Thermal model of lava in Mt. Agung during December 2017 episodes derived from Integrated SENTINEL 2A and ASTER remote sensing datasets

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Thermal model of lava in Mt. Agung during December 2017 episodes derived from Integrated SENTINEL 2A and ASTER remote sensing datasets

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Abstract. In the beginning of December 2017, Mt. Agung eruption powered down to minor ash emissions and on the middle of December, aerial photographs of the crater were taken by Indonesia Centre of Volcanology and Geological Hazard Mitigation (PVMBG) showing a steadily growing lava occupying approximately one third of the crater. 3D digital elevation model (DEM) of crater were created by PVMBG during and before the eruption, corresponded to lava volume around 2 x 10^{-2} km^3 has been filled the crater. Here we present a method for deriving thermal model within the lava during eruption on 8 and 9 December 2017 using observations from multi infrared satellite SENTINEL 2A and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). We use Thermal Eruption Index (TEI) based on the Shortwave infrared (SWIR) on SENTINEL 2A and Thermal Infrared (TIR) on ASTER, allowing us to differentiate thermal domain within the lava. This study has successfully produced model of sub-pixel temperature (T_h), radiant flux (Φrad) and crust thickness model of lava (Δh). The subpixel temperature and radiant flux during the eruption is in the range 655 to 975 ^oC and 179 MW respectively. The crust thickness model of the lava in the range of 9 to 14 m and the total volume of lava crust during this period is estimated at 3 x 10^{-3} km^3. The combination of infrared satellite remote sensing data shows a potential for fast and efficient classification of difference thermal domains and derive thermal model of lava.

1. Introduction

On the middle of August 2017 seismic activity in Mt. Agung were increased and during the middle of September led PVMBG to incrementally raise the Alert Level from I to IV (lowest to highest) between 14 and 22 September 2017 [1,2]. The end of September through October 2017, Steam and gas emissions were observed 50-500 m above the summit with occasional bursts as high as 1,500 m [1,2]. Thermal observation by Middle InfraRed Observation of Volcanic Activity (MIROVA) using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite indicated increasing in volcanic radiant power [3] to peak of ~100 MW indicated effusion of lava into the summit crater at the end of November throughout December. Emissions continued, primarily comprised of steam and gas, with intermittent plumes of dense ash, rising to 2.5 km above the summit [1,2]. An overhead image of the summit crater of 16 December revealed that new lava had filled about one third of the crater with an estimated 2 x 10^{-2} km^3 of material (Figure 1a), since a similar aerial photo was taken on 20 October (Figure 2b). This eruption offers an opportunity to improve our understanding effusive activity in Mt. Agung using satellite-based remote sensing. Here we present a new approach based on integrated infrared satellite images to derive thermal model of lava during effusive activity in Mt. Agung. In this study we provide results from a shortwave infrared (SWIR) and thermal infrared (TIR) remotely-sensed data to estimate the thermal structures of active lava [4–7], radiant flux [6,8] and crust thickness [6,9,10].

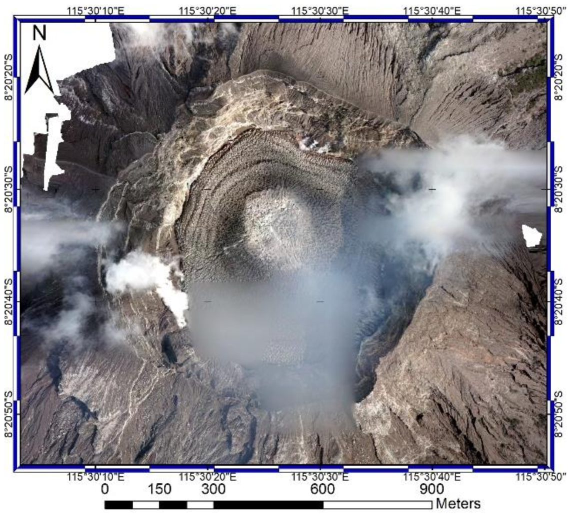

Figure 1a. Agung summit crater taken by AeroTerrascan and PVMBG on 16 December 2017 showed new lava filling about 1/3 of the crater with an estimated 2 x 10^{-2} km^3 of material [2].

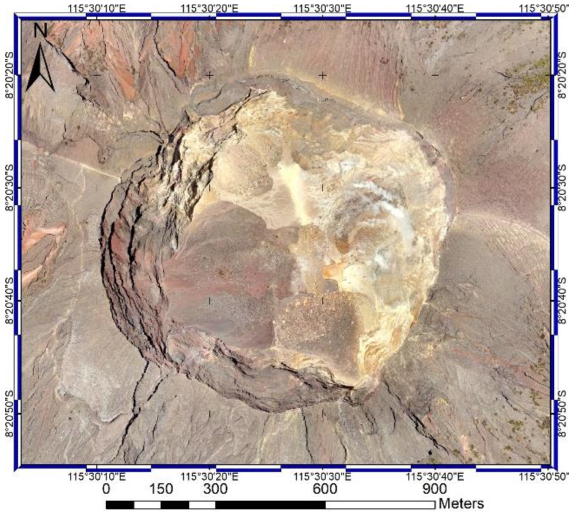

Figure 1b. Agung summit crater taken by AeroTerrascan and PVMBG on 20 October 2017 (before lava effusion) [2].

2. Data and Method

2.1 Datasets

Remote sensing observations were made using Sentinel 2A SWIR band 11 (1.61 µm) and ASTER TIR band 14 (10.95 - 11.65 µm) during 9 December and 8 December 2017 respectively. Acquisition dates are selected according to the availability and quality of data covering the effusive eruption period during December 2017, we only took the data where cloud coverage is minimal. The data is open access and can be downloaded from the Copernicus and U.S Geological survey (USGS) website (https://scihub.copernicus.eu/dhus/#/home and https://earthexplorer.usgs.gov). We resampled ASTER TIR spatial resolution to 20 m to level the resolution with SENTINEL 2A SWIR. Both images are subset into the Mt. Agung crater and then converted the satellite-recorded digital numbers (DN) to sensor radiance for both SWIR and TIR bands (Figure 2a and Figure 2b). Both of datasets were atmospheric corrected using MODTRAN model atmosphere [7,11].

2.2 Thermal Eruption Index (TEI)

In this study, we use the thermal eruption index (TEI), based on the SWIR and TIR as a threshold for differentiating between different thermal domains; and applying a dual-band method to estimate subpixel temperature within thermal domains and differentiating between the types of lava surface [6]. This index uses the square of the TIR spectral radiance (R_{TIR}) and the maximum of the SWIR (R_{SWIR}) spectral radiance to differentiate between the thermal domains [6]. TEI is expressed as

$$TEI = \frac{R_{SWIR} - \frac{(R_{TIR})^2}{10\, R_{SWIR\,MAX}}}{R_{SWIR} + \frac{(R_{TIR})^2}{10\, R_{SWIR\,MAX}}} \; \frac{(R_{TIR})^2}{(\frac{R_{SWIR\,MAX}}{3})^2} \tag{1}$$

where $R_{SWIR\,MAX}$ are the maximum spectral radiances (Wm^{-2} sr^{-1} m^{-1}) detected in SWIR. In the next step we applied the dual band method to automatically calculate the sub pixel temperature within the hotspot threshold (TEI > 0.10) [6].

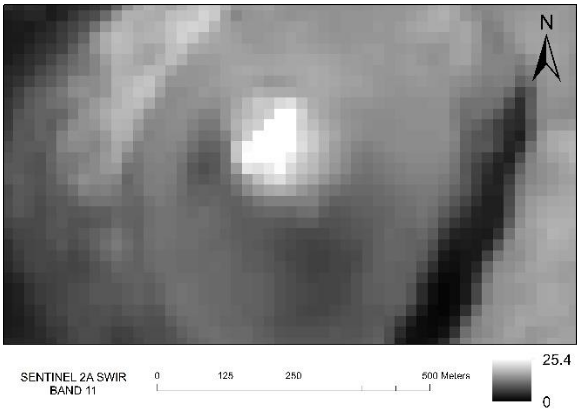

Figure 2a. Spectral radiance from SENTINEL 2A SWIR detects the emission of active lava in Mt. Agung during 9 December 2017.

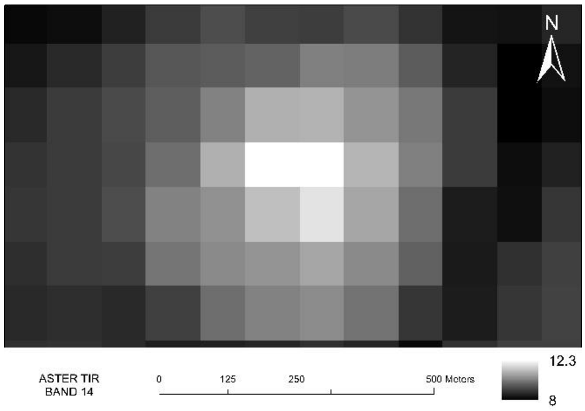

Figure 2b. Spectral radiance from ASTER TIR detects the emission of active lava in Mt. Agung during 8 December 2017.

2.3 Dual band method

In this method we use dual band method that involve a solution two distinct infrared bands (SWIR and TIR) to formulate a system of two equations from the simultaneous solution of the Planck equation in each band as shown below [12]:

$$R_{SWIR} = pR\left(\lambda_{SWIR,} T_h\right) + (1-p)R(\lambda_{SWIR}, T_c) \tag{2}$$

$$R_{TIR} = pR(\lambda_{TIR}, T_h) + (1-p)R(\lambda_{TIR}, T_c) \tag{3}$$

where p is pixel portion occupied by the hot component temperature; $R(\lambda, T_h)$ and $R(\lambda, T_c)$ are radiance emitted in a particular band by a surface at temperature T_h (hot component) or T_c (cool component). In this study we assumed T_c as the lowest brightness temperature detected in hotspot by band TIR [6] and then we solve p by iterating on T_h , until $p(\lambda_{TIR}) = p(\lambda_{SWIR,})$.

2.4 Radiant Flux Estimation

In this approach we use effective temperature model (T_e), which is the average surface temperature of lava for the two thermal component present on an active lava flow surface [6,13,14], as expressed

$$T_e = (p{T_h}^4 + (1-p){T_c}^4)^{1/4} \tag{4}$$

Following this model, the radiant flux (Φ_{rad}) for each pixel that contains lava can be estimated as

$$\Phi_{\text{rad}} = \varepsilon\sigma A{T_e}^4 \tag{5}$$

Where in Φ_{rad} radiant flux (W), σ is the Stefan- Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}) and A is the satellite pixel area, this case is 400 m^2.

2.5 Convective Flux Estimation

We calculate convective flux (Φ_{conv}) by assumed free convection case, where the heat transfer coefficient (h_c) values 5 W m^{-2} K^{-1} [7,10], this expressed as:

$$\Phi_{\text{conv}} = Ah_c(T_e - T_a) \tag{12}$$

T_a is the ambient air temperature that is unaffected by eruption processes, in this work we use T_a = 25 °C.

2.6 Crust thickness

In this study we calculate crust thickness model (Δh) by assuming that the conductive flux density across the surface crust is equal to the total of the radiative and convective flux densities leaving the same surface of lava (here we use andesite lava [15]), so that:

$$\text{M}_{\text{rad}} + \text{M}_{\text{conv}} = -\text{k}\,\frac{(T_i - T_e)}{\Delta h} \tag{13}$$

Then re-arranged for Δh:

$$\Delta\text{h} = -\text{k}\,\frac{T_i - T_e}{\text{M}_{\text{rad}} + \text{M}_{\text{conv}}} \tag{14}$$

where Δh is the crust thickness (m), M_{rad} and M_{conv} (W m^{-2}) are radiative and convective flux densities that acquired after dividing Φ_{rad} and Φ_{conv} by the pixel area A. that k is thermal conductivity, we use 2.6 Wm^{-1} K^{-1} as our input for andesite lava [16], and T_i use interior temperature for the andesite of lava, in this case we use 800 °C for the outside vent and 900 °C in the vent.

3 Results and Discussion

TEI detects hotspots in Mt. Agung crater within TEI > 0.10, in total 571 pixels (0.22 km^2) were detected as hotspot due to lava within range of 0.10 – 0.16 (Figure 3). These hotspot pixels are used for calculating sub pixel temperature, radiant flux and crust thickness.

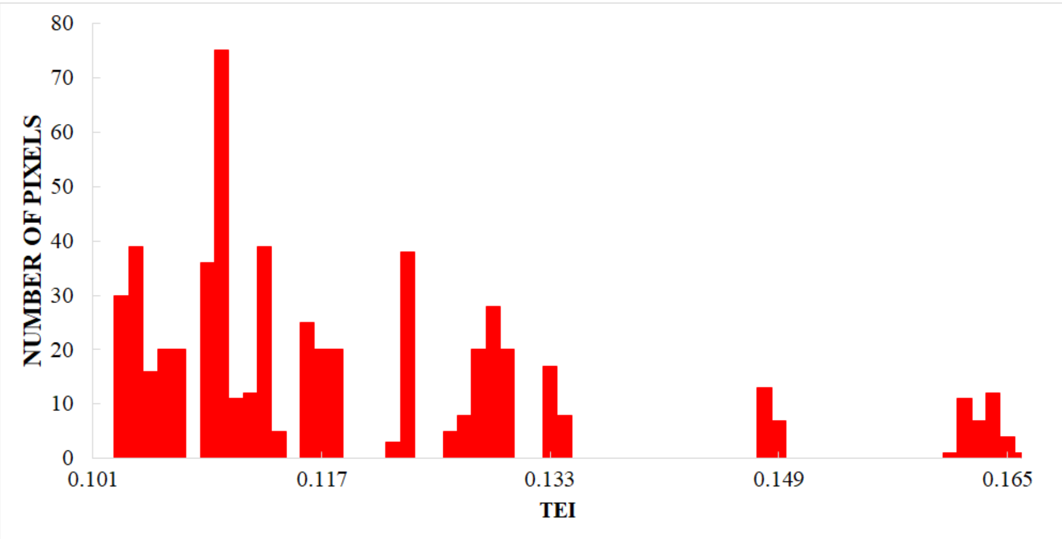

Figure 3. TEI distributions in Mt. Agung during 8 and 9 December 2017.

3.1 Spatial distribution of T_h, Φ_{rad} and Δh

Model of sub-pixel temperature (T_h), radiant flux (Φ_{rad}) and crust thickness model of lava (Δh) in Mt. Agung has been produce in this study. The subpixel temperature and radiant flux during the eruption is in the range 655 to 975 °C (Figure 4a) and 179 MW (Figure 4b) respectively. The highest T_h is in the central vent of Mt. Agung where lava come out. The result shows the range of T_h, are lower than 1000 ºC which is can be assumed as viscous lava, According to 1963 eruption of Mt. Agung the lava is basaltic andesite [15,17]. The total radiant flux from this technique shows a good agreement with MIROVA from MODIS satellite in December 2017 which is show the flux in the range ~ 10^7 W, although the radiant flux from SENTINEL 2A and ASTER show slightly overestimated due to higher spatial resolution that could lead to better sensitivity. Figure 5a show the crust thickness model of the lava in the range of 9 to 14 m and the total volume of lava crust during this period is estimated at 3 x 10^{-3} km^3. Figure 5b show the 2D cross section model of lava filled in the crater. On the 16 December 2017, PVMBG revealed that new lava had filled about one third of the crater with an estimated 2 x 10^{-2} km^3 of lava [2], This reveal that during this effusive period the lava in the crater has not completely cooled since there are still have fluid interior layer beneath the crust and this leads to smaller lava crust volume compared to total volume on 16 December 2017.

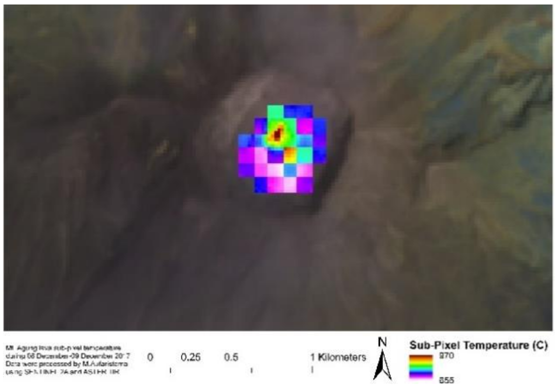

Figure 4a. Spatial distribution map of T_h during the effusive activity in Mt. Agung 8 and 9 December 2017.

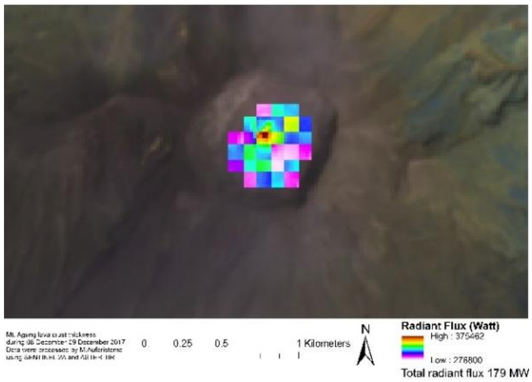

Figure 4b. Spatial distribution map of Φ_{rad} during the effusive activity in Mt. Agung 8 and 9 December 2017.

Figure 5a. Spatial distribution map of Δh during the effusive activity in Mt. Agung 8 and 9 December 2017.

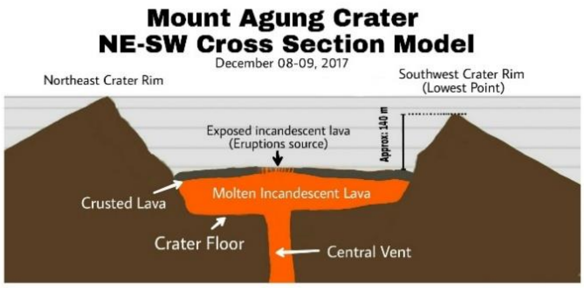

Figure 5b. 2D cross section model of Δh and lava filled in Mt. Agung crater of Φ_{rad} during 8 and 9 December 2017.

4 Conclusions

In this study we have been successfully produced the Model of sub-pixel temperature (T_h), radiant flux (Φ_{rad}) and crust thickness model of lava (Δh) in Mt. Agung during 8 and 9 December 2017. The subpixel temperature and radiant flux during the eruption is in the range 655 to 975 ºC and 179 MW respectively. The crust thickness model of the lava in the range of 9 to 14 m and the total volume of lava crust during this period is estimated at 3 x 10^{-3} km^3. The combination of SENTINEL 2A SWIR and ASTER TIR data shows a potential for fast and efficient classification of difference thermal domains and derive thermal model of lava.

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