2002 where the interpolated radiance values are quite high. Partly cloudy data appears to indicate a drop in excess radiance during late April–early May before returning to high levels indicated by the clear data; but, there is no way to know if those are better estimates of the radiance emitted by the flow field than interpolating the sparse clear data during that time. Using our data selection method, we were able to add 567 partly cloudy images to the 747 clear-sky images to form a time series with 1,314 data points to compare with SO2 measurements. One of the advantages of using long temporal time series of satellite data (and looking for general trends in emitted radiance rather than very specific events) is that the effect of intermittent cloud cover can be reduced.

For most of this work, we relate measurements of SO2 in units of metric tons per day to measurements of radiance in watts per square meter per micrometer per steradian over Kilauea. However, to directly compare with SO2-based effusion rates, we also converted the excess 4-μm radiance values to apparent effusion rates. Many studies have been published on the topic (e.g., Harris et al. 1998, 2007; Wright et al. 2001), and they show that the apparent area of each image ($A_{\text{lava}}$) covered by the thermal anomaly can be determined by the equation:

$$A_{\text{lava}} = \sum \frac{L_{\text{sat}} - L_{\text{bg}}}{L_{\text{lava}} - L_{\text{bg}}} \times A_{\text{pixel}}$$  \hspace{1cm} ([2])

where $L_{\text{sat}}$ is the measured MODIS band 22/21 radiance, $L_{\text{bg}}$ is the normal (ambient) band 22/21 radiance of the pixel when no anomaly is present, $L_{\text{lava}}$ is the black-body radiance at 3.96 μm emitted by a thermal anomaly of an assumed lava temperature, and $A_{\text{pixel}}$ is the area of a pixel (square meters). By making assumptions about the lava’s density, specific heat capacity, surface temperature, cooling temperature from liquidus to solidus, latent heat of crystallization, and convective heat transfer coefficients, the area of the lava in each image can be further converted into a time-averaged effusion rate ($E_r$) by:

$$E_r = A_{\text{lava}} \times \alpha$$  \hspace{1cm} ([3])

where $\alpha$ is a scaling factor dependent on the assumed values. Harris et al. (2007) present a range of typical values for $\alpha$ at Kilauea based on values and equations that they explain in detail. For this work, we used their derived values and calculated a minimum effusion rate based on an assumed lava temperature of 773.15 K (500 °C) and an $\alpha$ value of $29 \times 10^{-6}$ m s$^{-1}$ and a maximum effusion rate based on an assumed lava temperature of 373.15 K (100 °C) and an $\alpha$ value of $0.9 \times 10^{-6}$ m s$^{-1}$. For comparison with the SO2 effusion rates, we present the average of the two rates and use the minimum and maximum to estimate errors.

It is important to note that, while effusion rates are a more intuitive way to describe what’s happening within the flow field, errors in these rates from satellite-based radiance data can be quite large. Harris et al. (2007) estimate that uncertainties in the remote sensing method can be as high as 50%. However, both the radiance-based and SO2-based discharge rates are, for the most part, linear transformations, i.e., the absolute values of the effusion rates may change with the various assumptions made, but the relative differences between data points are constant, regardless of the assumptions. The discharge rate estimated from radiance is not completely linear because it includes the $L_{\text{bg}}$ term, which changes through time; however, in Hawai’i, these differences are minimized because ambient temperatures (and, therefore, $L_{\text{bg}}$) have only a small range of values.

A semiquantitative measure of the relative proportions of tube vs. surface flows obtained from field observations

The HVO conducts field observations and flow mapping on a regular basis. Helicopter flights approximately once per week provide a synoptic view of flow field activity. Recent and active flows are mapped using a handheld GPS from the helicopter or by foot on a similar frequency. Reports summarizing the activity are then written on a bimonthly or quarterly basis.

We reviewed all of the activity reports compiled between 2000 and 2009 to characterize the emplacement style of the active flows during the study period. Activity on each day was assigned to one of six categories, designated by a number (Table 1). Assigning these categories based on the activity reports is partly subjective, particularly in choosing between categories 2 and 3 (major vs. minor breakouts). However, these descriptions are still valuable observational data, and they provided a serviceable depiction of emplacement style that can be used to compare against our quantitative calculations of surface vs. tube-fed flow.

**Results**

Figure 4 shows the clear-sky excess thermal radiance, the SO2 output, and the recorded degree of tubing in the ERZ flow field from 2000 through 2009. Both the excess radiance and the SO2 data show large variations in their point-to-point values;
however, on the monthly and yearly timescales there are clear trends. For example, peaks in SO2 are generally correlated with periods of high excess radiance. In May 2001 and February 2005, there is close agreement in the timing of increases in both datasets. An increase in both SO2 flux and emitted thermal radiance is consistent with (a) increased lava effusion from the vent and (b) the distribution of this lava predominantly as surface flows. Field observations confirm that these periods were times when surface flows were conspicuous (surface flows and/or major breakouts from the tube system in Fig. 3). On the other hand, troughs in emitted thermal radiance are generally decorrelated with SO2 flux. There are at least five periods during which the data show reduced excess radiance values that do not correspond to any notable decrease in SO2, including the following: October–December 2000, June–August 2001, June–July 2004, May–September 2005, February–May 2006, and March–June 2008. These radiance troughs that are decoupled from the SO2 data occur during periods in which the flow field was observed to have a well-established tube system. In the following sections, we describe patterns in the time series during five specific time periods in the context of observed eruptive activity.

January 2000–December 2001

In 2000 to 2001, the data show only one major SO2 spike and two drops in emitted thermal radiance attributed to tubing of the surface flows (Fig. 5a). From January 2000

<table>
<thead>
<tr>
<th>Category</th>
<th>Summary</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>All surface flows</td>
<td>No discernible lava tube system was present on the flow field.</td>
</tr>
<tr>
<td>4</td>
<td>Surface flows, advancing tube</td>
<td>A developing lava tube system was migrating towards the ocean. Flows were partially tubed but exited at its front and margins without entering the ocean.</td>
</tr>
<tr>
<td>3</td>
<td>Established tube, major breakouts</td>
<td>A significant amount of lava was contained in lava tubes, which reached the ocean. Major breakouts still fed large surface flows.</td>
</tr>
<tr>
<td>2</td>
<td>Established tube, minor breakouts</td>
<td>A significant amount of lava was contained in lava tubes, which reached the ocean. Only minor breakouts fed small surface flows.</td>
</tr>
<tr>
<td>1</td>
<td>All tubed</td>
<td>All erupted lava was contained within the lava tube system, which reached the ocean.</td>
</tr>
<tr>
<td>0</td>
<td>No eruption</td>
<td>No lava was erupting from the vent.</td>
</tr>
</tbody>
</table>

![Fig. 4](https://example.com/fig4.png) Time series of excess radiance calculated for oversampled MODIS images (gray points), SO2 (black line), and flow field characterizations (colors). Points in the SO2 data that were measured more than 60 days apart are not connected, and SO2 data after July 7, 2008 were excluded from this study because of complications from summit degassing discussed in the text.
to April 2001, SO$_2$ values maintained a relatively stable level, between 850 and 1,700 t day$^{-1}$. Radiance values remained generally constant for the first part of this period, from February to September 2000, and there were no significant excursions in the clear-sky data during this period. At the end of October, excess radiance values decreased to very low levels ($<$6 W m$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$) in November and December, a period when HVO observed the ERZ lava to be mostly confined to tubes. This ~30-day period of tubed flow was capped by a 2-day pause in the eruption on December 15 and 16 (Heliker and Mattox 2003); however, there were no SO$_2$ measurements or valid radiance data available on either of these days. When the eruption resumed, surface flows were prevalent again and excess radiance values returned to their pre-September 2000 values. A stable ocean entry was not established until late April 2001.

A spike in SO$_2$ and thermal radiance occurred over a very brief period in May 2001, with SO$_2$ reaching $>$4,000 t day$^{-1}$ on May 15 and radiance peaking at 330 W m$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$ on May 21. The radiance spike corresponded with two short-lived surges in tube breakouts and surface flows on May 20 to 21 and May 23, which were presumed to be caused by a brief increase in effusion rate (Heliker and Mattox 2003). Following the May 2001 surges, SO$_2$ emissions returned to background levels, whereas radiance values continued to decrease into August 2001, a drop associated with field observations that surface flows were only intermittently active. From September to December 2001, radiance values
remained relatively steady (≈100 W m\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\)), with variations in the data corresponding to individual breakout events.

June 2003–October 2004

From June 2003 to May 2004, there was a nearly 11-month stretch of surface flows that displayed a gradual decrease in both SO\(_2\) and thermal radiance (Fig. 5b). While SO\(_2\) values followed a steady decline, an abrupt drop in excess radiance values occurred at the end of May 2004 with low values maintained until July 23, 2004. This change represented a phase during which the PKK flows developed tube system that reached the ocean, albeit with major breakouts (Fig. 2b).

In August 2004, the established tube to the ocean was abandoned and a new, partly tubed flow from the PKK vent area began to advance. Breakouts from the new advancing tube and surface flows along its margins were recorded by MODIS as moderate excess radiance values. By September 2004, SO\(_2\) emission rates averaged ≈1,000 t day\(^{-1}\) and nontubed radiance values were ≈75 W m\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\) (compared to average SO\(_2\) values of ≈1,800 t day\(^{-1}\) and excess radiance values of ≈175 W m\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\) at the beginning of June 2003).

October 2004–December 2005

Beginning in October 2004, both SO\(_2\) and thermal radiance rapidly rose to a level that was unprecedented in our decadal dataset (Fig. 5c). In February 2005, SO\(_2\) discharge peaked at ≈5,500 t day\(^{-1}\), or about four times the typical average of ≈1,500 t day\(^{-1}\), and excess radiance values reached ≈450 W m\(^{-2}\) μm\(^{-1}\) sr\(^{-1}\), approximately three times the average for the preceding 5 years. During this period of increasing SO\(_2\) and thermal radiance, surface activity on the PKK flow field (Fig. 2b) intensified, possibly as a result of increased magma supply at Kīlauea’s summit (Poland et al. 2012). Small lava fountaining events occurred sporadically at Pu‘u ‘Ō‘ō during this time period, and field observations point to an abundance of surface flows and major breakouts.

Radiance and SO\(_2\) fell jointly between March and May 2005 as the frequency and scale of surface flows decreased. The declining SO\(_2\) flux leveled off in May 2005 and remained relatively constant through the end of 2005, albeit at a higher level than the 2000 to 2004 average (Elias and Sutton 2007), whereas radiance values continued to decrease, reaching very low levels in late August that were maintained until October. This decoupling of the emitted thermal radiance observations from the SO\(_2\) between May and October corresponded with a steady increase in tubing and a consistent drop in the number of breakouts on the flow field. For most of September 2005, when radiance was at its minimum, lava on the flow field was entirely tubed and HVO scientists observed no significant breakouts. Radiance values returned to more typical levels in mid-October, when surface breakouts from the tube system resumed.

January 2007–May 2008

Moderate levels of SO\(_2\) and thermal radiance persisted between January and early June 2007; however, in late June, both datasets show a precipitous drop related to the Father’s Day intrusive event (Fig. 5d). The event started on June 17, culminated in a very small volume flow in the upper ERZ, and triggered a 2-week pause in eruptive activity at Pu‘u ‘Ō‘ō. Between July 1 and 20, the eruption resumed within the Pu‘u ‘Ō‘ō crater, but thermal radiance and SO\(_2\) remained low during this phase, and no surface flows on the ERZ were observed. In late July and August, SO\(_2\) and excess radiance began climbing in concert, concurrent with the onset of new fissures and surface flows beginning July 21. Relatively high levels of thermal radiance and SO\(_2\) were measured between August 2007 and March 2008, associated with the presence of an open lava channel, followed by a series of perched lava ponds and surface flows (Fig. 2c; Patrick et al. 2011; Patrick and Orr 2011). Though SO\(_2\) levels remained high throughout 2008, thermal radiance values declined in March relative to measured SO\(_2\) flux, again corresponding with the establishment of a tube to the ocean and subsequent decrease in surface flow activity in March to June as the tube stabilized (Fig. 2c). In late June 2008, Pu‘u ‘Ō‘ō (along with the Kīlauea summit) began inflating, followed by deflation and surface breakouts during the first week of July, an episode recorded by a spike in the excess radiance data that reflected the surge in lava supply.

July 2008–December 2009

From July 2008 until the end of 2009, the excess radiance data correlates well with observations of the surface flow activity. In August and September 2008, there were at least four DI events (Poland et al. 2011) visible in the thermal radiance data, with each one lasting approximately a week or two. The inflation portion of each event was expressed as a cycle of increasing excess radiance values associated with a surge of lava and increased number of surface flows, whereas the deflation phase is associated with a decrease in lava supply, sometimes pausing entirely, and declining excess radiance values. The DI events gave way to sustained moderate excess radiance values in October 2008. In 2009, the excess radiance data recorded three longer period events (3- to 4-month timescales), with each event being a sequence of breakouts that each declined until surface flows subsided. The data show that each of these cycles ended with surface flows becoming entirely tubed in May, August, and December of 2009.
Discussion

SO₂ flux data and satellite-derived thermal radiance observations as an index of lava emplacement style at Kīlauea volcano

Figure 6 shows histograms of the total thermal radiance emitted by the flow field (clear-sky observations only), as a function of each of the qualitative flow field categories that we identified (Table 1). In general, as the abundance of surface flow decreases and the abundance of tubed flow increases, the satellite-derived thermal radiance histograms display lower means, positive skewness, and a decrease in the maximum value. This is sensible, as a larger proportion of the available lava is partitioned from the surface into the tube system, effectively hiding much of it from the satellite sensor.

Correlating SO₂ flux and thermal radiance measurements confirms that the development of tubes carrying a greater proportion of the available lava, and not a cessation in the eruption, is the cause of these changes. Both the SO₂ emission rates and excess radiance values were converted to a common variable (effusion rate; cubic meters per second) using Eqs. 1, 2, and 3, and Fig. 7 displays the full time series of each variable on the same scale along with their associated envelopes of uncertainties. Although the uncertainties in the effusion rate calculations are large, the drops in radiance data relative to the SO₂ data are still clearly present outside the margin of error.

To more clearly associate the derived effusion rates with the observed character of the flow field, we also calculated the ratio of thermal emission-based effusion rate to the SO₂-based effusion rate \( \frac{E_r}{V_m} \) for measurements that were taken relatively close together in time. At Kīlauea, the ratio of the two rates can be thought of as the percentage of lava present on the surface relative to the total amount supplied to the ERZ flow field. This was done by selecting SO₂ measurements that had a clear-sky radiance image taken within 3 days, a process that reduced the dataset to only 334 comparable data points for the nearly 10-year record. We calculated the respective effusion rates for the points, calculated the ratio between them, and plotted them alongside the flow field observations (Fig. 8). As expected, this plot reiterates our previous results (e.g., Fig. 4), but it also adds some insight. First, the ratio time series predominantly falls below the one-to-one line, which indicates that, at Kīlauea, it is normal for lava that rises and degasses at a shallow level to be erupted through tubes with a varying amount of surface activity—the amount of lava degassed almost always exceeds the amount of lava detected as surface flows. The use of the word “detected” is significant here because lava flows that become ponded or which grow via inflation begin to violate the assumed relationships between at-satellite spectral radiance and lava effusion rates. For example, an eruption that accommodates additional lava via flow inflation would cease to expand laterally, and any changes in effusion rate, inferred using lava area as a proxy, would be impossible to document. Second, lack of data above the one-to-one line confirms that the contrary condition, where more lava is erupted as surface flows than apparently has been supplied, is relatively rare. Such a condition could occur where magma emplaced and degassed at shallow levels is later entrained and erupted contemporaneous with fresh material (Steffke et al. 2011; Patrick and Orr 2011). This may have been a process that contributed to the large spike in radiance relative to SO₂ that occurred in June and July of 2007, when the upper section of the flow field was inundated with fissures and open lava channels after a brief eruption pause. During that period, the effusion rate ratio was very low (~0.2) before becoming very high (~4.1). The rest of the ratio time series is as we expected, the ratio of the apparent effusion rates is generally close to 1 when the flow field was classified as having all surface flows or an advancing tube with significant surface flow activity. Under those circumstances, the percentage of the total lava supplied to the flow field, which is exposed to the satellite sensor, is greatest. The ratio decreases during periods characterized by an established tube system, and it is lowest when there are only minor breakouts or when it is all tubed; during these times, lava is obscured from the spacecraft and the apparent satellite-derived effusion rates fall to their minima.

![Fig. 6 Histograms of clear-sky excess radiance values based on the oversampled MODIS images associated with flow field characterizations. The dotted line on each plot represents the mean excess radiance value for the histogram](image-url)
To summarize, using the SO$_2$ emission rates with the satellite-derived thermal flux to monitor surface vs. tubed flows on a daily basis must be done with care. Given the errors and uncertainties associated with each individual measurement and the probability of clouds obscuring the satellite data, these data may be useful in only the best circumstances. However, our results show how trends made evident by analyzing decadal time series of these data can be used to classify the manner of lava emplacement at Kilauea. The clear-sky thermal radiance measured by MODIS over Kilauea’s ERZ is primarily controlled by two factors, the lava effusion rate and the degree to which the lava supplied to the vent is distributed as surface flows or through lava tubes. When there is no established tube system, all of the erupted lava is visible to the satellite and recorded as radiance in excess of the typical background values. In this case, variations in the radiance data (and any derived parameters) are generally coupled with variations in the SO$_2$ (Fig. 4). This finding agrees with the notion that SO$_2$ can be used as a proxy for all of the lava that is erupted onto the flow field (Sutton et al. 2003). Consequently, this implies that, at Kilauea, during our study period, lava was not being erupted faster than SO$_2$ can exsolve nor was a substantial amount of lava being degassed at shallow levels without erupting (previously identified shallow intrusive events, such as the Father’s Day intrusion, prove exceptions to this rule).

Once the lava flow establishes an active tube system on the flow field, lava is hidden from the satellite. This results in thermal radiance variations that become decoupled from the measured SO$_2$ flux. At Kilauea, this is most easily recognized when the thermal radiance decreases while the SO$_2$ remains relatively constant, situations which occurred in November 2000, June 2001, July 2004, September 2005, most of 2006, and March–July of 2008. This pattern is most easily observed for the period April–September 2005 (Fig. 5c), when the radiance data showed a smooth and steady decline over the course of 6 months, whereas the SO$_2$ maintained relatively consistent values.

Temporal trends in thermal radiance and SO$_2$ flux data

There appears to be a statistical basis for categorizing flows as predominantly surface or tubed based on the temporal evolution of SO$_2$ gas and heat flux measurements, and we show good agreements in the data over longer (e.g., monthly) timescales. An idealized progression in the development of the established tube system might involve initial abundance of surface flows, which gradually coalesce to form tubes. The tubes themselves gradually coalesce and eventually form a conduit from the source to the ocean. Thereafter, the incidence of surface flows gradually decreases as the tube system becomes more utilized. Such a progression would result initially in high (and correlated) thermal radiance and SO$_2$ fluxes until the tube reached the ocean, followed by a period of gradual decrease in thermal radiance.
and its decoupling from the SO$_2$ observations as more and more lava utilizes it. This simplified scenario has the SO$_2$ and thermal radiance observations falling within distinct fields in radiance–gas feature space for each flow field condition. If this occurs, can the development of a predominantly tube-fed flow field from one dominated by surface flows be tracked as a trajectory of sequential thermal radiance and SO$_2$ ratio values, as idealized in Fig. 9?

The answer appears to be yes and no. Scatter plots of the SO$_2$ and thermal radiance data split out by flow field character show weak clustering (Fig. 10). Observations from when the eruption was producing all surface flows overlap with those of surface flows with an advancing tube. That is not surprising given the efficiency of lava tubes—the length of the tube system does not affect the excess radiance values until it reaches the ocean. However, the latter shows a much tighter distribution of points, however, possibly because an advancing tube system requires a somewhat steady lava supply, whereas the former case does not. Similarly, when major breakouts were observed on the flow field, the radiance and SO$_2$ data is more widely spread. Indeed, breakouts from an established tube system often occur when the supply of lava is variable. The distribution of data for the case of an established tube system with minor breakouts shows a narrower distribution in terms of SO$_2$ (suggesting uniform lava supply) and it falls lower on the excess radiance scale (because lava is transported to the ocean under cover). There are only a few points in the tubed and no-eruption cases at Kilauea and all show low values. The lack of data in these two categories is a testament to the longevity and consistency of surface flows at Kilauea, but it also illustrates how short-lived the completely tubed systems are.

In some cases, it appears possible to use the SO$_2$ and thermal radiance datasets to estimate the degree of tubing more quantitatively than the characterizations that are currently employed (i.e., Table 1). To illustrate this, we again used the ratio of the radiance-based effusion rate to the SO$_2$-based effusion rate ($E_r/E_{r,SO2}$). We plotted the fields containing 10 % increments of these ratios into SO$_2$ vs. excess radiance space. The result is a plot that shows the path of data points identified by their SO$_2$ and excess radiance values as they move through the ratio fields, which represent a quantitative measure of the degree of tubing.

As just one example, the time series of data from February to September 2005 is plotted in Fig. 11. In early February, both SO$_2$ and radiance were near their peak; field reports indicate major breakouts from the tube system, and the effusion rate ratios indicate a high percentage of the available lava was present on the surface of the ERZ. The SO$_2$ flux increased by up to 300 % (suggesting an increasing total effusion rate) by the end of February, but radiance values increased only by ~30 %, suggesting that the established tube system was accommodating more lava and, consequently, the path moves to fields with lower effusion rate ratios. On February 28, the ratio data estimate that only 50 to 60 % of the supplied lava was present as surface flows. Through March, excess thermal radiance fell by 50 % as did SO$_2$ flux, consistent with an overall decrease in lava supply and the proportion of that lava erupted as surface flows; written records describe an overall decrease in surface activity through March, and in this feature space, the percentage of available lava emplaced as surface flows decreases to 30–50 %. During April, this percentage increases to 60–80 %, consistent with field observations of a new, advancing flow front. From May to September 2005, SO$_2$ measurements varied, sometimes significantly, but emitted radiance steadily decreased, indicating a systematic switch from surface flows to tube-fed flow, during which time field observations point to the preponderance of an established tube with minor breakouts. Excess radiance values finally bottomed out in September when effusion rate ratios estimate that ~90 % of the lava was accommodated within the tube system. Although during this period of time the qualitative summary of flow field condition we use here indicates that the flows were “all tubed,” nighttime MODIS data show that there was some lava still present on the surface for at least some of that month, possibly in the form of small breakouts on the ocean entry delta, which are common; weak surface activity was observed by the HVO through September.

There are other times within our study period when the trends are less evident or indiscernible, and we provide two

![Fig. 9 Diagram depicting the relationship between excess radiance, SO$_2$, and flow field characterizations. The dashed trajectory shows a very simplified scenario where an eruption begins as surface flows, establishes a tube system to the ocean, and eventually stops altogether.](image-url)
examples. Between September 2000 and April 2001, the flow field was observed to follow a cycle from a condition of advancing tube with surface flows, established tube with minor breakouts, completely tubed, eruption pause, and back to advancing tube with surface flows (Fig. 12). Such a cycle might be expected to show an observable change through time when contemporaneous SO$_2$ and thermal radiance observations are plotted. However, from September 23 to December 13, there were only three data points that had concurrent SO$_2$ measurements and clear-sky radiance values. As such, this may be a situation in which lack of data prevents a consistent pattern from emerging.

The period July 2007 to June 2008 illustrates the second case (Fig. 13). Here, the gross characteristics of the circular, clockwise, trajectory seen in the scatter plots of Fig. 9 are somewhat apparent. However, during a 7-month period (August 2007 to March 2008), there is
no consistent path discernible for the SO$_2$ and thermal radiance observations. In early to mid-July, both SO$_2$ and thermal radiance were extremely low following a pause in the eruption. SO$_2$ values spiked in late July followed by, but not concurrent with, a spike in thermal emission. This led to a calculated effusion rate ratio of $>1.0$, a case that is not typical at Kīlauea. From late August 2007 to mid-March 2008, the data showed high daily variations, resulting in no discernible pattern in terms of the calculated ratios. The scatter in these data and the effusion rate ratio of $>1$ could be produced if there was a lag time between magma degassing, which drives the SO$_2$ values, and the exposure of lava at the surface, which drives the thermal radiance values.

Alternatively, the low effusion rate ratio values that occurred in June 2007 (visible in Fig. 8) may have indicated that at least some shallow magma emplacement and degassing may have been taking place. Most likely, this shows that the physical processes occurring on the flow field are often more complicated than the very simple model we present in Fig. 9. Even clear-sky radiance values derived from satellite measurements can be modulated by many physical processes. During this period, for example, lava was mostly confined to perched lava ponds and rootless shields (Patrick and Orr 2011), situations that hide thermal energy from the satellite, and violate the assumptions of satellite-based effusion rate calculations.
Conclusions

By comparing satellite-derived thermal radiance measurements (a proxy for the abundance of surface lava flows) against the measured SO$_2$ flux (a proxy for the total amount of lava supplied to the flow field and ocean entries), we developed a semiquantitative framework for estimating the relative dominance of tube-fed vs. surface flows at Kīlauea volcano. Comparison of SO$_2$ and thermal flux with semiquantitative flow field observations support the notion that SO$_2$ and thermal radiance observations are correlated during periods when surface flows dominate in distributing lava within Kīlauea’s ERZ and that these two parameters become decoupled during periods when established tube systems dominate lava distribution. Attempts to place this relationship on a more quantitative footing met with limited success. Simple statistical clustering of the data provides some evidence that the SO$_2$ and thermal emission data do record transitions from purely surface flows to the establishment of an advancing tube system and from an unstable tube system showing major breakout to a more stable one that has only minor breakouts. However, the five discrete observational eruption categories (Table 1) do not appear to correspond to clear, unambiguous quantitative data fields. At least in part, this is due to the subjective nature of the observational classifications. Although one might expect to be able to trace the development of an eruption phase from an abundance of surface flows to an established tube system with few surface flows as a trajectory through an SO$_2$–thermal radiance feature space, this is not always possible either. Relating the data using effusion rates does not help, unfortunately, as the errors and uncertainties in the calculation of effusion rates from thermal radiance and SO$_2$ measurements may be as high as 50%.

Our results could be improved by leveraging more satellite assets to provide the necessary thermal radiance data, with more imaging opportunities serving to ameliorate the effects of clouds. At Kīlauea, in situ monitoring of SO$_2$ is also limited to days on which the northeast trades blow the plume across the path of the monitoring network (which happens for most, but not all, of the year). In particular, data with finer spatial resolution (e.g., <100 m resolution) would be of use in calibrating the low-resolution MODIS class radiance data and constraining the spatial distribution of surface flows. MODIS class (1 km spatial resolution) thermal radiance measurements acquired at ~24 h separation have been shown to scale well with those acquired by the Geostationary Operational Environmental Satellites (GOES) spacecraft (Koeppen et al. 2010), which is acquired with a temporal frequency of tens of minutes at 4 km spatial resolution. A suite of thermal radiance data acquired at high spatial resolution (i.e., <100 m) but low temporal resolution (once every 2 weeks) by sensors such as ASTER or the forthcoming Landsat Data Continuity Mission, combined with moderate and low spatial resolution data acquired by MODIS class and GOES class missions (at temporal frequencies of decamnutes to days), may allow the effects of cloud to be reduced (but obviously never eliminated). From this perspective, the proposed NASA HyspIRI mission may provide a useful bridge between these end-members: HyspIRI is proposed to acquire data once by night and once by day every 5 days at a spatial resolution of 60 m. At Kīlauea and other volcanoes, improved SO$_2$ emission rate retrieval could similarly be achieved through enhanced leveraging of satellite assets such as the Ozone Monitoring Instrument carried aboard NASA’s Aura spacecraft (e.g., Carn and Lopez 2011; Prata et al. 2013).
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