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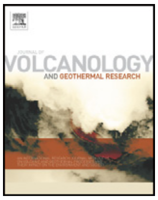

The influence of wind on the estimation of lava effusion rate from thermal remote-sensing

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ABSTRACT

Effusion rate is a key parameter to model lava flow advance and associated risks. Estimation of effusion rate from thermal remote-sensing using satellite data has matured to the point where it can be an operational monitoring tool, notably for volcanoes without a ground observatory. However, robust physical models, as required for quantitative interpretations, have not yet been adequately developed. The current and widely used method relates the satellite-measured radiated power to the flow effusion rate through the lava area, with an empirical fit that assumes a low surface cooling efficiency. Here we use novel fluid dynamic laboratory experiments and viscous flow theory to show that assuming low convective cooling at the surface of the flow leads to a systematic underestimation of the effusion rate. This result, obtained for the case of a hot isoviscous gravity current which cools as it flows, relies only on the respective efficiency of convection and radiation at the flow surface, and is independent of the details of the internal flow model. Applying this model to lava flows cooling under classical wind conditions, we find that the model compares well to data acquired on basaltic eruptions within the error bars corresponding to the uncertainties on natural wind conditions. Hence the thermal proxy deduced from the isoviscous model does not seem to require an additional fitting parameter accounting for internal flow processes such as crystallization. The predictions of the model are not correct however for thick lava flows such as highly viscous domes, because a thermal steady state is probably not reached for these flows. Furthermore, in the case of very large basaltic flows, extra cooling is expected due to self-induced convection currents. The increased efficiency of surface cooling for these large eruptions must be taken into account to avoid a gross – and dangerously misleading – underestimate of the effusion rate.

1. Introduction

A knowledge of magma discharge rate (effusion rate) is crucial for risk assessment on the flanks of a volcano (e.g. Guest et al., 1987; Ishihara et al., 1990; Vicari et al., 2009; Hérault et al., 2011), and is required to model, hence to anticipate, the advance of a lava flow during an effusive volcanic eruption (Walker, 1973; Griffiths, 2000). Effusion rate influences the regime of lava flow and cooling, with high effusion rates more likely to produce long, hazardous lava flow (Guest et al., 1987; Harris and Rowland, 2009). Retrieving the range and variation of effusion rate also brings information about the internal plumbing system of the volcano (Wadge, 1981). Gaining access to these key features requires the measurement or estimation of the effusion rate, as near as possible to real-time.

Effusion rate remains however an elusive parameter, hardly measurable in near real-time, and for which several proxies have been developed (see review in Harris et al. (2007)). Technologically advanced measurements using repeated plane-flown topographic surveys have been on occasion performed during a few eruptions on Mt. Etna (Coltelli et al., 2007; Favalli et al., 2010), but this remains costly and impractical as a general approach. One of the approaches currently most used to provide systematic quantitative measurements of effusion rate is thermal remote-sensing, exploiting satellite payloads. Since early pioneering studies (e.g. Glaze et al., 1989; Oppenheimer, 1991), this approach has steadily developed into a tool that has been used on several volcanoes (e.g. Harris et al., 2007; Spampinato et al., 2011). With respect to the more specific problem of real-time operational monitoring, a promising development has come with operation over the last few years of the SEVIRI payload on-board Meteosat (MSG2), which makes thermal radiance measurements every 15 min (Hirn et al., 2009; Ganci et al., 2012). For example, the *GMES-Downstream* project EVOSS makes operational use of SEVIRI to achieve continent-scale monitoring for countries with weak ground infrastructure that are nevertheless subject to serious volcanic risk (Ferrucci et al., 2013).

While thermal remote-sensing proxies are used as operational monitoring tools, there is still a need to better identify their limitations. Part of

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the uncertainty is related to the satellite measurement itself (e.g. Wright and Flynn, 2003; Ball and Pinkerton, 2006; Gouhier et al., 2012), and another part to the modeling and parameterization of the relationship between the thermal energy radiated at the surface of the flow and the flow rate (Dragoni and Tallarico, 2009; Harris and Baloga, 2009). In a previous study we have established a theoretical model relating the thermal structure of a hot isoviscous gravity current to its flow rate (Garel et al., 2012). This model gives one description of how the thermal evolution of the flow is controlled by the balance between heat advection within the flow, and heat lost at the surface by convection and radiation.

There are thus two major ways for improvement of the use of thermal-remote sensing techniques on lava flows: (1) more realistic modeling of heat advection within the flow (e.g. Filippucci et al. (2013)), with the possibility to take into account substrate geometries and complex rheologies with solidification, and (2) more precise description of effective heat loss at the surface of the flow by both radiation and convection in the air. The aim of the present paper is to quantify and discuss the effect of wind on lava flow cooling and on the resulting link between surface thermal signal and effusion rate.

2. Current thermal proxy

The thermal proxy in predominant current use is the time-independent model of Harris et al. (2007). Initially derived from a static heat budget for a lava flow that has stopped advancing (Pieri and Baloga, 1986), it was later applied to advancing lavas assuming that the heat losses at the surface and at the base of the lava flow are at all time balanced by the heat supplied by advection and crystallization (Harris et al., 1997), i.e. a kind of "frozen-time" approximation. This approximation is at odds with evidence for heat storage in the lava flow at the beginning of an eruption (Wooster et al., 1997). Nevertheless, Garel et al. (2012) have demonstrated that in the simple case of the spreading of a hot isoviscous, non-crystallizing fluid, initial heat storage in the current did not prevent the establishment of a thermal steady state after a transient period (during which the radiated power increased even though the input rate was constant). Hence this study established a first theoretical basis for the empirical relationship assuming proportionality between lava area and time-averaged effusion rate, which remains widely used (e.g. Wright et al., 2001; Harris et al., 2007; Harris and Baloga, 2009; Coppola et al., 2013).

The thermal proxy of Harris et al. (2007, 2010) is:

$$Q = \frac{\varepsilon\sigma\left(T_{top}^4 - T_a^4\right) + \lambda\left(T_{top} - T_a\right)}{c} A \tag{1}$$

with Q the effusion rate, A the lava flow area, ε the lava emissivity, σ the Stefan–Boltzmann constant, T_{top} the surface temperature of the lava flow, T_a the ambient temperature, λ the convective heat transfer coefficient (CHTC) that quantifies the convective cooling at the surface of the flow, and c a best-fit parameter, which should depend on the internal structure of the flow, on crystallization, on rheology and/or topography. The lava area A is derived from the satellite-measured power radiated by the flow assuming a range of possible surface temperatures (e.g. Wright et al. (2001)). The parameter c is defined by Harris et al. (1997) as $\rho(C_p \Delta T + \phi c_L)$, with ρ, ϕ, C_p, and c_L the lava density, crystal content, specific heat and latent heat of crystallization, respectively, and ΔT a temperature range (Harris et al., 2007, 2010). Note that Eq. (1) does not contain any reference to the flow dynamics (viscosity does not appear, for example). The detailed calculation of c remains controversial, as well as the physical justification of ΔT (Dragoni and Tallarico, 2009; Harris and Baloga, 2009). Recently, Coppola et al. (2013) introduced the global parameter of "radiant density" that integrates the influence of all control parameters into a unique best-fit coefficient given by the proportionality between lava area and effusion rate.

The maximal uncertainty on the calculation of the effusion rate from Eq. (1) is estimated around 50% (Harris et al., 2007). While significant, such an error is similar to the error on the estimate on average mass flux that might be achieved from ground-based measurements (Harris et al., 2007). The question remains however open about how the parameterization of surface cooling due to wind can introduce additional errors or can change the best-fit calculation in the estimation of effusion rate through Eq. (1). This issue is crucial for estimating uncertainties in the effusion rate calculation for poorly monitored volcanoes, considering that the best-fit relationship is established a posteriori (i.e. after the eruption).

We focus in the following on the influence of wind on the lava flows' thermal signature. All else being equal (effusion rate, topography, rheology) the influence of convective cooling depends only on the surface temperature of the flow and on the wind velocity, hence is independent of the treatment of the internal flow dynamics. We thus build on the theoretical and experimental model of Garel et al. (2012) to investigate quantitatively the influence of cooling by forced convection (wind).

3. Parameterization of convective cooling in the current thermal proxy

The rate of cooling of a lava flow with a surface temperature T_{top} occurs by radiation, which scales as $\varepsilon\sigma(T_{top}^4 - T_a^4)$, and by convection, either natural or forced by ambient winds, which scales as $\lambda(T_{top} - T_a)$. Radiation is the dominant heat transfer process when surface temperature T_{top} is still high. There is however a threshold surface temperature below which convection becomes the dominant heat loss process as the lava cools down (Head and Wilson, 1986; Keszthelyi et al., 2003). The surface temperature at which the two mechanisms switch roles as the dominant cooling process is higher for larger values of λ: 140, 300, 740 and 1010 °C for CHTC of 10, 20, 80 and 150 W m^{-2} K^{-1}, respectively, with an ambient temperature of 20 °C and an emissivity of 0.97.

In the absence of wind, natural convection (also called free convection) above the flow is driven by the buoyancy of the air heated by contact with the hot surface. For lava flows, the free CHTC λ has been theoretically estimated around 8–11 W m^{-2} K^{-1} (Keszthelyi and Denlinger, 1996; Neri, 1998). Most of the applications of the thermal proxy of Harris et al. (2007) use an average value of 10 W m^{-2} K^{-1}, i.e. implicitly assume only free convective cooling. However, wind (forced convection) is expected to increase the cooling rate at the surface of a lava flow (Neri, 1998).

This can be explained by a wind-induced thinning of the thermal boundary layer above the hot lava surface, which corresponds to larger CHTC λ, and which shows that contribution of ambient wind to convective cooling cannot be neglected a priori.

While the neglect of forced convection is likely to introduce a systematic bias on the estimation of eruption rates from the surface thermal signal of a lava flow, the rapid variations of wind in natural conditions (Keszthelyi et al., 2003) and the uncertainty on near real-time lava flow rate determination (Harris et al., 2007) make it difficult to provide a robust measurement of the convective cooling induced by ambient wind, hence of its quantitative consequences for the use of the thermal proxy. We thus perform laboratory experiments in controlled conditions to estimate the effect of forced convection on the surface thermal signal of a hot, viscous gravity current.

4. Experimental and theoretical investigation of wind-induced cooling

We measured the cooling of silicone oil, initially at a temperature T_0, spreading horizontally beneath air (at temperature $T_a < T_0$) onto a polystyrene plate, that is injected at a constant supply rate Q from a point source. A series of experiments with only natural convection in the air (i.e. no wind) was first performed with the set-up, and used to establish and validate a theoretical model for the cooling of an isoviscous gravity current (Garel et al., 2012). For the experiments used in this paper, we have added an additional experimental device blowing wind over the