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Rainfall-induced volcanic activity on Montserrat

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[1] Dome-forming volcanic eruptions cyclically extrude bodies of lava over several months, which then become gravitationally unstable and collapse, generating pyroclastic flows. On 29 July 2001 extreme rainfall over Montserrat coincided with a major collapse of the Soufrière Hills lava dome. We present rainfall and seismic records that demonstrate, for the first time, a relationship between intense rainfall and lava dome collapse, with associated pyroclastic flow generation. After seven months of little rain and a period of sustained dome growth, the onset of intense rain was followed within hours by dome collapse and pyroclastic flows. The large-scale weather system responsible for the rain was identifiable in satellite images and predicted by meteorological forecasts issued 60 hours prior to the volcanic activity. It is suggested that weather prediction of intense rainfall be incorporated with existing geophysical and geochemical measurements to improve warnings of these hazardous events. *INDEX TERMS:* 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 7280 Seismology: Volcanology seismology (8419); 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280); 8409 Volcanology: Atmospheric effects (0370)

1. Introduction

[2] Of the approximately 1500 active or potentially active volcanoes in the world [*Simkin and Siebert*, 1994], about 45% lie in the Tropics [*Pareschi*, 1996], and are thus particularly prone to high intensity precipitation from both localised convective storms and larger scale synoptic tropical weather systems such as hurricanes [*Gray*, 1979]. Such synoptic systems have shown a recent increase in number and strength that is predicted to continue into the future as a consequence of natural decadal climate variability [*Goldenberg et al.*, 2001].

[3] The Soufrière Hills volcano on the Caribbean island of Montserrat (16°N, 62°W) has been active since July 1995 [*Young et al.*, 1998] up to the present day and the course of the eruption has been well documented [*Geophys. Res. Lett.*, special sections, 1998; *Kokelaar and Druitt*, 2002]. Montserrat is a relatively small island (15 × 8 km) and the volcano is 5 km across, rising to a height of 1 km (Figure 1a). Since 1995, pyroclastic flows [*Cole et al.*, 1998; *Ui et al.*, 1999] have caused 22 fatalities and together with lahars [*Vallance*, 2000] have caused extensive damage to property. A statistical link has been previously noted between explosive volcanic activity at Mount St. Helens and meteorological conditions [*Mastin*, 1994]. However, no data have yet been published showing an unequivocal link between volcanic dome collapses and extreme precipitation.

[4] A dense network of tipping-bucket rain gauges with a one-minute temporal resolution was deployed on Montserrat in January 2001 (Figure 1a). The resulting continuous data have been supplemented by daily rainfall totals from four pre-existing rain gauges operated by the Department For International Development (DFID) since December 1998.

2. The 29 July 2001 Dome Collapse

[5] The volcanic dome collapse of 29 July 2001 was preceded by approximately 16 months of near-continuous dome growth [*MVO*, 2001]. Since the previous wet season, which ended in December 2000, the largest daily rainfall total at the Montserrat Volcano Observatory (MVO) was only 20 mm on 16 June 2001 (Figures 1b, 1c) and no lahars had been recorded. Hence the volcanic system was primed both for a major dome collapse with attendant pyroclastic flows and for lahars. The trigger arrived on 29 July 2001, in the form of a synoptic-scale easterly wave weather system [*Reed et al.*, 1977]. A total of 86 mm of rain was recorded at the MVO (Figure 1c), with similar values at other stations. These were by far the highest daily totals in the 7-month record from the tipping-bucket gauges.

[6] The meteorological situation during this period was examined using GOES geostationary satellite infra-red (IR) images (Figure 2) produced by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) [*Nieman et al.*, 1997]. Low values of IR (light shading) correspond to regions of cold, deep, precipitating convective clouds [*Arkin and Ardanuy*, 1989]. The winds at different levels are inferred from the cloud drift between successive IR images at 3-hour intervals.

[7] At 0200 local time (GMT – 4 hours) on 28 July 2001, 24 hours before the rainfall started on Montserrat and almost 48 hours before the dome collapse, a developing easterly wave could be seen in the low-level cloud-drift winds (Figure 2a) to the east of the Lesser Antilles with its axis running north–south at approximately 48°E. The low-level flow was east-northeasterly ahead (to the west) of the axis, easterly along the axis, and east-southeasterly behind (to the east) of the axis. Associated with the wave, there was scattered deep convection, mainly to the west of the wave axis. A day later, at 0200 on 29 July, the easterly wave had moved westward and strengthened considerably (Figure 2b). A large region of organised deep convection had developed within the wave, the leading edge of which had just reached

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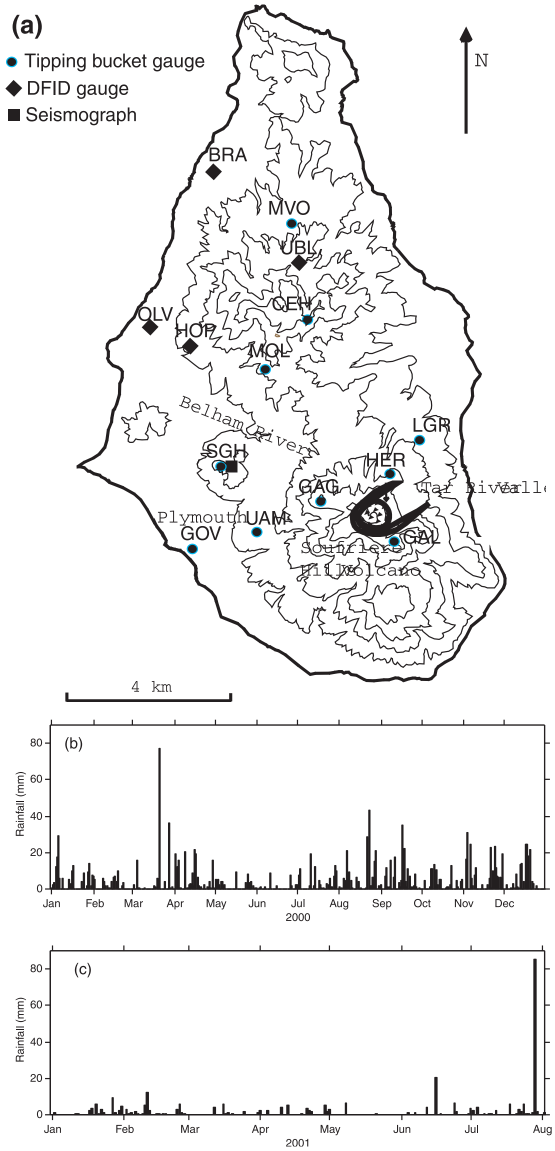

Figure 1. (a) Map of Montserrat, with height contours at 150 m interval. Locations of the tipping-bucket gauges are shown by circles, and of the DFID gauges by diamonds. The location of the St. George's Hill seismograph is shown by the black square. Daily rainfall totals at (b) Hope for 2000, and (c) MVO for January–August 2001. Tick marks correspond to the first day of the month. The locations of the gauges are marked HOP and MVO, respectively, in (a).

Montserrat. During 29 July, the system moved slowly westward and strengthened further. At 1700, Montserrat lay within the region of most extensive convective clouds (Figure 2c); by 2300 the system had moved further westward, leaving Montserrat behind (Figure 2d).

[8] The development of this tropical system was captured by the United Kingdom Met Office weather forecast. The 2.5 day forecast valid at 0800 Montserrat time on 29 July 2001 shows a low pressure centre at 16°N, 58°W (Figure 3a). This coincides with the observed tropical disturbance in the satellite images in Figures 2b, 2c, although the exact longitudinal position differs slightly. The system can be traced back as a westward-propagating low pressure anomaly that was located at 40°W at the start of the forecast 2.5 days earlier (Figure 3b).

[9] The rainfall during 29 July at the four tipping-bucket stations for which data have been reliably retrieved (see Figure 1a for locations) started around 0215 (Figure 4a), coincident with the arrival of the large area of organised deep convective clouds within the easterly wave (Figure 2b). There were three bursts of rain of increasing intensity up to 0630, totalling about 20 mm, at high sustained (10-minute average) rainfall rates of up to 0.8 mm minute^{-1} (Figure 4b) with peak instantaneous rates up to 1.8 mm minute^{-1}. Lahars were reported in the Belham Valley during this period of rainfall. They were also detected by the seismograph at St. George's Hill (see Figure 1a for location) as a sustained

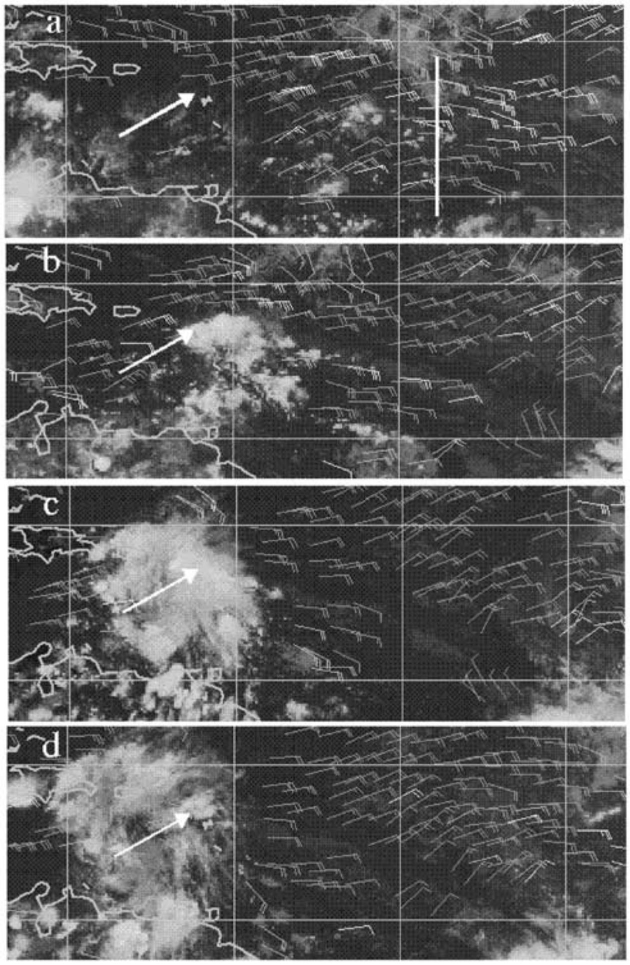

Figure 2. GOES-8 IR satellite images and low-level cloud-drift winds for the tropical North Atlantic region: (a) 0200 Montserrat time 28 July 2001, (b) 0200 29 July 2001, (c) 1700 29 July 2001, (d) 2300 29 July 2001. Low IR values are coloured lightly. Cloud-drift wind vectors are shown for the lower troposphere. The wind speed is shown by the number of barbs on the vector tail; each full barb corresponds to 10 knots, and a half barb to 5 knots. The axis of the easterly wave is indicated by a white line in (a). The images are overlayed by a 10° longitude ×10° latitude grid and the location of Montserrat (16°N, 62°W) is indicated by a white arrow.

increase in signal amplitude between 0200 and 0400 and a short-lived pulse of activity at 0530 coincident with the start of the third burst of rain.

[10] A second period of significant rainfall started at 1000 (Figures 4a and 4b), and this also coincided with an increase in the seismic signal (Figure 4c), although there were no visual reports of lahars at this time. This rainfall peaked at around 1400 with up to 18 mm of rain in one hour, and the lahar seismic signal peaked shortly before 1600, when this period of rainfall ended. There were visual reports of lahars from 1500 onwards, peaking between 1600 and 1700.

[11] The heaviest and most intense period of rain was from 1700 to 2000 (Figures 4a and 4b), consistent with the satellite imagery (Figure 2c). There were sustained 10-minute average rainfall rates of up to 1.1 mm minute^{-1}, with peak instantaneous values up to 2.0 mm minute^{-1}. During this period, pyroclastic flows were observed in the Tar River Valley and detected by the seismic network (Figure 4c). As the seismic signal generated by the pyroclastic flows is an order of magnitude larger than that of the corresponding lahar signals (note the logarithmic scale in Figure 4c), lahars cannot be detected from the seismic data during pyroclastic flows. At 1950, immediately after the final burst of intense rainfall at St. George's Hill, which is the closest rain gauge to the volcano for which data was retrieved, the dome collapse escalated with a large pyroclastic flow and associated surge cloud that moved eastwards over the sea (Figure 4c). This was followed by fallout of ash and lithic and pumiceous rock fragments (up to 6 cm in length) over the inhabited northwest part of the island. The rainfall intensity diminished rapidly and stopped at 2300, as the convectively active region of the easterly wave moved away to the west (Figure 2d). Pyroclastic flow activity continued, with a second major event at 2204, that

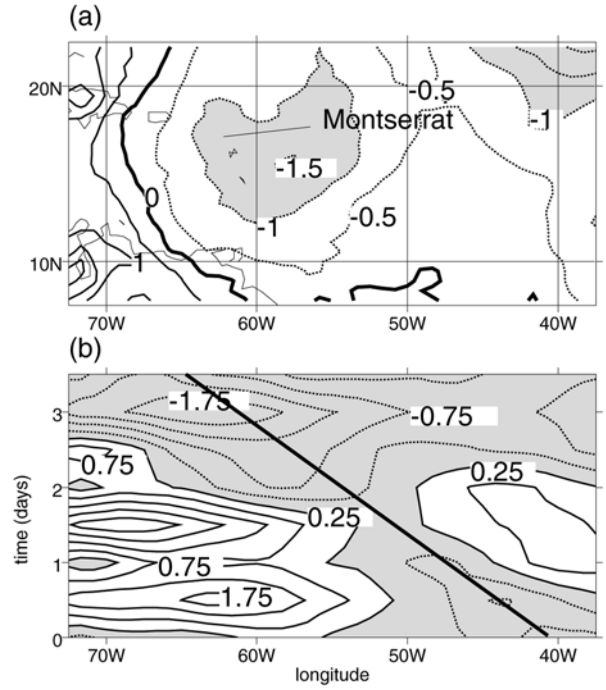

Figure 3. Anomalous mean sea level pressure (MSLP) from the UKMO forecast issued at 2000 Montserrat time on 27 July 2001. (a) The 60 hour forecast, valid at 0800 Montserrat time on 29 July 2001. Contour interval is 0.5 hPa and values below −1 hPa are shaded. (b) Time-longitude diagram of anomalous MSLP averaged over 10°–15°N for the first 3.5 days of the forecast. Contour interval is 0.5 hPa; first positive contour is at 0.25 hPa, and values below 0.25 hPa are shaded. The thick black line traces the westward propagation of the low pressure centre at a speed of 8.4 m s^{-1}.

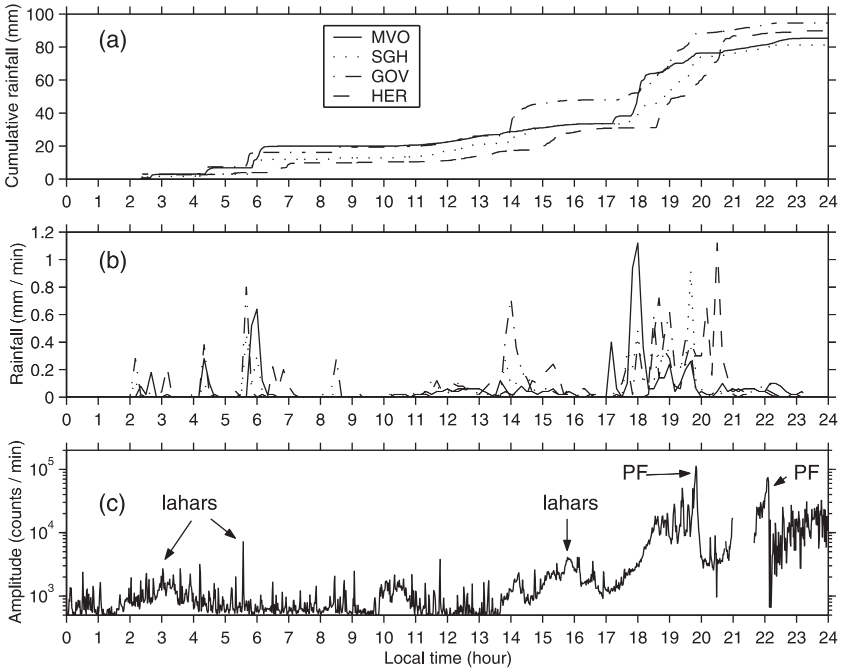

Figure 4. (a) Cumulative rainfall totals at selected stations for 29 July 2001. (b) Rainfall rates (10-minute averages). (c) Signal root mean square amplitude from the St. George's Hill seismograph. The seismograph has a flat response over a broad frequency range (0.03–37.5 Hz) and can detect signals from lahars and pyroclastic flows (PFs) in addition to seismic activity.

extended out from the shore by 500 m and was also followed by falls of rock fragments over the island. The violent volcanic activity finally abated by about 0200 the following day. A large proportion of the dome (approximately 4.5×10^7 m^3) had collapsed, with the summit of the volcano lowered by 150 m, and a scar over 200 m deep incised into the core of the dome at the head of the Tar River Valley. Five days later, a new dome was observed growing within this scar, starting the next phase of the dome growth–collapse cycle.

3. Previous Dome Collapses

[12] Prior to the events of 29 July 2001, the previous major dome collapse had occurred on 20 March 2000 [*MVO*, 2000]. This was also immediately preceded by intense rainfall; 78 mm of rain fell at the DFID Hope station (Figure 1b), which was the second highest daily total at this station in the 33-month record. Once again, there had been no extreme rainfall events in the preceeding few months. However, the rainfall on 20 March 2000 was due to a short-lived and highly localised convective weather system over Montserrat that was essentially unpredictable.

[13] Previous dome collapses in 1996 and 1997 were preceded by hybrid earthquake swarms [*Miller et al.*, 1998], implying that an internal mechanism may have initiated these events. However, no such seismic or other geophysical precursors were detected before the collapses of 20 March 2000 and 29 July 2001, indicating that an external forcing such as intense rainfall may have been responsible for initiating these collapses.

[14] Direct observations of the dome were not possible so we can only suggest possible mechanisms by which the intense rainfall could have triggered the collapse. Rainfall could percolate into cracks in the hot dome rock (typically with a sub-surface temperature of at least 350°C) [*MVO*, 1996]. Such rainwater would quickly vapourise into high-pressure steam which could provide sufficient energy to destabilise the already oversteepened dome, leading to its collapse and the generation of pyroclastic flows. This mechanism requires rainfall rates sufficiently high that water can penetrate cracks in the dome rock rather than being vapourised on the surface. This is consistent with the dome collapse of 29 July 2001 occuring immediately after the most intense burst of rainfall over the volcano. In addition, the intense rainfall could erode the talus at the base of the dome, further destabilising it.

4. Conclusions

[15] We have shown that the two most recent major dome collapses at the Soufrière Hills volcano occured on the same days as the two most extreme rainfall events over the same period. Regarding hazard prediction, both events were preceded by periods of several months of dome growth and destabilisation with no intense rainfall. One of the events was due to the passage of a large-scale tropical weather system that was predicted 2.5 days in advance [*Goerss*, 2000; *Kurihara et al.*, 1998], while the other was due to a localised weather system. In future, a warning of these hazardous events could be issued, based on a joint assessment of dome stability, geophysical and geochemical measurements, the recent rainfall record and the current weather forecast, although much work remains to be done to make this a practical proposition. In the case of large-scale weather systems, this warning could be given up to a few days ahead.

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