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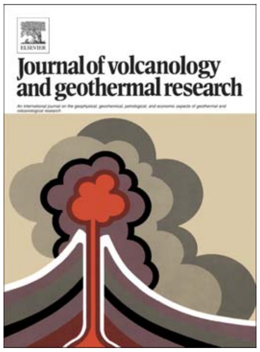

$SO_2$ flux from Stromboli during the 2007 eruption: Results from the FLAME network and traverse measurements

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PII: S0377-0273(08)00624-0
DOI: doi: 10.1016/j.jvolgeores.2008.11.025
Reference: VOLGEO 4196

To appear in: *Journal of Volcanology and Geothermal Research*

Received date: 14 April 2008
Accepted date: 19 November 2008

Please cite this article as: Burton, M.R., Caltabiano, T., Murè, F., Salerno, G., Randazzo, D., $SO_2$ flux from Stromboli during the 2007 eruption: Results from the FLAME network and traverse measurements, *Journal of Volcanology and Geothermal Research* (2008), doi: 10.1016/j.jvolgeores.2008.11.025

# $SO_2$ flux from Stromboli during the 2007 eruption: results from the FLAME network and traverse measurements

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## Abstract

$SO_2$ fluxes emitted by Stromboli during the 27th February – 2nd April 2007 effusive eruption were regularly measured both by an automatic network of scanning ultraviolet spectrometers and by traverse measurements conducted by boat and helicopter. The results from both methodologies agree reasonably well, providing a validation for the automatic flux calculations produced by the network. Approximately 22,000 tonnes of $SO_2$ were degassed during the course of the 35 day eruption at an average rate of 620 tonnes per day. Such a degassing rate is much higher than that normally observed (150-200 t/d), because the cross-sectional area occupied by ascending degassed magma is much greater than normal during the effusion, as descending, degassed magma that would normally occupy a large volume of the conduit is absent. We propose that the hydrostatically controlled magma level within Stromboli's conduit is the main control on eruptive activity, and that a high effusion rate led to the depressurisation of an intermediate magma reservoir, creating a decrease in the magma level until it dropped beneath the eruptive fissure, causing the rapid end of the eruption. A significant decrease in $SO_2$ flux was observed prior to a paroxysm on 15th March 2007, suggesting that choking of the gas flowing in the conduit may have induced a coalescence event, and consequent rapid ascent of gas and magma that produced the explosion.

## Introduction

Stromboli is the northernmost island of the Aeolian Archipelago, 100 km off the north coast of Sicily. The island is a 924 m tall stratocone volcano, which rests on the Tyrrhenian Sea floor at ~2000m below sea level. For ~2000 years, Stromboli has been characterized by persistent eruptive activity at the summit craters [e.g., *Mercalli*, 1881; *Barberi et al.*, 1974; *Rosi et al.*, 2000]. The eruptive style, that has become synonymous with the volcano, consists of intermittent explosions of incandescent lava fragments, bombs and scoriae, ejected up to a few hundred meters above the craters every ~10-20 minutes [*Barberi et al.*, 1993; *Rosi et al.*, 2000]. This strombolian activity is interrupted once or twice per year by larger major explosions, which can deposit material in areas where tourists observe the activity. Such explosions can draw from the deeper feeding system of Stromboli, producing a blond scoria [*Barberi et al.*, 1993] whose source is poorly crystallised magma that during ascent, degassing and crystallisation becomes the black scoria observed during normal explosive activity [*Bertagnini et al*., 2003]. On longer intervals the persistent eruptive activity has been interrupted by effusive eruptions [*Barberi et al.*, 1993], the last of which occurred in 2002/03 [*Landi et al.*, 2006]. The most intense explosions are observed rarely, and are termed 'paroxysms' in order to distinguish from the more frequent major explosions. The 5th April 2002/03 and 15th March 2007 explosions have been classed as paroxysmal due to the wide area covered by fall deposits.

The steady-state explosive activity is driven by the intermittent rise and bursting of gas slugs rising separately from their source melt 2-3km beneath the summit craters [*Ripepe et al.*, 2001; *Chouet et al*., 2003, *Burton et al*., 2007a]. Allard et al. [1994] estimated that explosive degassing is a minor contributor to the total gas flux, which is dominated by quiescent degassing.

Sulphur dioxide ($SO_2$) is one of the main magmatic volatile species released from Stromboli. $SO_2$ possesses a strong absorption band in the ultraviolet, measurable using scattered sunlight. For these reasons $SO_2$ is probably the most frequently measured volcanic species, and its study provides helpful indications on magma transfer processes in the shallow part of the volcano [*e.g., Allard et al.*, 1994; *Caltabiano et al.*, 1994; *Sutton et al.* 2001; *Fisher et al.* 2002; *Badalamenti et al.*, 2004, *Burton et al*., 2007]. Knowledge of the original sulphur content of Strombolian magma allows determination of the mass of magma required to produce observed $SO_2$ fluxes, and several papers have used this approach to constrain the magma supply rate at Stromboli (*Stoiber et al*, 1983, *Allard et al.*, 1994, *Francis et al*., 1993, *Burton et al*., 2007b).

$SO_2$ flux measurements have been performed sporadically on Stromboli using a Correlation Spectrometer (COSPEC) since 1975. These measurements demonstrate $SO_2$ fluxes fluctuated between ~ 130 - 1,500 tons per day (t $d^{-1}$), with mean values of ~300 t $d^{-1}$ [*Malinconico 1987*; *Allard et al.*, 1994; *Weibring et al.*, 1998, 2002; *Salerno et al.*, 2003]. The 2002/03 eruption of Stromboli (*Landi et al*., 2006) was carefully monitored using mini-DOAS spectrometers (*Burton et al*., submitted, *Galle et al*., 2003) and prompted the installation of a permanent network of automatic scanning ultraviolet spectrometers (*Burton et al*., 2004). This network has been fully operational since March 2004.

On 27th February 2007 a new effusive eruption began on Stromboli, after a period of elevated explosivity at the summit craters. The eruption ceased on the 2nd April 2007. During the eruption, and for 10 days after the cessation of activity, measurements of $SO_2$ flux were conducted with a mini-DOAS spectrometer in traverse mode, via boat and helicopter. These measurements were made alongside the scanning network measurements, that were performed before, during and after the eruption. In this paper we present and interpret the results of these $SO_2$ flux measurements.

## Methods

Traverse measurements of SO2 flux were collected during the 2007 Stromboli eruption using an Ocean Optics USB2000 spectrometer carried under the plume via boat whilst recording position with a GPS sensor. Data reduction was performed with a custom program which fitted the measured ultraviolet spectrum with a forward model spectrum in real-time during data collection, allowing the time series of recorded SO2 column amounts to be displayed during data acquisition. SO2 flux was determined by geometrically correcting the measured SO2 amounts such that they represented a cross-section orthogonal to the wind-direction, integrating the cross-section and multiplying with wind speed.

After the 2002/03 eruption of Stromboli a network of scanning ultraviolet spectrometers was installed on the island, with the objective of automatically measuring $SO_2$ fluxes from the summit craters. The FLux Automatic MEasurement (FLAME) network (Burton et al., 2004) began operation in 2004, with the installation of 4 scanners around Stromboli (see figure 1), connected via WiFi network to the main observatory in San Vincenzo. Each scanner consists of a Lantronix ethernet to serial convertor, a custom-made circuit board, a stepper motor driving a rotating head and an Ocean Optics USB2000 spectrometer, connected via 10cm fibre optic cable to a telescope that views a 45° angle ultraviolet-coated mirror in the rotating head. The entrance aperture was protected with a Hoya U330 filter to remove longer wavelengths.

The spectrometer was optimised for maximum optical throughput, with a wide slit of 500 microns, and a 4800 groove/cm grating tuned to 290-380 nm. This produced an instrument lineshape with 1.1nm full width at half maximum height for a monochromatic source. The telescope produced a field of view of 5mrad. The circuit board consisted of a microcontroller, programmed to allow control of either the stepper motor or the spectrometer. In this way, a control program running on a remote PC directly commands the scanner to alternately move the motor and then collect a spectrum.

The integration time and number of spectrum coadditions are specified by the control program. The stepper motor has 6000 steps in one rotation giving an angular resolution of 1mrad. Each measurement from a scanner consists of one dark spectrum, collected when viewing downwards, followed by a user-defined number of spectra collected between a user-defined angle range. The nominal setting for the FLAME (Flux Automatic Measurement) network on Stromboli was 60 spectra collected over 180°, from one horizon to the other.

Data reduction to $SO_2$ slant column amounts was performed using a custom-written program that utilised an artificial reference spectrum rather than a measured reference spectrum. Salerno et al. [2008] describe both the retrieval and its validation in detail. The main advantage of using an artificial reference spectrum is that retrieved $SO_2$ amounts are in absolute units, even if the entire arc of sky visible to the instrument contains volcanic gas; a fairly common occurence on Stromboli. Scans are converted in real-time to $SO_2$ slant column amounts, before being passed to a flux calculation program.

Flux determination from a network of ultraviolet scanners is a challenge. Many factors come into play, not all of which can be independently measured; the geometry and location of the plume, the wind speed, multiple scattering effects, in-scattering of light that has not passed through the plume. The original design of the network planned for two lines of measurements by paired scanners, in order to accurately define the plume height. This strategy was successfully used on Montserrat, BWI, (Edmonds et al., 2003) aided by a stable prevailing wind direction. On Stromboli, unfortunately, stable wind directions are a rarity. We found that the frequency of measurements in which only one station observed the complete plume and its pair observed only a partial side of the plume was high, and that well-constrained measurments were relatively rare for both paired scanners. Given the focus on monitoring we decided that the priority should be to maximise the probability of a plume measurement; changes in $SO_2$ flux are often of an order of magnitude, allowing us to accept the cost of slightly lower precision if there is a gain in the number of days we successfully constrain the $SO_2$ flux. This led us to adopt a new measurement strategy in which the flux was calculated using single stations, and the plume height determined by wind speed. Direct observations of the volcanic plume showed that when wind speed is low the plume can rise 100-200m above the crater terrace. In high winds the plume could be observed to be grounding. We used a combination of empirical comparison with traverse measurements and observations of pairs of scans from different stations that observed the same plume at various windspeeds to deduce a relationship between plume height and wind speed, with height decreasing as wind speed increased (see table 1). This then allowed us to greatly increase the frequency of measurements; even this strategy does not produce 100% coverage, on approximately 10% of days no plume is visible to the network, usually because the wind direction is unfavourable or because the plume has grounded due to high winds. The orientation of the scanners was changed in order be pointed directly away from the summit craters, such that when the plume was directly overhead scans were perpendicular to the plume direction.. Static measurements of $SO_2$ slant column amounts require projection onto either cartesian or polar coordinates in order to determine a cross-section. We found that using cartesian coordinates induced large randome errors, particularly when the plume was close to the horizion, due to the large projected distance between each slant column measurement. To avoid this problem we project the slant column amounts onto a polar coordinate geometry in which the radial distance to the plume is determined using the derived plume height and angle of maximum $SO_2$ concentration. This distance is then fixed for the whole scan and a cross-section can be readily determined.

From 2004 until November 2006 an anenometer at Vancori recorded windspeed data. From December 2006 until 25th March 2007 this anenometer malfunctioned, and we instead used data from the LAMI model (Limited Area Model Italy). This is a mesoscale forecast model nested in the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/). The model is calculated on a 7-km grid spacing with 35 vertical terrain-following levels every 3 hours, and produces a 48-h forecast once a day (Doms and Shattler, 1999; Cacciamani et al., 2002; http://www.cosmo-model.org). After 25th March a new anenometer was installed at Pizzo, on the north side of the summit, which is currently being used to provide wind data. Comparing the time series of measured winds with forecast winds calculated with LAMI shows a reasonable agreement in capturing the general trends in variation of the wind speed, but direct comparison shows a relatively poor correlation (see figure 2). It is clear that plume speed determinations remain the greatest source of uncertainty in $SO_2$ flux measurements; whilst typical errors for retrieved $SO_2$ amounts are up to 10%, fluxes have a higher estimated error of 25%. Error bars on network data presented here represent the standard deviation around a mean of all measurements during one day.

## Results

In figure 3 we present the results from the Stromboli FLAME network for the period 1st August 2006 until 31st October 2007. A major explosion was recorded with the INGV seismic network on 15th December 2006, preceded by a peak in $SO_2$ flux. There is a clear increase in the $SO_2$ flux visible from the beginning of 2007 until just before the eruption onset, when the $SO_2$ flux drops. During the eruption the $SO_2$ flux is highly elevated, averaging 700 t/d, about four times normal degassing rates. After the cessation of effusive activity on 2nd April the $SO_2$ flux decreased until 17th April, before a secondary burst of $SO_2$ was observed, which lasted until 25th May. After that date $SO_2$ fluxes maintained an average value slightly higher than the preeruptive level (220 t/d compared with 150 t/d), with some peaks up to 400 t/d. A total of 24,600 tonnes of $SO_2$ were released during the course of the eruption.

In figure 4 $SO_2$ fluxes measured ~contemporaneously with the FLAME network and traverses (both helicopter- and boat-borne) are plotted together and against one another. The general trends are comparable in the two time series; magnitudes are also in good agreement between the two time series. Errors due to plume height determination via the empirical wind speed approach also contribute to the discrepancies. Independently collected traverse data can therefore serve as a validation of our plume height derivation from wind speed approach.

Of particular note are the SO2 flux data collected on 14th and 15th March 2007, the day before and of the paroxysm. On 14th March two traverse measurements were conducted,at 09:00 and 15:00, producing fluxes of 950 and 920 respectively (all times GMT). On 15th March the plume was measured at 08:00 by the FLAMES network to be 832 t/d; this was followed by traverse measurements at at 09:40 (720 t/d) and at 15:30 (450 t/d), see figure 5. The 15th March 2007 paroxysm occurred at 20:03 less than 5 hours after the last traverse measurement. Thus we clearly observe a decreasing trend in SO2 flux in the hours preceding the paroxysmal event.

## Discussion

The basis for the interpretation of $SO_2$ flux variations during the 2007 eruption of Stromboli comes in part from the conceptual model of magma circulation proposed by Burton et al. (2007), in which upflowing, degassing magma produces percolation pathways along which gas can readily flow at faster ascent velocity than the ascending magma. Degassing magma is surrounded by an annulus of viscous, degassed magma, descending back down the conduit. This model's main advantages are explaining the relatively low vesicularity of eruption products, which would be much higher if gas and magma ascended together, and in constraining the relative velocity of degassed and degassing magmas that, together with gas flux data, allow a quantitative constraint to be placed on the diameter of the feeding conduit. The effect of an effusive eruption on this magma circulation is to remove the source of degassed magma; it erupts instead of flowing back down the conduit. This removal has the effect of effectively increasing the diamater of the conduit available to ascending magma. Burton et al. (GRL, in revision) proposed this model to explain the increased $SO_2$ flux observed during the 2002/03 eruption of Stromboli (*Ripepe et al*., 2005). They also proposed that one of the main controls on eruptive activity is the level of magma within the conduits; both the 2002/03 and 2007 eruptions were triggered when the level of magma was high in the volcanic conduits, producing vigorous explosive activity at the surface, and pressurising the superficial crater structures until failure occurred and lava could pour out (Burton et al., in press). The magma level is controlled by the balance between the pressure of the magma reservoir and the weight of magma in the conduit. The lower density of magma compared with host rock accounts for the elevated height of the magma column. Given this, the main controls on magma levels are magma density and reservoir pressure. It is clear that removal of degassed magma from the conduit during an effusive eruption not only increases the area available for ascending magma, but also decreases the average density of magma within the conduit system, a process that will augment the longer the effusion continues. The effect of the decrease in density is to increase the hydrostatic equilibrium level of magma in the conduit, however, if the conduit is breached then the effect is to sustain a prolonged effusive eruption, that can continue until the magma reservoir depressurises.

Observations reported by Bonaccorso et al., (2008) are fully consistent with this conceptual model. They observed a deflationary response from an intermediate depth of 2-3km beneath sea level (a zone which has previously been highlighted as a storage depth by petrological studies (*Francalanci et al*., 2005)), contemperaneously with the start of the lava effusion. The long-term stability of Stromboli’s explosive activity over many hundreds of years strongly suggests a very stable magma input rate. We propose that the observed deflation was therefore a response to a larger exiting magma flux from the intermediate reservoir compared with that entering the reservoir from below.

The 2007 eruption of Stromboli was much briefer than its 2002/03 eruption, lasting only 35 days compared with almost 6 months. The probable reason for this difference is that the magma removal rate was slightly lower in the 2002/03 eruption, as evidenced by a lower $SO_2$ flux compared with 2007 and volcanologically by a higher effusion rate in 2007, evidenced by lava flowing into the sea for at least 10 days after the eruption onset. A broad conclusion of this discussion would therefore be that low effusion rate eruptions at Stromboli may well have much longer durations than high effusion rate eruptions.

The high degassing rate observed during the eruption evidences two coupled processes; (i) a wider area of ascending magma due to the lack of degassed magma; (ii) deeper extension of permeable networks of vesicles (Burton et al., 2007b), due to the reduced average density of magma in the column. Extension of the permeable network to greater depths allows a larger volume of magma to contribute to the gas emission observed at the surface, however, if that gas supply is reduced due to a decompression of the deeper feeding system (as evidenced by the observed deflation during the eruption, Bonaccorso et al., 2008) then the permeable network may become unstable. We speculate that rapidly reducing gas flow through a permeable bubble network may induce a collapse of that network and production of localised zones of highly vesiculated magma that may coalesce into gas slugs. These may then rise rapidly from depth and induce the observed paroxysm.

We propose therefore that the decrease in $SO_2$ flux on 15th March prior to the paroxysm was an indicator of the collapse of the permeable network, that produced stranded vesicle-rich pockets of magma at depth that could then coalesce and produce fast rising gas slugs, leading to the explosion.

Finally, interpolating the $SO_2$ flux data to include the few days when data was not collected allows us to estimate the total amount of gas released during the course of the 35 day effusive eruption from 27th February to 2nd April 2007. This total is 24,600 tonnes of $SO_2$, released at an average rate of appoximately 700 t/d. Assuming complete degassing of magma that originally contained 0.2 wt% S (Bertagini et al., 2003) each tonne of released $SO_2$ implies the complete degassing of 250 tonnes of magma, and therefore our observations imply degassing of 250 x 22,000 = $5.5\text{x}10^6$ tonnes of magma. Landi et al. [this issue] measured the vesicularity of lavas erupted during the 2007 eruption and found an average vesicularity of 14% ± 3% for eight samples, utiltising a methodology that could not accurately measure vesicles with diameter <50 micron. Assuming a degassed magma density of 2700 $\text{kgm}^{-3}$, this vesicularity would produce lava with an average density of 2320 $\text{kgm}^{-3}$. If all the magma that degassed was also erupted then the effusion would therefore have produced $5.5\text{x}10^6$ x 1000 / 2320 = 2.37 million $m^3$ of vesiculated lavas. In order to compare this degassed lava volume with measurements of the eruption deposit volume we must take account of two additional factors. Firstly, the volume of degassed magma resident in the shallow plumbing system must be included, as this flowed out at the start of the eruption. Estimates from the 2002/03 indicate that ~2 million $m^3$ of lava effusion was sourced by the initial outflow of resident degassed magma [Landi et al., 2006]. Secondly, during emplacement lava flows will contain large scale voids, due to the compound nature of the deposits, increasing the apparent volume compared with the net ~4.4 million $m^3$ calculated by summing degassed lava and resident degassed magma. Marsella et al., (this issue) report an erupted deposit volume of 11 million m$^3$, approximately double that determined here. This discrepancy suggests that either voids occupy ~60% of the deposit or that much more lava was erupted than was degassed.

We note that while $SO_2$ fluxes increased rapidly at eruption onset, the return to background degassing levels took much longer. This is probably due to a slow resumption of the flow of sinking degassed magma as the shallow plumbing system refilled. The reduced flow rate of degassed magma allowed a larger than normal cross-sectional area to be occupied with ascending magma, sustaining higher gas fluxes for several months after the cessation of eruptive activity.

## Conclusions

The 2007 eruption of Stromboli allowed us to test both the FLAME network and our theories of magma dynamics at Stromboli during both quiescent and eruptive periods. Measurements of $SO_2$ flux conducted with the network agree reasonably well with measurements made with traditional traverse methods. The elevated $SO_2$ fluxes observed during the eruption are the result of an effective increase in the area of the conduit occupied by ascending magma, an increase afforded by the absence of degassed magma that is erupted instead of sinking slowly back down the conduit, as is normally the case. We propose that the higher output rate of magma from an intermediate magma reservoir outpaced the long term input rate, leading to deflation and rapid cessation of effusive activity. The level of magma within the conduit system exerts a dominant control on the nature of volcanic activity at Stromboli, and is controlled by the balance between the pressure within the magma reservoir and the weight of the magma column supported by that pressure. Reservoir pressure and magma density are therefore critical parameters in understanding Stromboli's behaviour. The decrease in $SO_2$ flux preceding the 15th March 2007 paroxysm may have catalysed the collapse of gas percolation pathways into a major coalescence event, powering the rapid ascent of gas and magma from depth that caused the paroxysm. Degassing measurements, combined with geophysical studies, can give unique insights into Stromboli's behaviour. The capability of the FLAME network to automatically monitor $SO_2$ flux is therefore a major step forward in our ability to comprehend Stromboli.

## Acknowledgements

We are greatly indebted to the Dipartimento di Protezione Civile for their multifarious support, and to Franco Barberi, Roberto Scandone and Mauro Rosi for stimulating discussions during the course of the eruption. Alessandro Bonaccorso assisted greatly by facilitating rapid administrative responses to dynamic situations during the eruption. We also wish to acknowledge the generous and fruitful collaboration with our colleagues from all over INGV and from Italian universities and institutions who participated in the eruption with us. Scientific discussions with Alessandro Aiuppa, Patrick Allard and Maurizio Ripepe are gratefully acknowledged in particular. We thank the helicopter pilots without whom our work would have been impossible. Support from DPC projects and the EC NOVAC project were critical to the development of the concepts presented here. Finally we acknowledge Roberto Scandone for producing this special issue on the 2007 eruption of Stromboli.

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## Figure Captions

Figure 1: Image of Stromboli volcano viewed from the Northeast with ultraviolet scanning stations indicated, as well as WiFi radio communication paths. COA is the main observatory building on Stromboli where the PC which directly controls the UV scanners is kept. Meteorological data reported here was measured at Pizzo. The island is approximately 5km long (NE-SW) and 3km wide (NW-SE).

Figure 2: Comparison of wind speed data from LAMI model and measurements at Pizzo, (a) Time series showing the trends in both series (b) The two datasets plotted against one another.

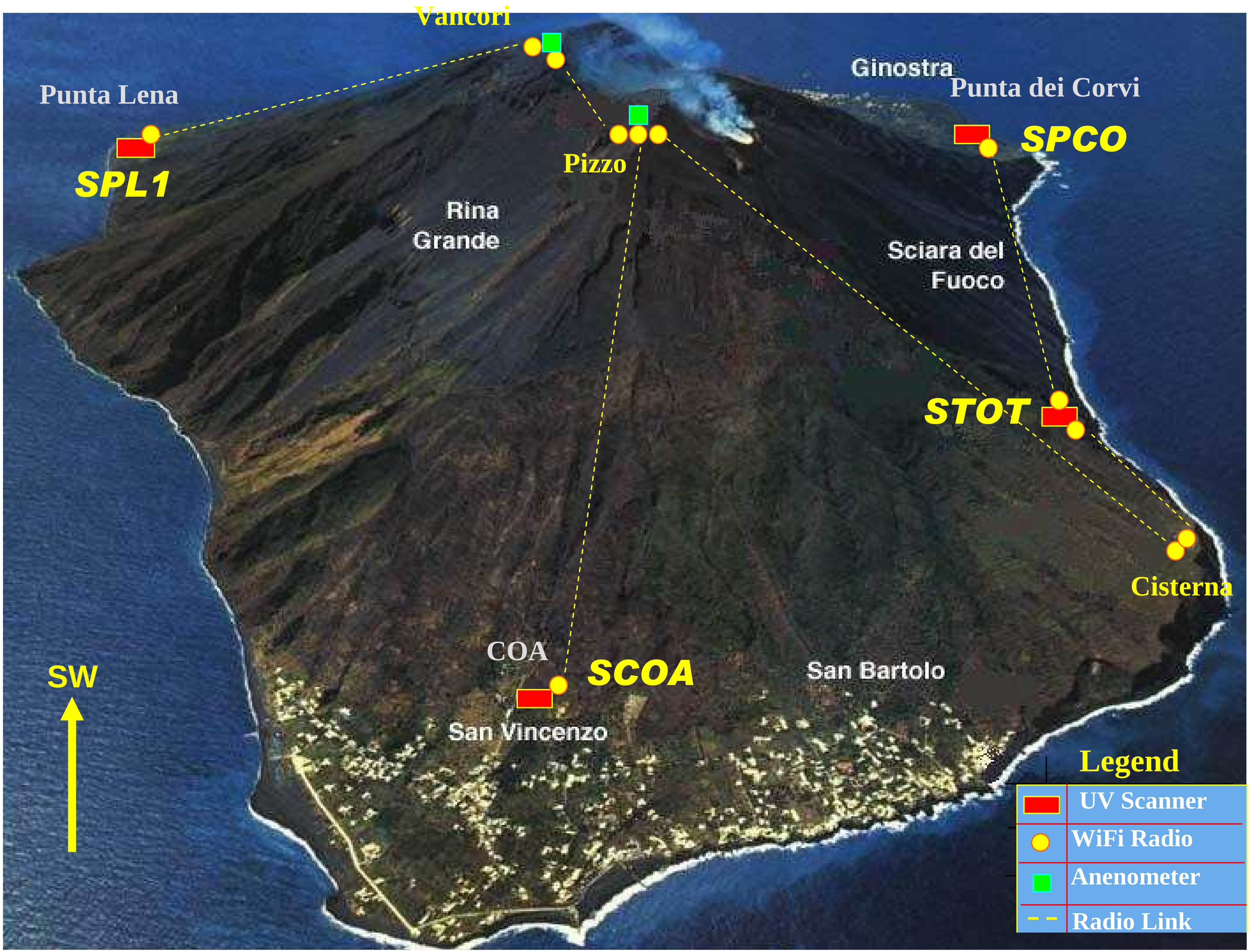
Figure 3: Average daily $SO_2$ flux from Stromboli, measured with the FLAME network. Error bars indicate the standard deviation of measurements collected during each day. Shaded area indicates the 2007 eruption.

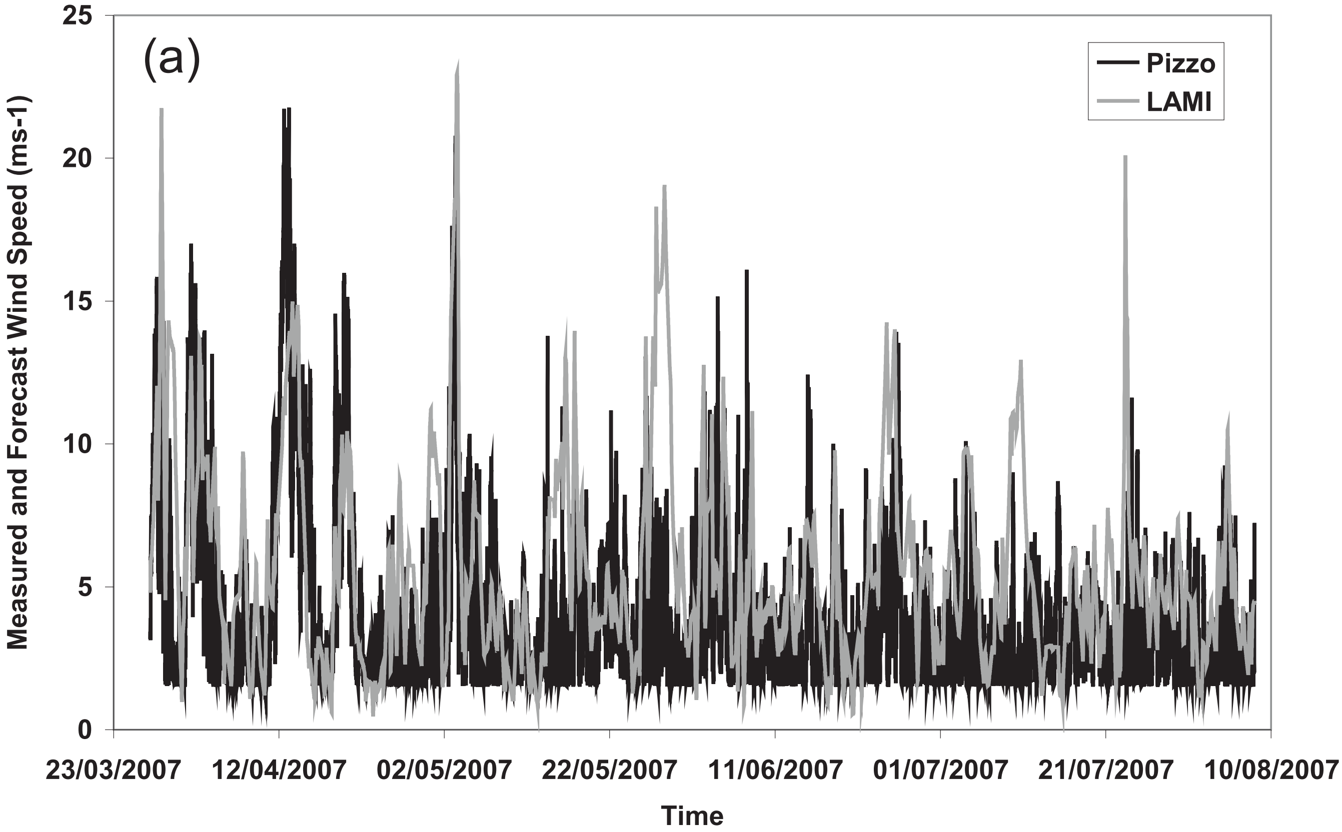
Figure 4: Comparison of $SO_2$ flux data collected with the FLAMES network and traverse methods: (a) Time series of SO2 fluxes collected utiltising both methodologies; (b) Network flux plotted against traverse flux. Each network data point is the flux measured closest in time to the traverses. Error bars are ±25%.

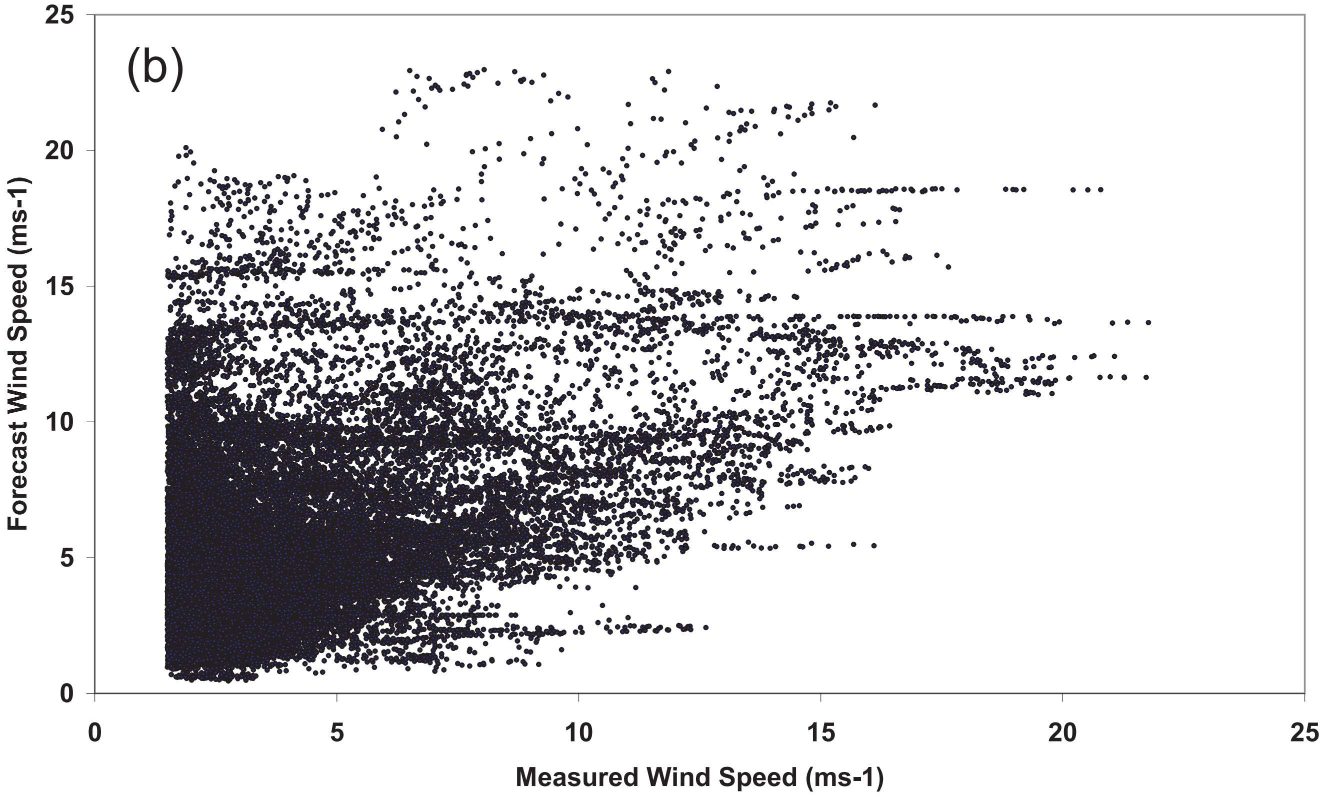
Figure 5: Variation of $SO_2$ flux measured with traverses and the network on 15th March, prior to the paroxysm at 20:03 GMT.

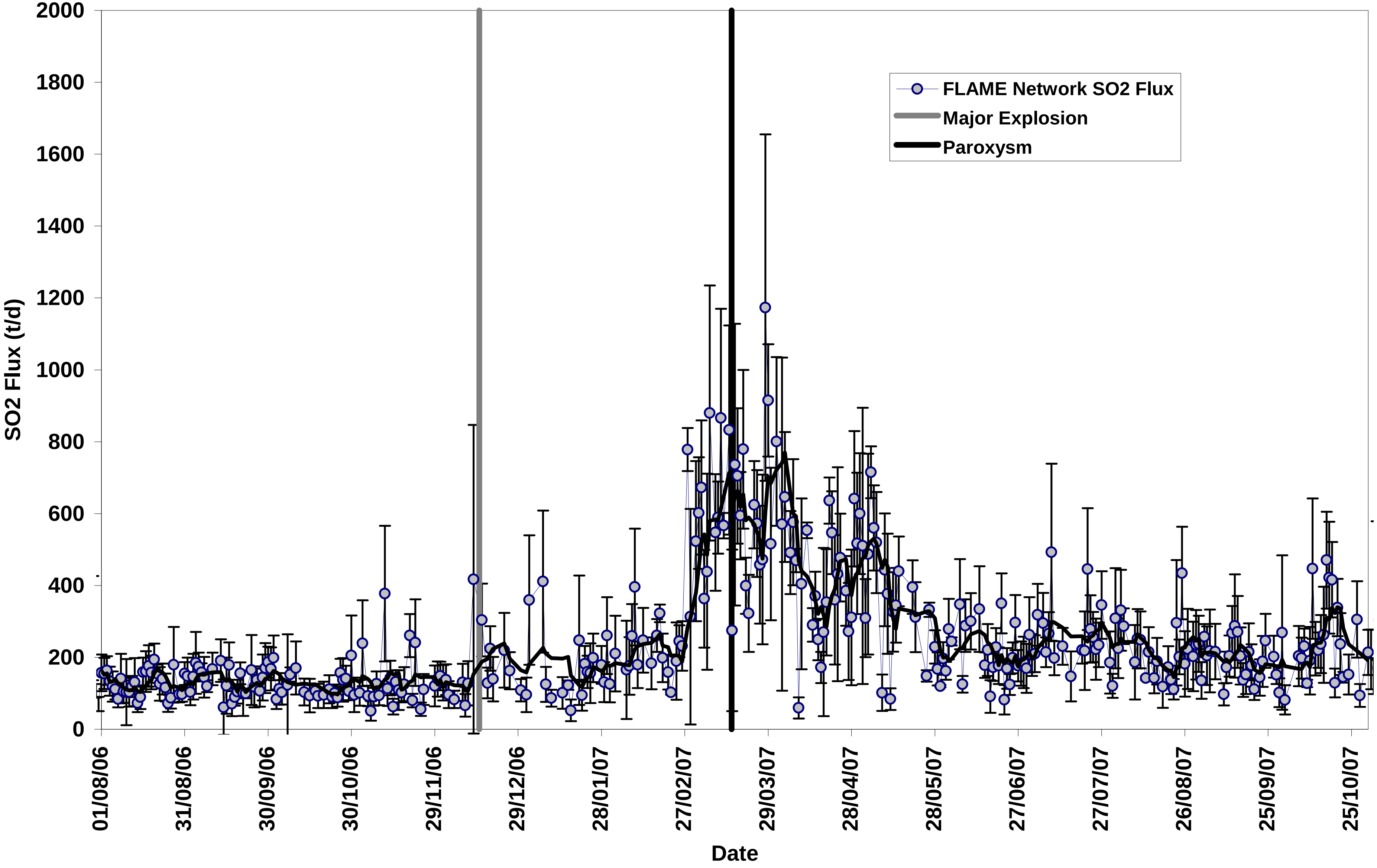
Table 1: Plume height estimates from wind speeds

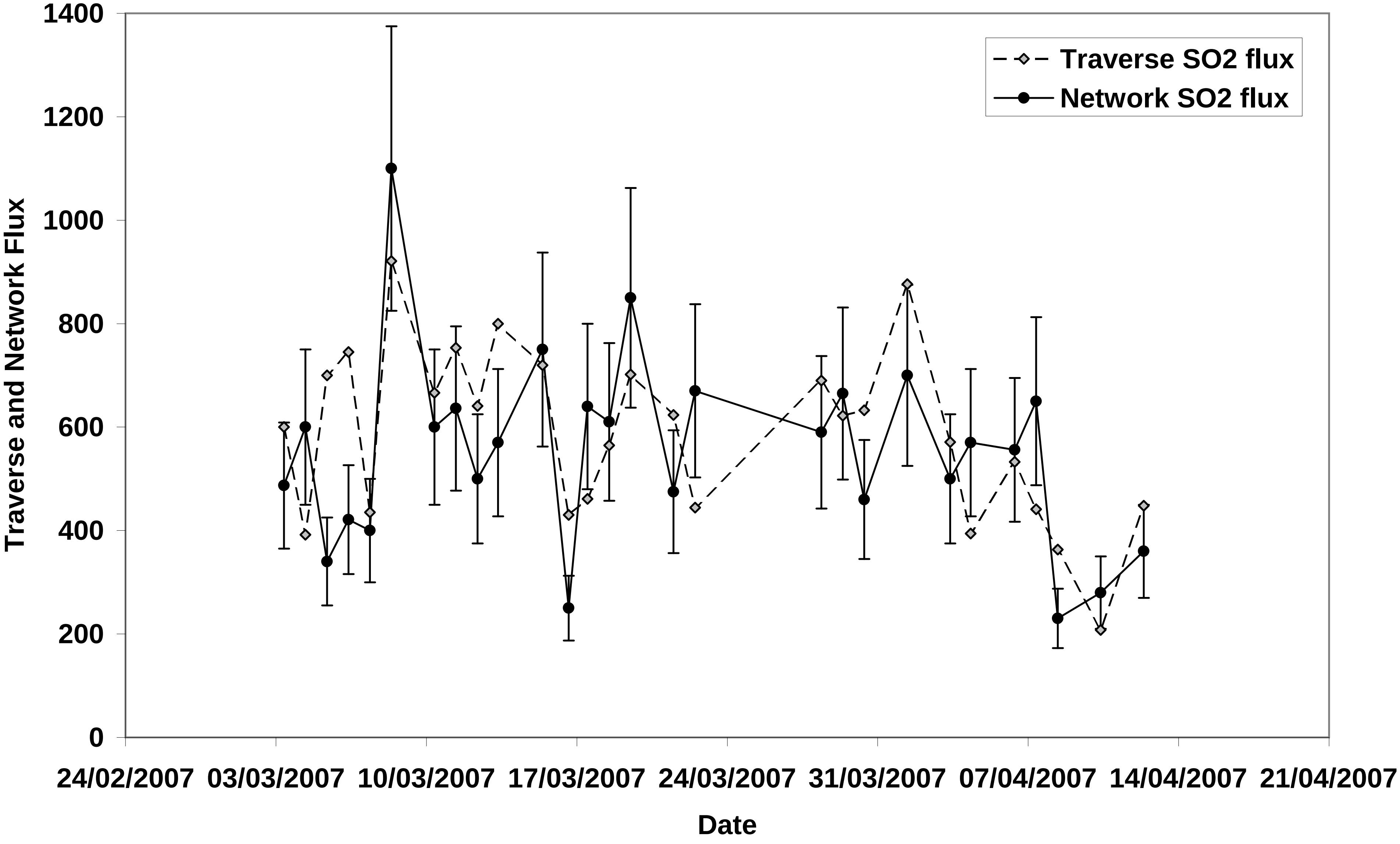
| Wind Speed ($ms^{-1}$) | Plume Height (m) |
|---|---|
| 2 | 900 |
| 4 | 700 |
| 6 | 500 |
| 8 | 450 |
| 10 | 300 |
| 15 | 200 |
| 20 | 150 |
| 20+ | 100 |

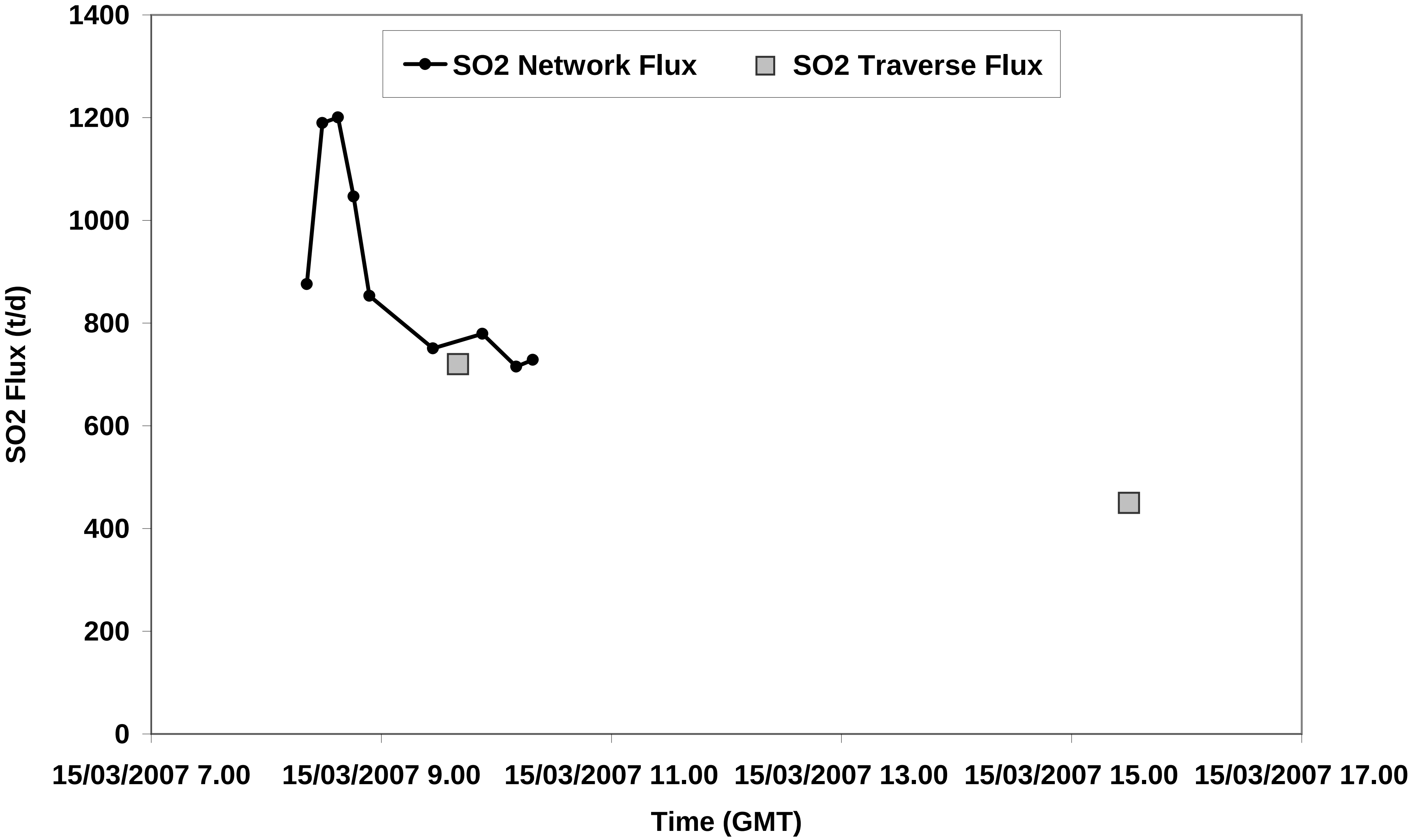

Vancori
Punta Lena
Ginostra
Punta dei Corvi
Pizzo
SPCO
SPL1
Rina
Grande
Sciara del
Fuoco
STOT
Cisterna
COA
SCOA
San Bartolo
SW
San Vincenzo
Legend
UV Scanner
WiFi Radio
Anenometer
Radio Link


(a)
Pizzo
LAMI
Measured and Forecast Wind Speed (ms-1)
0
5
10
15
20
25
23/03/2007
12/04/2007
02/05/2007
22/05/2007
11/06/2007
01/07/2007
21/07/2007
10/08/2007
Time


(b)
Forecast Wind Speed (ms-1)
0
5
10
15
20
25
0
5
10
15
20
25
Measured Wind Speed (ms-1)


2000
1800
1600
1400
1200
1000
800
600
400
200
0
SO2 Flux (t/d)
01/08/06
31/08/06
30/09/06
30/10/06
29/11/06
29/12/06
28/01/07
27/02/07
29/03/07
28/04/07
28/05/07
27/06/07
27/07/07
26/08/07
25/09/07
25/10/07
Date
FLAME Network SO2 Flux
Major Explosion
Paroxysm


Traverse SO2 flux
Network SO2 flux
Traverse and Network Flux
1400
1200
1000
800
600
400
200
0
24/02/2007
03/03/2007
10/03/2007
17/03/2007
24/03/2007
31/03/2007
07/04/2007
14/04/2007
21/04/2007
Date


SO2 Network Flux
SO2 Traverse Flux
SO2 Flux (t/d)
0
200
400
600
800
1000
1200
1400
15/03/2007 7.00
15/03/2007 9.00
15/03/2007 11.00
15/03/2007 13.00
15/03/2007 15.00
15/03/2007 17.00
Time (GMT)