Monitoring the spatial extent of thermal anomalies at Mount Erebus (Antarctica)

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Abstract. Volcanic thermal anomalies measured from space can vary in both size and intensity. These changes are directly related to heat loss from the Earth's surface, a process which is of critical importance to the dynamics of active volcanoes. We use a time series of multispectral thermal infrared images, acquired by the ASTER sensor throughout 2000-2009, to investigate the change in thermal anomalies at Mount Erebus (Antarctica) through time. Differences in the behaviour of low temperature anomalies and high temperature anomalies are observed. The more abundant, seasonally dependent, low temperature anomalies are associated with vaporous volcanic plumes and highlights that caution should be applied when interpreting low temperature anomalies as thermal precursors to eruptive events. The smaller, spatially more consistent, higher temperature anomalies are associated with an actively overturning lava lake and complement previous findings drawn from course resolution time series of the volcano. Measuring the size and intensity of volcanic thermal anomalies through time is possible because of the relatively high spatial and spectral resolution of the ASTER sensor and represents an innovative and useful contribution to volcano monitoring efforts. The methodology developed during this study is likely to facilitate the analysis of volcanic behaviour at other volcanoes as well.

Key words: Volcano, monitoring, ASTER, TIR

1. Introduction

Volcanoes are hazardous, non-linear systems and so require monitoring if timely forecasts of eruptive behaviour are to be given and if we are to improve our understanding of volcano dynamics. Ideally volcanologists would have access to information from all the world’s subaerial volcanoes, this way a greater understanding of fundamental volcanic processes can be used to contribute to the expert knowledge required to deal with specific volcanoes that may be endangering communities or property. Orbital remote sensing provides the necessary perspective to fulfil such an ideal and is often the only source of information available for volcanoes in remote and/or poorly funded locations. Therefore, whilst Mount Erebus does not pose a direct threat to a large urban population, its consistent volcanic activity and the arid environment in which it is situated offer an excellent site for developing remote sensing techniques for monitoring volcanoes.

The approach adopted in this study is to measure the temperature of Mount Erebus through time using multispectral thermal infrared (TIR) images from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), currently the only such sensor in orbit with moderate (< 100 m) spatial resolution available to the civilian community. Previous authors have utilized the reliability of terrestrial surface temperature estimates at these wavelengths to describe volcanic activity. The parameters used to quantify these observations have included the maximum pixel temperature (Ramsey and Dehn 2004, Vaughan and Hook 2006), the average crater temperature (Vaughan and Hook 2006) and the maximum pixel temperature above background (Ramsey and Dehn 2004, Pieri and Abrams 2005, Vaughan et al. 2008 and Carter et al. 2008). Although these thermal parameters were all shown to correlate with volcanic activity, they do not measure the actual size of the anomaly in space (Carter et al. 2008). We seek to measure both the intensity and size of thermal anomalies as well as determine how these anomalies change through time.

2. Study Area

Mount Erebus (77°32'S, 167 ° 10'E, 3794 m) is an alkaline intraplate stratovolcano situated on Ross Island, Antarctica. It contains one of the few permanent, terrestrial lava lakes. The phonolite lava lake is thought to be sustained by magma convection via a conduit leading to a reservoir at an as yet unknown depth (Kyle 1992). The first sighting of the volcano was in 1841 (Ross, 1847), with a lava lake having been observed in the active crater since 1972 (Giggenbach 1973).

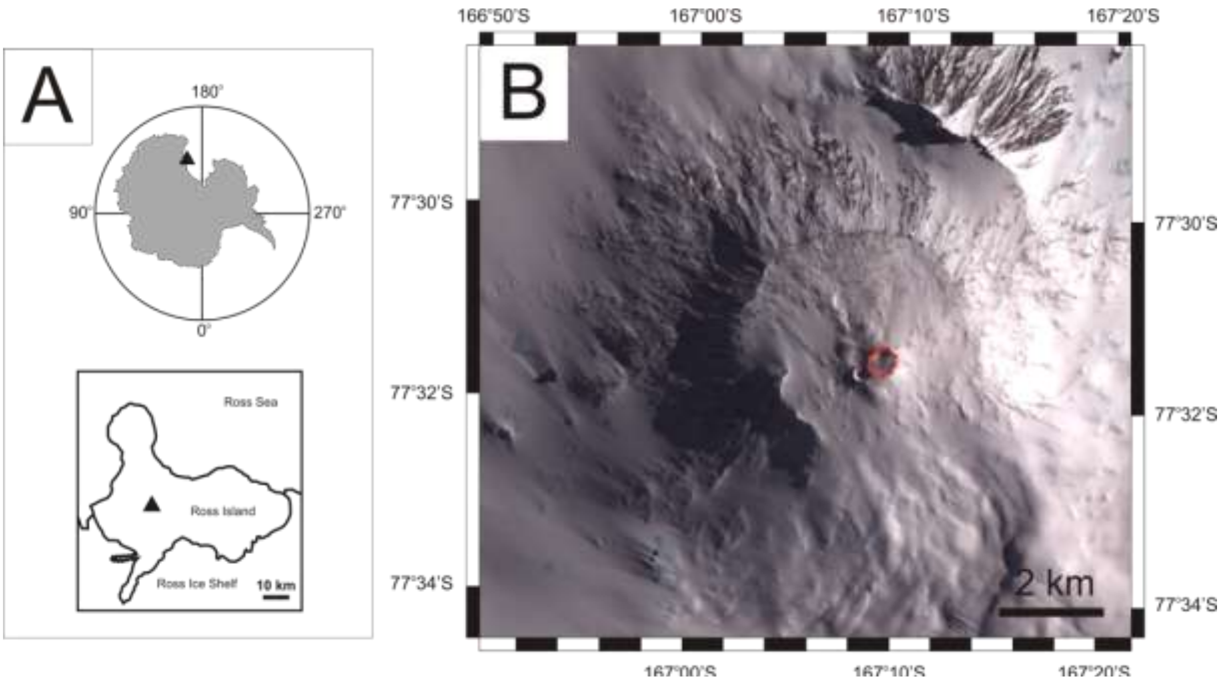

Figure 1. a) The location of Mount Erebus (Antarctica) and b) An ASTER VNIR image of the volcano with active crater highlighted (dashed line).

The volcano began its construction around 1.3 million years ago and is associated with crustal thinning and a possible mantle plume. The arid, polar climate in which the volcano is situated suppresses cloud cover and, coupled with the volcano's constant activity, make Mount Erebus an ideal target for developing space-based thermal monitoring techniques of active volcanoes (e.g. Harris et al. 1999, Davies et al. 2008, Wright & Pilger 2008, Vaughan et al. 2010)

3. Methodology

The ASTER sensor, onboard the Terra satellite, has been taking moderate resolution (90 m), multispectral thermal infrared images of the Earth's surface for just over a decade. These images consist of five spectral bands with wavelengths from 8.125 - 11.65 μm (Yamaguchi et al. 1998). ASTER also contains 4 visible to near infrared bands (VNIR) with 15 m resolution and stereoscopic viewing capability as well as 6 shortwave infrared bands (SWIR) with 30 m spatial resolution. The functioning life-span of the later set terminated in early 2008 due to degradation of the SWIR detector cooler system. ASTER scenes are available at various processing levels, these include: raw at-sensor radiance values (L1A) as well as geometrically and radiometrically corrected radiance values (L1B) which can be further corrected for atmospheric effects to give 'land-leaving' radiance values (L2).

In order to obtain a measure of multispectral, thermal infrared radiance leaving the Earth's surface this study uses the corresponding Level 2 data product (AST_09T). These images are converted into land surface temperatures using the Normalized Emissivity Method (Realmuto, 1990). The resulting surface temperature estimates are dependent, among other factors, on seasonal and diurnal cycles as well as potential volcanic activity. To suppress non-volcanic variations we convert pixel temperatures into temperatures above background, ΔT, using (1).

$$\Delta T_{i,j,k} = T_{i,j,k} - \left[\sum_{n=1}^{n} T_{i,j,k \in \beta_k} \right] / n \qquad (1)$$

where i and j are pixel coordinates, k is a scene identifier, T is the original temperature estimate and n is the number of pixels in the background area, β. The background temperature is therefore the average temperature of pixels within a background area of a given scene.

3.1. Background Temperatures

As land surface temperatures are not homogenous the background temperature is dependent on the size, shape and location of the background area. Previous studies of volcanic surface temperatures derived from ASTER TIR imagery have used manually selected areas often close to or directly surrounding hot pixels (e.g. Ramsey and Dehn 2004, Pieri and Abrams 2005, Hirn et al. 2008 and Vaughan 2010) or from larger areas (i.e. 50 by 50 pixel arrays) from neighbouring peaks (e.g. Carter et al. 2008). In order to process large numbers of scenes in an automated environment we define the background area as a ring that surrounds the active crater. This ring has an inner radius of 10 pixels (i.e. 900 m) and an outer radius of 15 pixels (i.e. 1350 m). The only volcanic products that reach such distances at Erebus are low density vaporous plumes. Such plumes are unlikely to affect background temperatures significantly as they are neither large nor hot enough. Even so we envisage that such a ring shaped area could still be employed at volcanoes in which eruptive products would significantly affect background temperatures (e.g. due to radial lava flows or large pyroclastic deposits) as long as the background area was automatically screened for thermally anomalous pixels (e.g. based on in-scene statistical analysis). A notable benefit of a ring-shaped background area is that it provides stability against heterogeneous topographic heating effects and thus provides the basis for the calculation of a reliable background temperature through time without the need for manual selection.

We plot the background temperature for all cloud-free scenes throughout 2000 and 2009 (Fig. 2). Images acquired during the day (red squares) tend to be hotter than images acquired at night (black crosses). Background temperatures display a clear seasonality, with higher temperatures towards the start of the year and lower temperatures towards the middle of the year. Erebus, which is situated in polar latitudes, undergoes one continuous period of light (i.e. the Austral Summer), from late October to mid February, with a day and night effect occurring only during spring and autumn, and the rest of the year spent in total darkness. Although Erebus therefore spends a prolonged period of time exposed to sunlight at the end of the year the limited solar angle (< 25^{o}) and high albedo of the persistent snow and ice cover results in minimal absorption of solar irradiance.

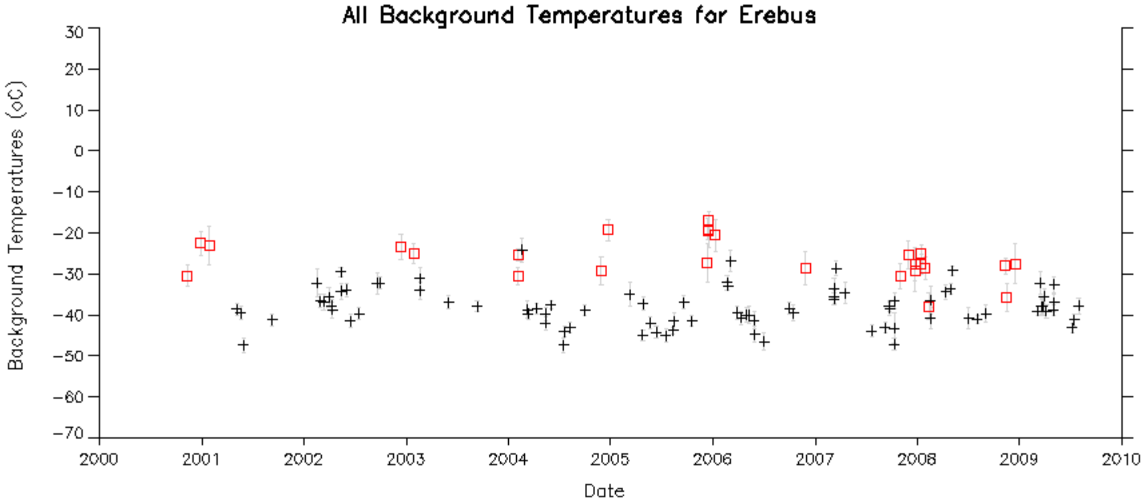

Figure 2. The background temperatures from Mount Erebus throughout 2000 to 2009. Red squares are daytime temperatures, black crosses are nighttime temperatures. Error bars are one standard deviation.

3.2. Anomalously Hot Pixels

Volcano monitoring is often based on attempting to distinguish anomalous behaviour from normal behaviour. With regards to volcanic temperatures it is necessary to define the point at which temperatures can be considered to be anomalously hot. The anomaly threshold used in this study is based on the natural variability within background temperatures by use of a two standard deviation limit. We find that 98.3% of background pixels fall within two standard deviations of the in-scene background temperature. Such an anomaly threshold will therefore provide a very low false alarm rate, which is a prerequisite for automated monitoring techniques.

The anomaly threshold could be defined on a scene by scene basis by using the respective standard deviation for that scene. However, to facilitate comparisons through time, we choose to fix the anomaly threshold using the maximum standard deviation in the time series (equation 2).

$$\Delta T_{anom} > 2\sigma_{\max} + \left[\sum_{n=1}^{n} T_{i,j,k \in \beta_k} \right] / n \qquad (2)$$

where ΔT_{anom} is an anomalously hot temperature above background and σ_{max} is the maximum background standard deviation in the time series. Furthermore, we separate daytime and nighttime series in order to facilitate subtle thermal anomaly detection in nighttime series. The maximum daytime and night-time standard deviations are 2.43 and 4.89, respectively. Therefore pixels would be considered anomalously hot if they exceeded the background temperature by 5.8^{o}C at night and 9.6^{o}C during the day. These values are similar to a previously reported threshold for ASTER derived measure of anomalous volcanic temperature (e.g. Pieri and Abrams 2005, Vaughan et al. 2008). This measure of anomaly accounts for the natural fluctuation within these data sets and describes a statistical limit beyond which we expect ΔTs to be volcanogenic.

3.3. Spatial Extent of Thermally Anomalous Regions

As we have defined an anomaly threshold it is possible to calculate the spatial extent of thermally anomalies in each scene. This could be executed in a simple binary fashion, i.e. pixels are either anomalous or they are not, however further information can be obtained by determining the frequency at which ΔTs fall within given temperature ranges (or 'bins'). The ASTER TIR bands will saturate at brightness temperatures of ~97^{o}C. The minimum recorded background temperature at Erebus during this time series is -52^{o}C. The maximum recordable temperature above background is therefore ~149^{o}C. Temperature bins have therefore been defined between the minimum anomalous ΔT and 150^{o}C above background (Table 1). These bins are wider at higher ΔT so as to avoid redundancy (i.e. bins which do not receive counts).

Table 1. The ranges of temperatures above background used to calculate the spatial extent of thermal anomalies.

Temperature Range (^{o}C)	bin width	intensity
100-150	50	extreme
60-100	40	high
40-60	20	moderate
20-40	20	moderate
T_{min}-20	10	low

4. Results

The spatial extent of thermal anomalies is represented as stacked frequency plots (Fig. 3). The 40-150^{o}C temperature ranges are plotted separately (Fig. 3a) from the more abundant lower temperature (< 40^{o}C) anomalies (Fig. 3b) so as to avoid visual compression. The area of these thermal anomalies is measured in both number of pixels (left y-axis) and in thousands of metres squared (right y-axis).

The higher temperature anomalies (ΔT > 60^{o}C) are fairly consistent, usually varying only between 2-4 pixels. This reflects the fact that Erebus contains an overturning lava lake which provides a consistent high temperature source with limited change in surface area through time. This is in agreement with previous studies (Wright and Pilger, 2008) that found little inter-annual variability in the thermal output from this volcano when using high temporal resolution (i.e. up to 4 revisits a day) but course spatial resolution (i.e. 1 km) data from the Moderate Resolution Imaging Spectroradiometer (MODIS). The small observed variations in high temperature anomalies for this ASTER data set may be due to fluctuations in i) the degree of sharing of the lava lake between up to 4 pixels, ii) the amount of incandescent material exposed at the time of image acquisition (i.e. due to bubble burst), iii) the extent and temperature of spatter around the lake and iv) the effect of fumes and aerosols on absorbing, scattering and/or emitting thermal radiation.

There are 15 separate occasions when not a single pixel is more than 40^{o}C above background and they are indicated by asterisks in Figure 3. This is notable because the lava lake at Erebus is thought to be a permanent feature. These scenes all occur between May and October during the polar winter. They may represent days when condensation of water vapour is particularly efficient in the active crater and consequently thick fumes of volcanic gases might develop and obscure the lava lake, alternatively they may be due to unforeseen meteorological conditions (e.g. snow blizzards). Complete solidification of the lake is possible although unlikely given that variations in ambient temperature (i.e. up to ~ 40°C peak difference between summer and winter temperatures; i.e. Fig. 2) are small compared to lava temperatures (i.e. crust temperatures of ~500°C and incandescent cracks ~1000°C; e.g. Calkins et al. 2008).

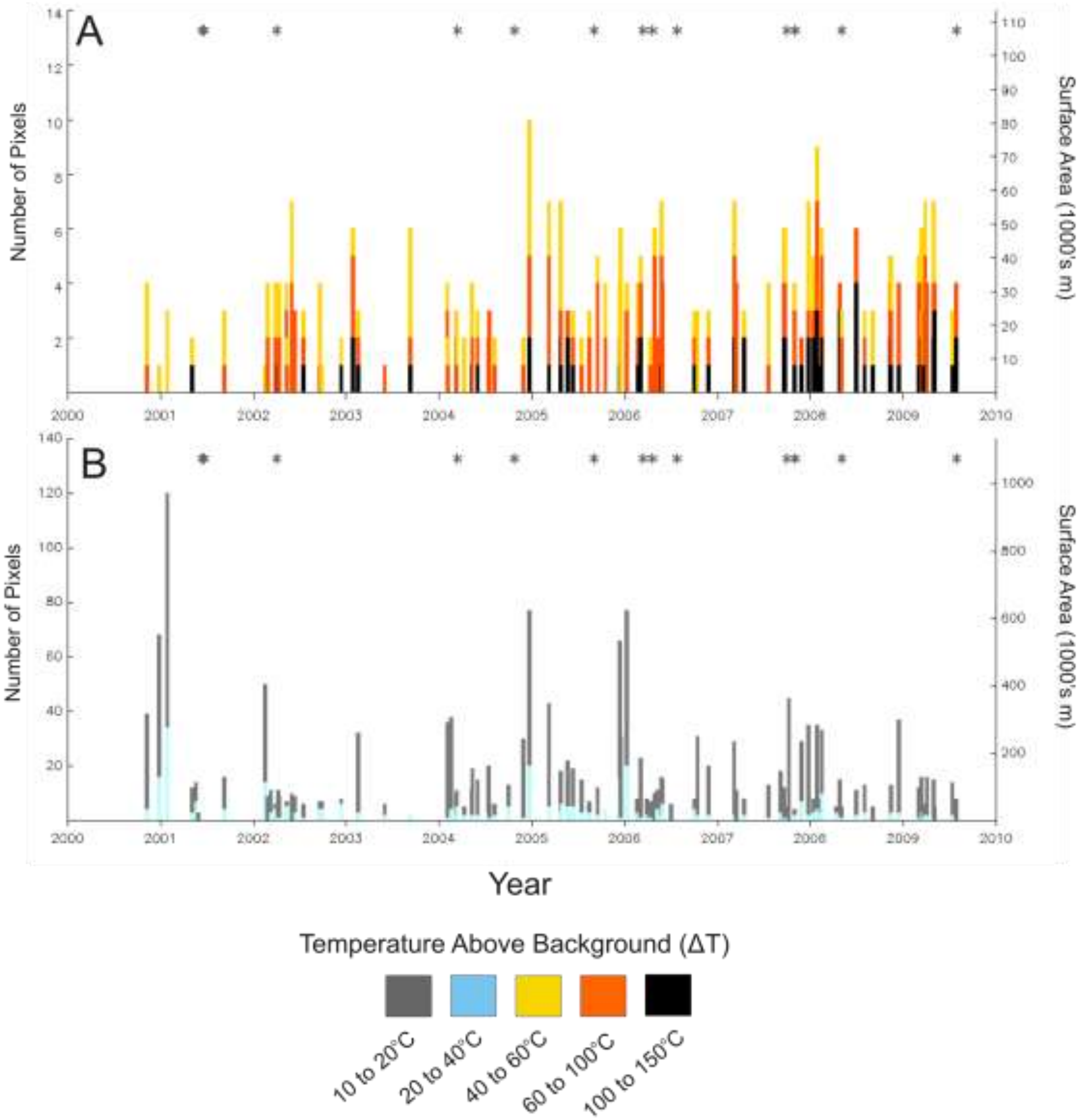

Figure 3. The spatial extent of thermal anomalies at Mount Erebus.

Low temperature anomalies at Erebus (Fig. 3b) display a strong dependence on solar irradiation with peaks occurring during the Austral Summer. It is unlikely that such peaks represent heterogeneous solar heating of the active crater given that most of this region remains in shadow due to the local relief and low solar angles at these latitudes. Instead we infer that these relatively large, low temperature anomalies are caused by the solar heating of volcanic plumes that are perhaps able to rise up into the sunlight. We note that, given the extreme aridity of the Antarctic climate, it is possible that solar radiation which is usually absorbed by atmospheric water vapour may be able to reach the plume in considerable abundance. This will perhaps allow such plumes to remain stable for longer periods of time and to expand across greater areas before eventually freezing and settling out. This seasonal dependence of low temperature thermal anomalies should be taken into consideration when looking for subtle thermal precursors to eruptive events as it is possible that solar irradiation can augment the temperature and/or size of vaporous plumes, especially in arid environments.

5. Discussion

Measuring the size and intensity of thermal features facilitates the quantitative analysis of volcanic scenes. This can be used to develop understanding of volcanic systems by direct observation, as in this study, or through incorporation into future probabilistic or physical models. These parameters can also be used in an automated processing environment. Future algorithms for volcanic activity detection may include searching for thermal anomalies which exceed a certain size and/or intensity. We note that such observations are only possible because of ASTER's combined spatial and spectral resolution.

The use of temperature as a measure of thermal activity is perhaps more compatible from one sensor to the other, as opposed to using spectral radiance or thermal heat flux for example, as wavebands may be situated at different wavelengths and may also have different spectral response functions. Facilitating comparison between different sensors is crucial for the development of global monitoring networks, which itself is necessary for the improvement in temporal resolution and response time required to react to potential volcanic crises.

6. Conclusion

We introduce the use of the spatial extent of anomalously hot pixel temperatures as a monitoring parameter of active volcanoes. This information was derived from orbital, multispectral, thermal infrared images of Erebus volcano acquired by the ASTER sensor between May 2000 and July 2009. The size and intensity of thermal features were used to interpret dynamic volcanic behaviour.

As the processing steps required to retrieve these observations can be fully automated, the spatial extent of thermal anomalies can be used as a parameter within a global monitoring network. This will aid in the rapid response to significant changes in volcanic activity, allowing effective warning times for hazards which may endanger communities and property.

7. Ackowledgements

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