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Eddy covariance measurements of hydrothermal heat flux at Solfatara volcano, Italy

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Abstract

The first measurements of volcanic/hydrothermal water vapor and heat flux using eddy covariance (EC) were made at Solfatara crater, Italy, June 8–25, 2001. Deployment at six different locations within the crater allowed areas of focused gas venting to be variably included in the measured flux. Turbulent (EC) fluxes of water vapor varied between 680 and 11 200 g H_2O m^{-2} d^{-1}. Heat fluxes varied diurnally with the solar input, and the volcanic component of sensible heat ranged from ~25 to 238 W m^{-2}. The highest measurements of both sensible and latent heat flux were made downwind of hot soil regions and degassing pools and during mid-day. The ratio of average volcanic heat (both latent and sensible) to CO_2 flux resulted in an equivalent H_2O/CO_2 flux ratio of 2.2 by weight, which reflects the deep source H_2O/CO_2 gas ratio. The amount latent heat flux/evaporation was determined to be consistent both with what would be expected from the magnitude of CO_2 fluxes and the fumarolic H_2O/CO_2 ratio, as well as with observed surface temperatures and wind speeds given a moist soil. This suggests that the water vapor that condenses in the shallow subsurface is remobilized at the soil–atmosphere interface through variable evaporation dependent on the deep heat flux and surface temperature. The results suggest that EC provides a quick and easy method to monitor average H_2O/CO_2 ratios continuously in volcanic regions, providing another important tool for volcanic hazards monitoring.

Keywords: eddy covariance; volcanic; heat flux; water vapor; hydrothermal; degassing; flux; emissions

1. Introduction

The majority of heat released from the Phlegrean Fields caldera is emitted at La Solfatara volcano. At Solfatara the H_2O/CO_2 ratio in volcanic emissions has been observed to be an effective parameter to monitor changes in the heat flow deep within the volcanic system. Increases in the H_2O/CO_2 ratio measured in Solfatara fumaroles, and consequently in heat transported from depth by water vapor, have been shown to correlate to periods of increased seismicity that occurred in Campi Flegrei since the 1970s [1]. Several of these periods of seismic unrest ('bradyseism') resulted in up to 1.5 m of uplift without any magmatic eruption. These periods are thought to be the result of injection of magmatic fluids into the hydrothermal system resulting first in uplift, and followed months later by increases in

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CO_2 relative to other gases. In the historic past, however, uplift has also been followed by an eruption, as was the case of the 1538 eruption at Monte Nuovo located within Campi Flegrei, where a volcanic eruption was preceded by several meters of uplift occurring over a few decades [2]. In all cases, seismic unrest and uplift is thought to be due to heat input at the base of the hydrothermal aquifer [1,2]. Thus, having the capability to measure the amount of heat and the average H_2O/CO_2 ratio continuously may provide more insight to magmatic processes at depth.

Recent studies have demonstrated that eddy covariance (EC) provides a reliable and complementary technique to ground-based studies for measuring diffuse and vent-released emissions of CO_2 in volcanic regions [3–5], but until now, spatially representative and continuous methods for monitoring H_2O and heat fluxes have not been tested. This paper builds on the previous work where CO_2 fluxes measured by EC were shown to compare well to ground-based measurements of flux, and proved to give representative measurements from regions containing degassing pools at Solfatara [4]. In this study we investigate if EC provides a viable technique for continuous monitoring of volcanic heat fluxes when measured coincident with CO_2 fluxes. Comparisons of EC measurements of heat and CO_2 fluxes with ground-based measurements of fluxes and fumarolic ratios of H_2O to CO_2 allow for interpretation of how heat and water vapor is transferred across the soil–atmosphere interface at Solfatara, and likely other hydrothermal regions.

In volcanic and hydrothermal systems, energy in the form of heat is transferred both conductively and convectively from deep magma chambers to the atmosphere. Heat transported convectively from depth (typically less than hundreds to thousands of meters) in the form of steam is typically orders of magnitude greater than the conductive heat transport. When rising steam reaches the surface, a portion of the steam condenses creating a heated condensate zone in the shallow subsurface. The remaining steam can be transferred to the atmosphere in the form of fumaroles or steam vents, and through bubbling hot-springs. In soils, vertical temperature gradients form in response to the condensation of steam beneath the relatively cool soil–atmosphere interface, and measurement of these gradients, albeit time consuming, can be used to determine the conductive component of volcanic heat flux [6–8]. While the convective heat loss is thought to occur mostly through fumaroles, recent studies have shown that convective heat transfer across the soil interface (i.e., diffusive steam flux) also occurs [6]. Primary steam loss (i.e., without condensation) could perhaps occur through microfractures in the soil, however secondary 'steam' loss is the result of evaporation at and below the soil surface.

Non-radiative surface heat fluxes can be quantified through above-ground micrometeorological methods. The surface heat budget can be expressed in terms of the energy conservation equation, $R=LE+H+G$, where R is the net radiation, L is the latent heat of evaporation, E is the evaporation or condensation rate, H is the sensible heat exchange between the ground and the atmosphere, and G is the sensible (or conductive) heat exchange between the surface and the subsurface (e.g., [9,10]). All terms in the heat budget are strongly affected by diurnal cycles of solar heating. Typically H and LE both increase during the day having maximums at mid-day when there is the greatest solar radiation (assuming there is sufficient surface water for evaporation) and act to transport heat away from the surface. In thermal areas like Solfatara, G is also principally directed toward the surface in response to subsurface thermal input and is minimally affected by solar variability below 20 cm depth (see also [6,8]). The magnitudes of the heat terms H and LE in thermal areas will have a component due to both solar heating, which is temporally variable, and a subsurface geothermal heat source, which is stationary on the timescale of measurement in this study. The geothermal heat is, however, spatially variable. Thus, the diurnal effect due to solar heating at any given time of the day can be assessed by comparing different sites across a thermal area at the same time.

Both H and LE are measured by EC based on the correlation of the fluctuations in vertical wind velocity with fluctuations of a scalar in the atmosphere (fluctuations are about the mean). In this study we investigate how H and LE measured by EC in a volcanic region relate to ground-based estimates of the volcanic heat flux, and their significance in understanding water vapor and heat transport across the soil surface.

2. Methods

2.1. Location

Solfatara was previously shown as an ideal site for continuous monitoring of volcanic CO_2 fluxes using EC [4]. The crater floor is flat (<1.5 m of relief over ~500 m), hosts a large area of intense diffuse degassing (0.5 km^2) and a few degassing pools (the Fangaia, Fig. 1). CO_2 fluxes and soil temperatures (including vertical temperature gradients) are periodically measured over a sampling array that covers 0.5 km^2 of the crater floor (Fig. 1), and CO_2 flux is measured hourly by