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Ash Sedimentation by Fingering and Sediment Thermals from Wind-Affected Volcanic Plumes

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ABSTRACT

Ash fallout and volcanic plume dispersion represent critical hazards for local and global human populations for minutes to years after the onset of an eruption. Understanding the key processes governing the sedimentation of ash particles is a major challenge in modern volcanology from modelling and risk management perspectives. Recent experiments predict that sedimentation

23 from eruption clouds rich in fine-grained ash can be driven by convective phenomena in the
24 form of ~100 m to km-scale ash fingers related to the intermittent formation and detaching of
25 ash-rich particle boundary layer. Remote sensing observations of mammatus and cloud veils
26 from numerous eruptions over recent years as well as field observations of spatially
27 discontinuous ash deposits are consistent with this prediction. Indeed, this mode of ash
28 sedimentation is predicted to be the predominant mechanism of fine ash removal for a
29 significant fraction of eruptions in the geological records. Here, we use a novel combination of
30 3 millimeter-wavelength Doppler radar observations and time series of optical disdrometer data
31 to characterize for the first time in real-time the time-varying structure and sedimentation
32 properties of volcanic ash plumes under steady wind conditions. As a case study, we apply this
33 new method to weak short-lived plumes from Stromboli Volcano. 96% of the disdrometer
34 proximal sedimentation data highlight pulsatory phases of increased sedimentation rate that are
35 20-60 s apart and characterized by particle size distribution variation with bulk concentrations
36 up to 681 mg/m³. Radar data also record intermittent periods of higher reflectivity (*i.e.* a factor
37 of 3 in mass concentration) inside the ash sedimentation interspersed by 30 to 50 s and
38 interpreted as ash fingers crossing the radar beam. From time series of radar signals and ground-
39 based disdrometer measurements, together with simple analog experiments, we develop a
40 conceptual model for intermittent sedimentation from wind-affected ash plumes. In particular,
41 we show that when wind speeds are comparable to or greater than ash settling velocities, the
42 dynamics of wind-driven rolls in ash clouds can govern the production of gravitational
43 instabilities and the occurrence and timing of ash fingers that form descending sediment
44 thermals in turn. This study suggests that ambient wind should affect the maximum size and
45 minimum concentration of ash particles needed to form fingers but also control where and when
46 fingers form at the base of wind-drifted ash plumes. These novel predictions highlight the need

47 for future work aimed at refining our understanding of ash finger formation under windy
48 conditions from the perspectives of in-situ characterization, numerical modelling and risk
49 assessment of fine ash dispersal from the most frequent style of eruptions on Earth.

50 **Highlights:**

- 51 • Novel observations of time-dependent ash sedimentation using a 3 mm-wavelength
52 Doppler radar and a ground-based disdrometer.
- 53 • Wind-induced counter-rotating rolls lead to the formation of ash fingers evolving into
54 sediment thermals.
- 55 • Wind controls when and where ash fingers form at the base of wind-drifted ash plumes.

56 **Keywords:** volcanic plume; ash sedimentation; ash finger; sediment thermal; Doppler radar;
57 optical disdrometer

58 **1 Introduction**

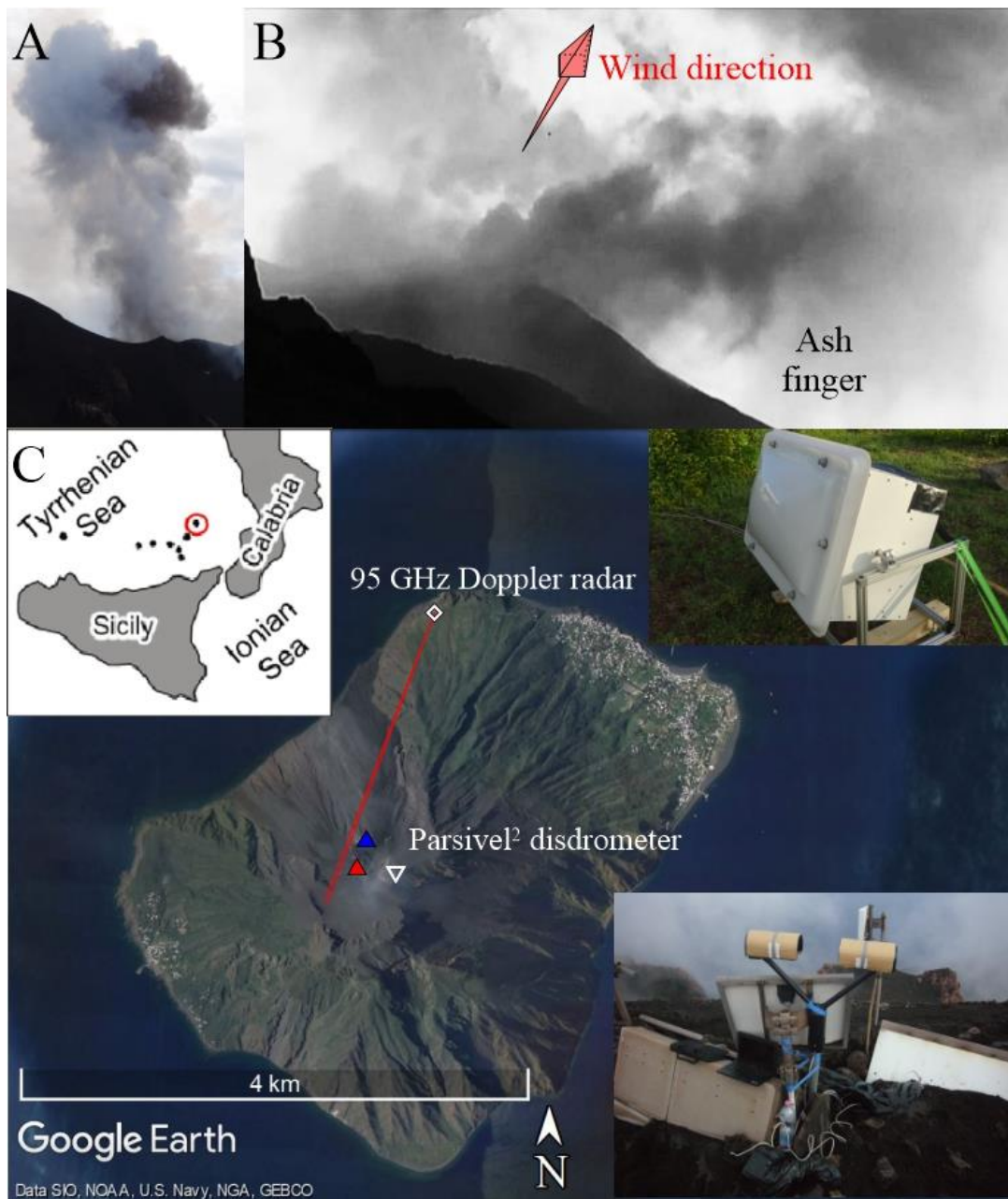
59 Ash plumes produced by explosive eruptions, such as the 2010 Eyjafjallajökull event,
60 disrupt air travel and affect infrastructure and surrounding human populations (Horwell &
61 Baxter, 2006; Tomašek *et al.*, 2016; Wilson *et al.*, 2012). Volcanic Ash Transport and
62 Dispersion models (VATDMs) are used to forecast ash dispersal in the atmosphere and to
63 predict impacted areas (Bonadonna *et al.*, 2011; Folch, 2012; Mastin *et al.*, 2009). VATDMs
64 are initialized with the source parameters of an eruption, which include the Mass Eruption Rate
65 (MER), plume heights, eruption duration, the Total Grain Size Distributions (TGSD) and the
66 vent location. In addition, VATDMs are initialized using scenarios from past eruptions (Scollo
67 *et al.*, 2009, 2010, 2013) or a calculation of mass load estimates from post-eruption deposit
68 analyses (Bonadonna *et al.*, 1998; Bonadonna & Houghton, 2005; Bonadonna & Costa, 2012,
69 2013; Andronico *et al.*, 2014; and references therein). Although some models consider ash

70 density variations and aggregation processes (Costa *et al.*, 2010; Carazzo & Jellinek, 2012;
71 Folch *et al.*, 2016), most of them assume ash settles via continuous individual particle settling,
72 with progressively smaller particles settling out with increasing distance from the eruptive
73 source (Pfeiffer *et al.*, 2005; Costa *et al.*, 2006; Folch, 2012; Bonadonna *et al.*, 2015). In these
74 models, the TGSD, the ash concentration and, in turn, terminal settling velocity of ash particles
75 control the description of ash sedimentation.

76 Many studies have shown that ash sedimentation from ash clouds can vary in space and
77 time. For example, intermittent sedimentation, via ash fingers and mammatus, has been
78 observed at Mount Saint Helens in 1980 (Hobbs *et al.*, 1991; Durant *et al.*, 2009; Carazzo &
79 Jellinek, 2012), Soufrière Hills volcano in 1997 (Bonadonna *et al.*, 2002) and Eyjafjallajökull
80 in 2010 (Manzella *et al.*, 2015). More generally, Carazzo & Jellinek (2012, Figure 8) show that
81 the dynamics giving rise to fingers probably governed ash sedimentation in nearly half the
82 deposits in geological record form which grain-size data is available. However, although
83 analogue laboratory experiments and scaling theory constrain the conditions favoring the
84 formation and evolution of ash fingers (Carazzo & Jellinek, 2012; Manzella *et al.*, 2015; Del
85 Bello *et al.*, 2017; Scollo *et al.*, 2017), a critical knowledge gap is that their dynamics have not
86 been characterized quantitatively *in situ*.

87 Accordingly, we use a novel 3 mm wavelength (95 GHz) Doppler radar together with
88 an optical disdrometer to characterize volcanic cloud sedimentation dynamics during a series
89 of eruptions at Stromboli in 2015, when the eruptive activity was mostly characterized by short-
90 lived weak ash plumes (**Figure 1A**). Guided by time series radar data from this campaign, and
91 qualitative observations of analog experiments, we propose that sedimentation through the
92 production of ash-laden fingers evident in **Figure 1B** (Patrick *et al.*, 2007) at Stromboli, is a
93 consequence of convective instabilities (*e.g.* Hoyal *et al.*, 1999; Bonadonna *et al.*, 2002; Bush

94 *et al.*, 2003; Durant *et al.*, 2009; Carazzo & Jellinek, 2012, 2013; Manzella *et al.*, 2015; Scollo
95 *et al.*, 2017) modified by wind effects including the production of wind counter-rotating rolls
96 (Turner, 1960). We will argue that resulting overturning and stirring of the ash-air mixture
97 enhances the production of Particle Boundary Layers (PBLs) and the formation of ash fingers.
98 This class of time-dependent sedimentation also predicts deposits with spatially-varying
99 textural characteristics that are readily identifiable in the field (Branney, 1991; Carazzo &
100 Jellinek, 2012). Finally, our results suggest that finger formation is not only a common feature
101 of sedimentation from transient and weak volcanic plumes, consistent with expectations from
102 Carazzo & Jellinek (2012, figure 8), but also that their formation depends strongly on the
103 character of wind-driven stirring.



104

105 **Figure 1:** *A) Photograph of an ash plume emitted by the Southwest crater of Stromboli. B) Strombolian*
 106 *ash plume drifted toward the North by the wind and forming an ash finger. The wind direction is shown*
 107 *by the red arrow. C) Instrument setup at Stromboli Island. Upper right panel: 95 GHz radar at Punta*
 108 *Labronzo (100 m a.s.l.) 2.1 km in slant distance from the vents (red line: radar beam direction). Lower*
 109 *right panel: Disdrometer near Pizzo Sopra La Fossa at 900 m a.s.l., 350-450 m ESE of the summit*
 110 *craters (SW crater, red triangle; NE Crater, blue triangle).*

111 Our paper is organized in the following way: in Section 2, we present the methodology
112 we applied at Stromboli as a case study, between the 28th of September 2015 and the 4th of
113 October 2015, for identifying and characterizing distinct sedimentation features of volcanic
114 plumes. In section 3, we present the combined radar and disdrometer results and highlight
115 principal observations. In section 4, we use observations and a small suite of analog experiments
116 to build a conceptual model for intermittent sedimentation from weak volcanic plumes
117 constrained by our principal observations before concluding in section 5.

118 **2 Methodology**

119 *2.1 The measurement campaign at Stromboli*

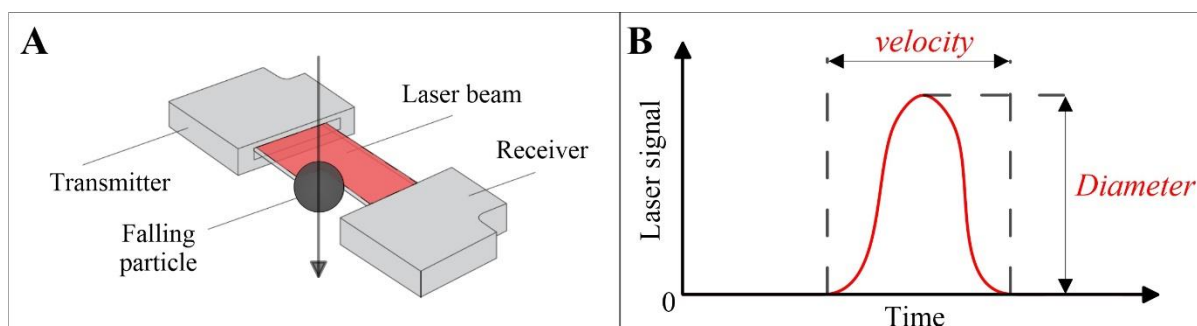
120 The goal of our measurement campaign is to characterize quantitatively the
121 sedimentation behavior of volcanic plumes with three techniques: (i) a 3 mm wavelength
122 Doppler radar (95 GHz), designed to track ash in volcanic plumes (**Figure 1C**); (ii) an optical
123 disdrometer Parsivel² (**Figure 1C**); and (iii) analyses of ground deposit samples acquired during
124 the campaign (Freret-Lorgeril *et al.*, 2019). In this study, it is important to note that each method
125 detects a local Particle Size Distribution (PSD). Such size distributions represent only a part of
126 the whole erupted mixture defined as the TGSD. From the disdrometer PSDs and phase delays
127 in radar return, we determine the modal settling velocity of ash particles.

128 During 39 hours of monitoring, 181 short-lived ash plumes (*i.e.*, from type 2a and 2b
129 explosions; Patrick *et al.*, 2007) were recorded by the radar and 26 sedimentation events by the
130 optical disdrometer. The geometry of the instrument locations (**Figure 1C**), which was the same
131 during the whole campaign, did not allow for simultaneous measurement of the same ash

132 sedimentation event as the wind was either blowing the sedimentation towards the radar or
133 towards the disdrometer.

134 2.2 The optical disdrometer

135 The optical disdrometer Parsivel² designed by OTT HydroMet (**Figure 1C**) can measure
136 particle settling velocities and diameter directly by converting the signal from a 780 nm
137 wavelength laser beam, emitted from a transmitter to a receiver, into a voltage signal (**Figure**
138 **2A** and **2B**). The laser obscuration time is used to determine the settling velocity of falling
139 particles, while the absorption amplitude, portion of the 54 cm² laser sheet surface obscured by
140 the particle, measures the particle size (Löffler-Mang & Jürg, 2000; **Figure 2B**). Measurable
141 settling velocity and size ranges are between 0.05-20.8 m/s and 0.250-26 mm. Disdrometers
142 were originally designed for detecting hydrometeor precipitation. Nevertheless, Freret-Lorgeril
143 *et al.* (2019) and Kozono *et al.* (2019) have highlighted the reliability of such instruments for
144 detecting volcanic ash fallout with a high temporal resolution. Usually, disdrometer
145 measurements are time-averaged either to avoid stochastic variations of measurements due to
146 complex hydrometeor shapes (Löffler-Mang & Jürg, 2000) or to obtain stable quantitative data,
147 e.g. rain-rates, for long-lasting meteorological events as opposed to short ash fallout events.
148 Accordingly, we used the disdrometer maximum sampling frequency of 0.1 Hz (Tokay *et al.*,
149 2014) in order to capture short time-varying sedimentation processes.



150

151 **Figure 2:** A) Sketch of the disdrometer detection procedure. A transmitter emits a laser sheet, i.e. in
 152 red, which is measured by a receiver. B) Signal of the laser as a function of time. The amplitude and
 153 time of the particle-induced laser obscuration are used to determine the size and the settling velocity of
 154 ash particles, respectively.

155 Because of its lower detection limit and for accessibility reasons, the Parsivel² was set
 156 up next to Pizzo Sopra La Fossa at ~900 m a.s.l, 370 m NE of the SW crater (**Figure 1C**). This
 157 location allowed recording of the proximal coarse ash sedimentation. In addition, ground
 158 tarpaulins were placed next to the disdrometer to collect ash samples for each event recorded
 159 by the disdrometer. Freret-Lorgeril *et al.* (2019) demonstrated the influence of ash particle
 160 shape on disdrometer terminal settling velocity and size measurements. Since the disdrometer
 161 is designed to measure the shape of spherical droplets for meteorological applications, the shape
 162 of settling ash particles were constrained and determined with a morpho-grainsizer Morphologi
 163 G3[®] by Freret-Lorgeril *et al.* (2019). Assuming particles fall parallel to their shortest axis, the
 164 disdrometer detects particle with circle-equivalent diameter $D_{CE} \geq 0.230$ mm (Freret-Lorgeril
 165 *et al.*, 2019). The particle detection resolution (*i.e.* the disdrometer size classes) is equal to 0.115
 166 mm in D_{CE} .

167 We calculate particle numbers over the range of measured particle D_{CE} and ash
 168 concentrations C_{ash} (kg/m³) with (Freret-Lorgeril *et al.*, 2019):

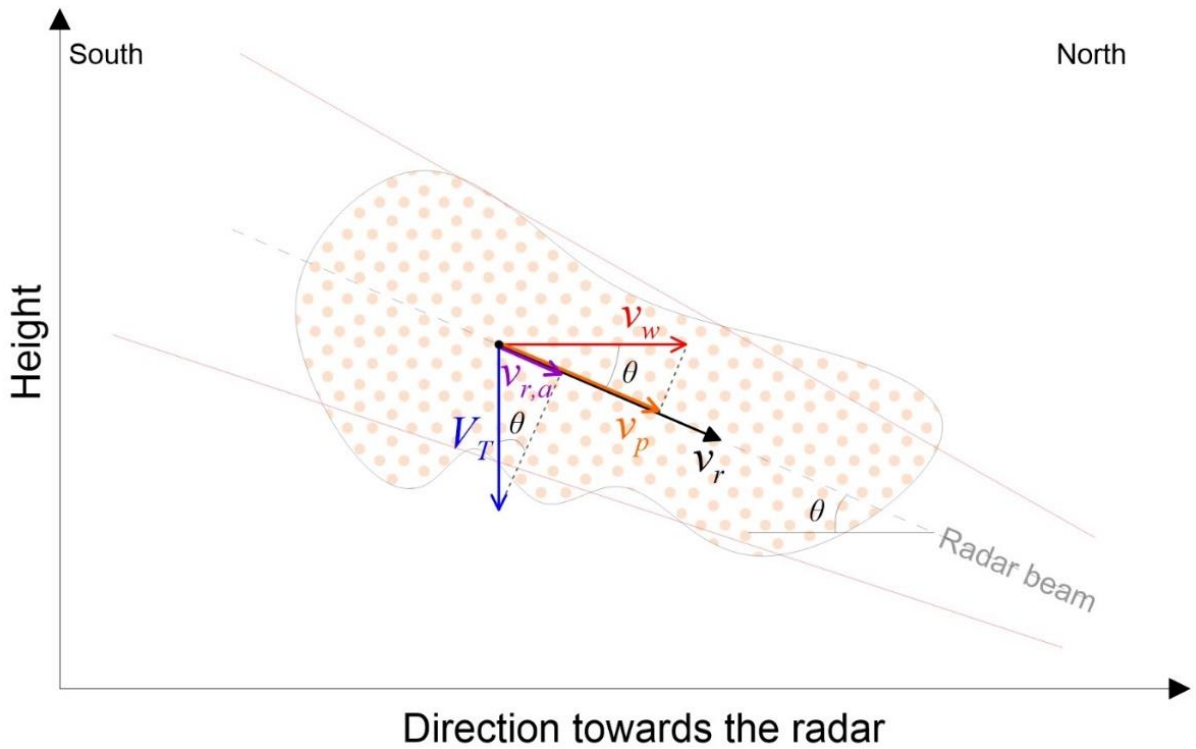
$$169 \quad C_{ash} = \frac{\pi \rho_{ash}}{6} \int_{D_{min}}^{D_{max}} N(D_{CE}) D_{CE}^3 dD_{CE}, \quad (1)$$

170 where $N(D_{CE})$ is the particle number density (m⁻³/mm) of a size class crossing the beam, dD_{CE}
 171 (mm) is the diameter class width, and $\rho_{ash} = 2739 \pm 50$ kg/m³ the average ash particle density
 172 measured by water pycnometry (Freret-Lorgeril *et al.*, 2019).

173 2.3 Radar observations of cloud structure and sedimentation

174 The 3 mm wavelength Doppler radar is a compact version of the prototype of Bistatic
175 Radar System for Atmospheric Studies (BASTA, Delanoë *et al.*, 2016), using smaller antennas
176 (30 cm wide). It was located at Punta Labronzo (**Figure 2A**), about 2 km NNE from Stromboli
177 summit craters. We chose this location to capture plume emissions and their subsequent
178 sedimentation that was preferentially dispersed towards the North due to ambient wind. The
179 radar beam (0.8° wide) aimed at an area 100 m above the SW crater. Particle radial (along-
180 beam) velocity components v_r and reflectivity factors Z are measured inside each probed volume
181 of the beam as a function of time and range with resolutions of 2 s and 12.5 m (*i.e.* 12.5 m mode),
182 respectively (See **Table S1 in Supplemental information**).

183 Radial velocities $v_r < 0$ characterize particles with a motion component toward the radar,
184 as expected for particles falling through the upward inclined beam (Sauvageot, 1992). The
185 maximum non-ambiguous (*i.e.* measurable by the radar without aliasing) velocity is ± 9.87 m/s
186 (resolution of 0.01 m/s) in the 12.5 m mode used in this study. When detecting ash
187 sedimentation, it is possible to estimate the settling velocity of detected particles V_T from their
188 radial velocities. Under the assumption of no vertical component to the ambient wind, V_T can
189 be estimated from the beam elevation angle ($\theta = 21.4^\circ$) and the range-time slope v_p of a
190 sedimentation pattern crossing the radar beam. However, horizontal winds, which were present
191 during the campaign, induce a velocity component along the radar beam axis and need to be
192 deconvolved from the radar measurements. We were unable to obtain reliable wind data during
193 the measurement campaign. Consequently, we exploit the radar beam geometry to constrain the
194 average horizontal wind velocity, and in turn, a more accurate estimate of V_T .



195

196 **Figure 3:** Schematic representation of measured and inferred velocity components of ash and wind,
 197 given a prescribed radar beam geometry. v_w is the horizontal wind velocity presumably inducing the
 198 along-beam (radial) displacement speed of the whole sedimentation pattern, v_p , measured from its
 199 range-time slope in reflectivity time series. v_r are the measured internal radial velocities of the recorded
 200 pattern. The measured differential velocity $v_{r,a} = |v_r| - |v_p|$, is assumed to be the radial velocity component
 201 related only to ash particles. The settling velocity V_T of particles in a sedimentation pattern is then
 202 calculated using **Equation 3**.

203 **Figure 3** shows each velocity component related to a sedimentation feature detected
 204 inside the radar beam. Under trigonometric considerations, the unknown horizontal wind
 205 velocity v_w , giving rise to the values of v_p , can be estimated with $|v_p|/\cos\theta$. Additionally, we can
 206 calculate the radial component velocity of the sedimentation, $v_{r,a}$, in the radar beam as:

207
$$v_{r,a} = |v_r| - |v_p|, \quad (2)$$

208 Finally, from the vertical component of $v_{r,a}$ the mean settling velocity of all the ash
209 particles V_T is:

$$210 \quad V_T = \frac{|v_r| - |v_p|}{\sin \theta} . \quad (3)$$

211 Assuming that radar returns are in the Rayleigh scattering limit, the radar reflectivity
212 factor, Z , characterizes the quantity of targets crossing the radar-beam and can also be calculated
213 for the local PSD measured by the disdrometer, as (Sauvageot, 1992):

$$214 \quad Z = \int_{D_{\min}}^{D_{\max}} N(D) D^6 dD , \quad (4)$$

215 where Z is in mm^6/m^3 , $N(D)$ is the particle number density ($\text{mm}^{-1}/\text{m}^3$), D is the particle size in
216 mm and dD is the range of particle size classes used (*e.g.* 0.115 mm resolution from disdrometer
217 size classes). Z is expressed in logarithmic units (dBZ) as:

$$218 \quad Z(\text{dBZ}) = 10 \times \log_{10}(Z(\text{mm}^6/\text{m}^3)) . \quad (5)$$

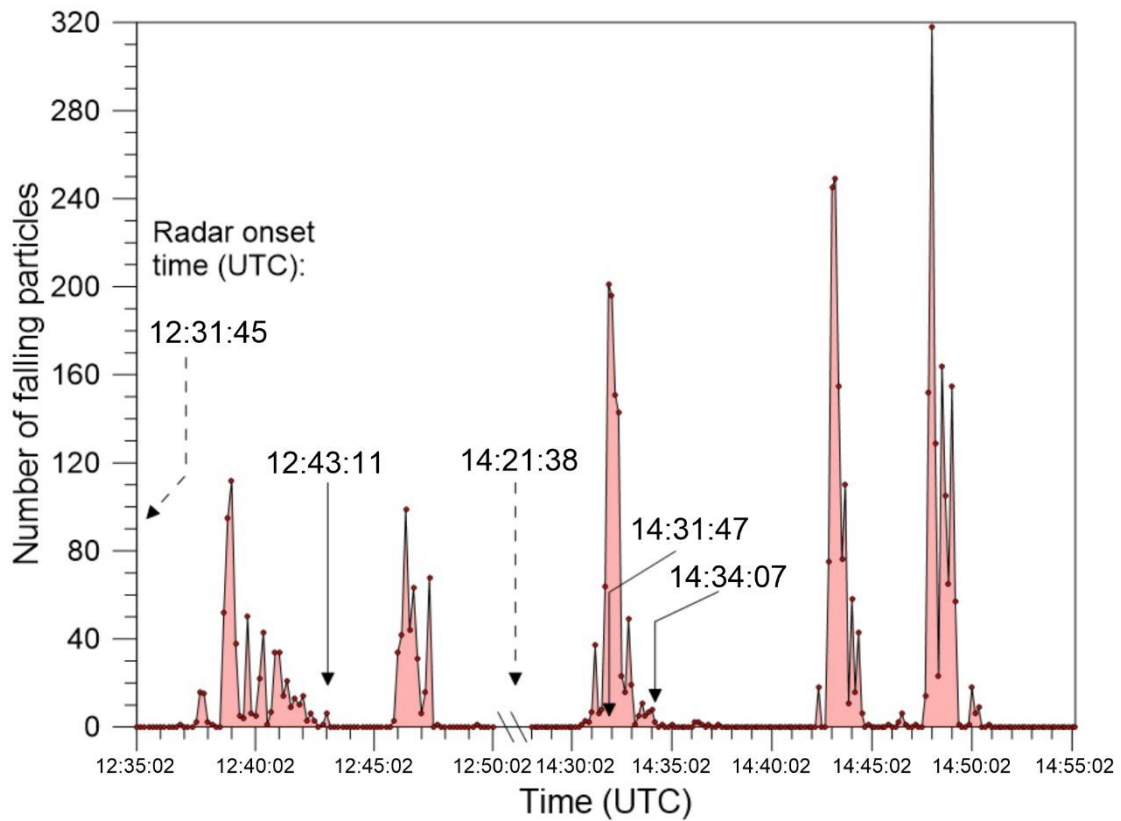
219 Strictly, **Equations 4** are valid if we assume that the ash-air mixture is a dilute and
220 homogeneous suspension of spherical particles with diameters less than about $\lambda/4$ (Gouhier &
221 Donnadieu, 2008).

222 **3 Results**

223 *3.1 Intermittent sedimentation from disdrometer records*

224 We observed 24 sedimentation events in the optical disdrometer data associated with
225 single ash plume emissions blown toward the instrument by an easterly wind. **Figure 4** shows
226 a time series of five sedimentation events recorded by the disdrometer on October 3, 2015

227 between 12:35:02 and 14:50:02 UTC. These events, lasting between 110 and 340 s, are
 228 distinguished by time breaks during which no particles were detected. The multi-peaked
 229 variations in sedimentation rate, *i.e.* the mass of particle falling as a function of time and per
 230 unit area, shown for the five events in **Figure 4** are characteristic of 96% of the 24 events
 231 recorded by the disdrometer.

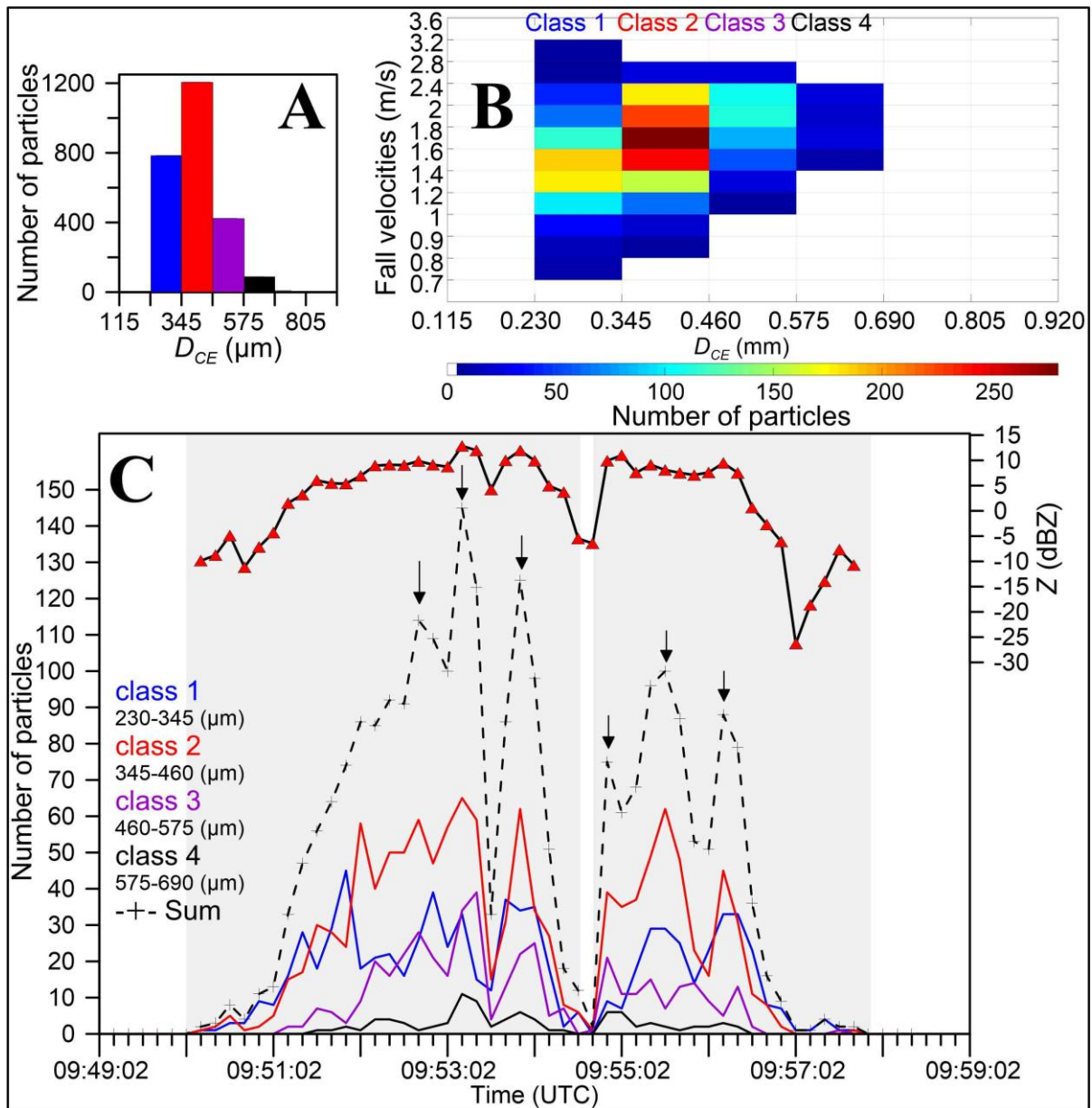


232
 233 **Figure 4:** Time series of the number of falling particles detected by the optical disdrometer on October
 234 3, 2015 between 12:35:02-12:50:02 UTC and 14:25:02-14:50:02 UTC. The arrows show the first time
 235 that the radar detects the ash plumes rising above the vent, which occurs a few seconds after the start
 236 of each explosion. The ash sedimentation events are recorded several minutes afterwards.

237 **Figure 5** shows another 8 min-long sedimentation event comprised of 2,514 detected
 238 ash particles on October 3, 2015 between 09:49:00 and 09:59:00 UTC, originating from an ash
 239 plume emitted 7 minutes prior at 09:41:52 UTC. The PSD (**Figure 5A**) ranges from $0.230 <$

240 $D_{CE} < 0.690$ mm (Class 1-4) and has a modal value between 0.345 and 0.460 mm (Class 2).
241 Settling velocities (**Figure 5B**) range between $0.7 < V_T < 3.2$ m/s with a modal value between
242 1.4 to 2 m/s. These are consistent with maximum settling velocities (cf., Ganser, 1993) of 1.8
243 $< V_T < 2.4$ m s⁻¹ for Class 2 particles using a measured sphericity of 0.75 and average sizes
244 between the longest and the intermediate axes of the particles (Freret-Lorgeril *et al.*, 2019).
245 **Figure 5B** shows the widespread distribution of settling velocities as a function of particle size
246 that is characteristic of all detected sedimentation events. In **Figure 5C**, the number of ash
247 particles falling through the laser beam over time, and hence the sedimentation rate, shows
248 significant fluctuations affecting all size classes. Six pulses of up to 145 particles occur with
249 variations of 98% of the maximum pulse amplitude. The sedimentation can be divided into two
250 main phases of 4 min 40 s and 3 min 10 s, respectively, that are separated by a 20 s interval
251 with very few detected particles. Successive pulses within each sedimentation phase occur at
252 intervals of 20 to 60 s and in between pulses, the sedimentation rate decreases for less than 10
253 s to one minute before increasing again.

254 **Figure 5C** shows expected radar reflectivity factor values derived from the
255 sedimentation rate measured by the disdrometer using **Equations 4-5**. Z varies from $-26.29 <$
256 $Z < +12.85$ dBZ for this event and, using **Equation 1**, we estimate average and maximum ash
257 concentrations of 0.64×10^{-4} and 1.88×10^{-4} kg/m³, respectively. For all sedimentation events
258 observed in this study, the disdrometer data shows relatively constant PSD modes of $0.403 \pm$
259 0.058 mm comprising on average 46% of the total number of detected particles, ranging from
260 45 to 1,261. The ash concentrations inferred from Z values on the whole set of disdrometer data
261 range between 7.61×10^{-7} to 6.81×10^{-4} kg/m³.



262

263 **Figure 5:** A) Disdrometer-derived local Particle Size Distribution of the ash sedimentation event

264 between 09:49:02 and 09:59:02 UTC on Oct. 3 2015. Each size class (± 0.05 mm) is color-coded. B)

265 Settling velocities (V_T) measured by the disdrometer as a function of circle-equivalent diameters (D_{CE}).

266 Bin colors represent number of particles. C) Temporal series of particle number of each class (colored

267 lines), the total number of particles (dashed crossed line) and calculated reflectivity factor Z (red

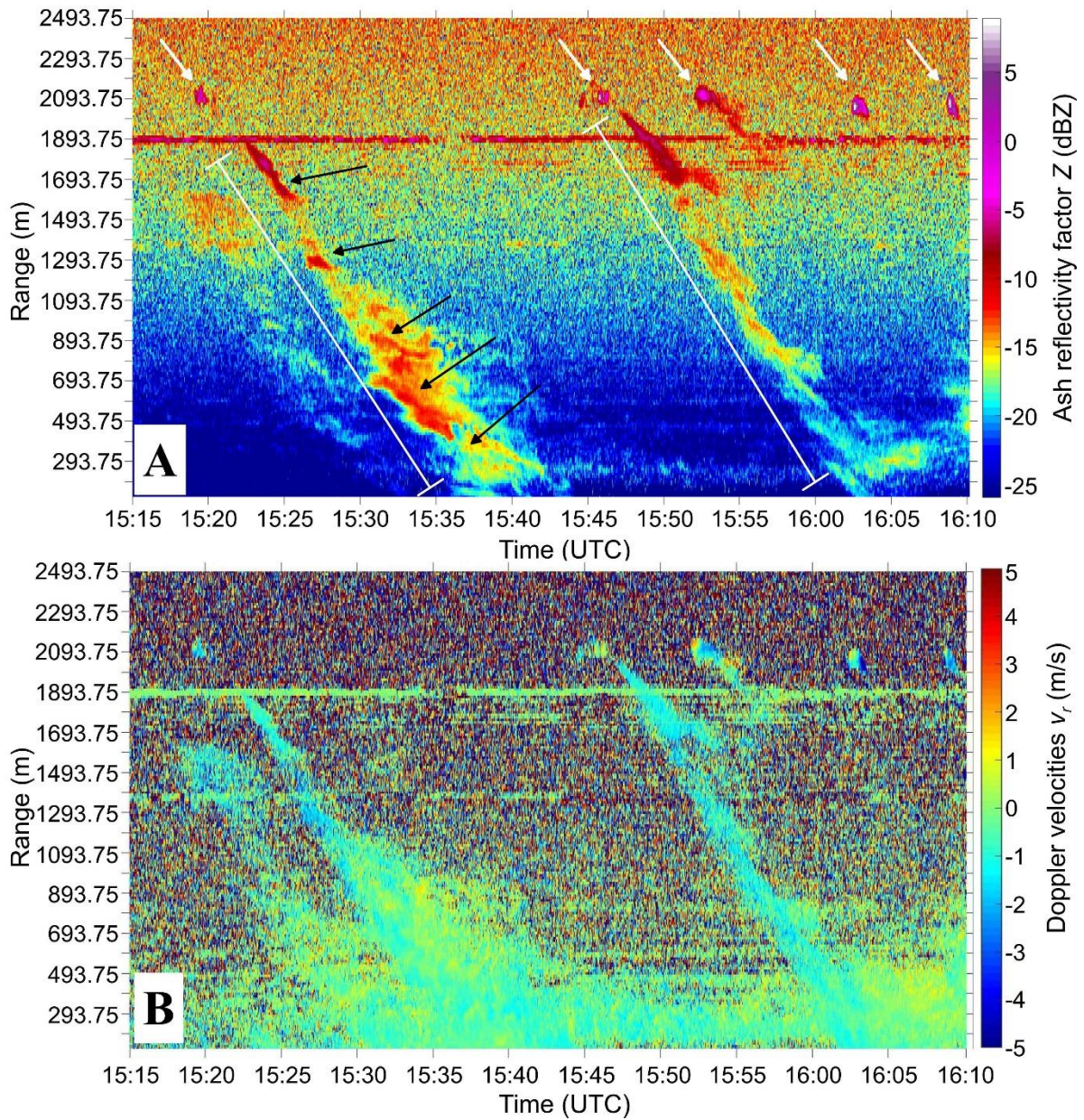
268 triangles). The grey areas and the black arrows represent the two sedimentation phases and the 6

269 sedimentation pulses, respectively.

270 3.2. Radar observations of evolving cloud structure in space and time

271 Between October 2 and 3, 2015, weak northerly winds advected transient ash plumes
272 towards the Doppler radar location at Punta Labronzo. The 3 mm wavelength Doppler radar
273 detected the emission of ash plumes ~100 m above the vent and 15 subsequent ash
274 sedimentation events over a ~2100 m slant distance. **Figure 6A** shows the range-time profiles
275 of ash reflectivity factor, Z , with white arrows marking detected ash plumes rising above the
276 vent at ~2000 m range. The first two detected ash plumes are followed by the detection of ash
277 fallout, appearing as Long Duration Reflectivity Features (LDRFs) that grow in size as they
278 move towards the radar site (white line in **Figure 6A**). The width of the first LDRF, detected at
279 15:23:00 UTC, is ~100 m until 15:29:00 UTC. During the following 3 min, it steadily widens
280 to ~600 m. The second LDRF, detected at 15:47:00 UTC, steadily widens over the following 4
281 min from <100 m to ~200 m. For the remainder of the detection, its width thins and widens
282 multiple times. The LDRFs do not appear to be homogeneous in Z along the radar beam axis
283 and show small-scale range-time trends spaced quasi-periodically within their large-scale
284 pattern (black arrows in **Figure 6A**). The slopes of the *small-scale reflectivity trends* are lower
285 than the slope of the large-scale pattern.

286 The overall Doppler velocities, v_r , within the first LDRF show a decrease from ~0 m/s
287 to ~-2 m/s around 15:26:00 UTC (**Figure 6B**). At about 15:28:00 UTC, the velocities vary
288 spatially and intermittently above and below 0 m/s within the LDRF at later time and closer
289 range. The second LDRF shows a similar evolution in v_r over time and range of detection.



290

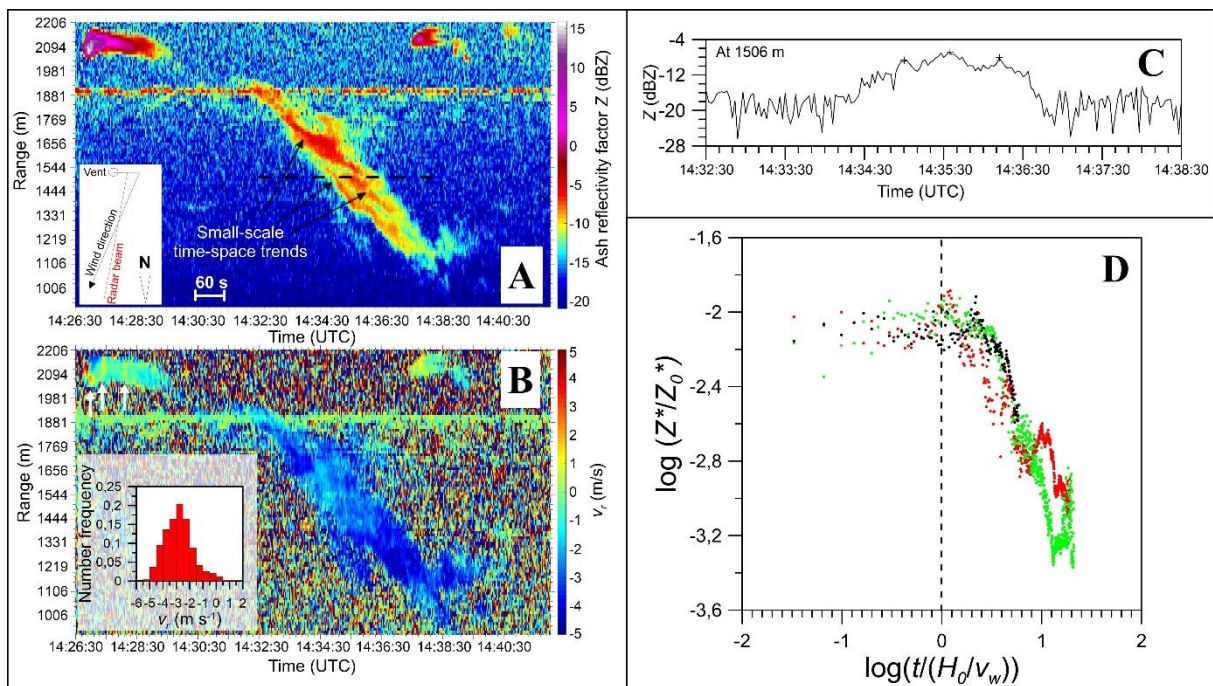
291 **Figure 6:** A) Ash reflectivity factor (Z) time series recorded on October 2 2015 (15:15-16:10 UTC) as
 292 a function of time (x -axis) and along-beam slant distance (y -axis: range). Five ash plumes are pointed
 293 by white arrows at crater distance (2100 m) while two Long Duration Reflectivity Features (LDRFs;
 294 indicated by white lines), lasting ~20 min each, are tracked over 2 km toward the radar location. Black
 295 arrows indicate example of small-scale range-time trends B) Range-time profiles of radial velocities of
 296 the same eruptions.

297 In **Figure 7**, we show the sedimentation occurring within 1000 m of the SW Crater. The
298 parent ash plume, which drifts to the north, is observed at slant distances of 2069-2119 m. As
299 in **Figure 6A**, the range-time Z measurements show the ash plume rise, followed by a
300 sedimentation event split into two phases. The first 20 s-long impulsive phase shows the ash
301 plume detected 100 m above the vent at 14:26:44 UTC. Initially, it is < 50 m wide and then
302 widens to 150 m in the N-S direction 16 s after detection (**Figure 7A**). 12 s after the detection
303 onset, a maximum of 16.52 dBZ is reached in the bin at 2081 m. The following 158 s-long
304 decrease in reflectivity until 14:29:42 UTC marks the ash plume exiting the radar beam. Radial
305 velocities (v_r) in the emitted plume alternate in time between negative and positive values with
306 a period of 24 s between the first and second yellow bands (see white arrows at top left in
307 **Figure 7B**) and 40 s between the second and third yellow bands. The variations of the ash
308 plume's internal velocities and reflectivity do not appear correlated.

309 After the initial ash plume exits the radar beam in **Figure 7**, there is a period of 123 s
310 without ash detection. We detect ash again between 14:31:45 and 14:40:01 UTC at a lower
311 altitude in downwind bins closer to the radar (994-1944 m) with a maximum reflectivity of Z_{max}
312 = -4 dBZ, which is weaker than that of the initial ash plume. The width of this LDRF increases
313 from 100 to 300 m from 14:33:30 to 14:34:45 UTC and its average slope indicates an average
314 speed of -2.3 m/s towards the radar. Similar LDRFs, between 15:22:25-15:43:46 UTC and
315 15:47:02-16:08:09 UTC in **Figure 6A**, are detected within 2000 m of the radar location.

316 In **Figure 7**, three continuous features, with $-14.23 < Z < -4.72$ dBZ, emerge within the
317 LDRF 160 s after its initial detection. These features are 25-100 m thick, 50 m on average and
318 have range-time slopes that are distinct from the average slope of the overall LDRF signal. At
319 14:35:07 UTC, we observe three local maxima in Z values located in the middle of these
320 features at different distances that have a relatively constant spacing of about 85 m (80 to 95

321 m) and intervals of 30 to 50 s (**Figures 7A and 7C**). These small-scale reflectivity trends are
 322 best described by a constant along-beam slope, indicating a constant velocity component
 323 towards the radar. Thus, the reflectivity of the emitted ash plumes is characterized by an initial
 324 maximum decaying continuously, whereas the LDRFs detected closer to the radar are
 325 characterized by the emergence of multiple small-scale and evenly spaced reflectivity trends
 326 (**Figure 6A and Figure 7A**).

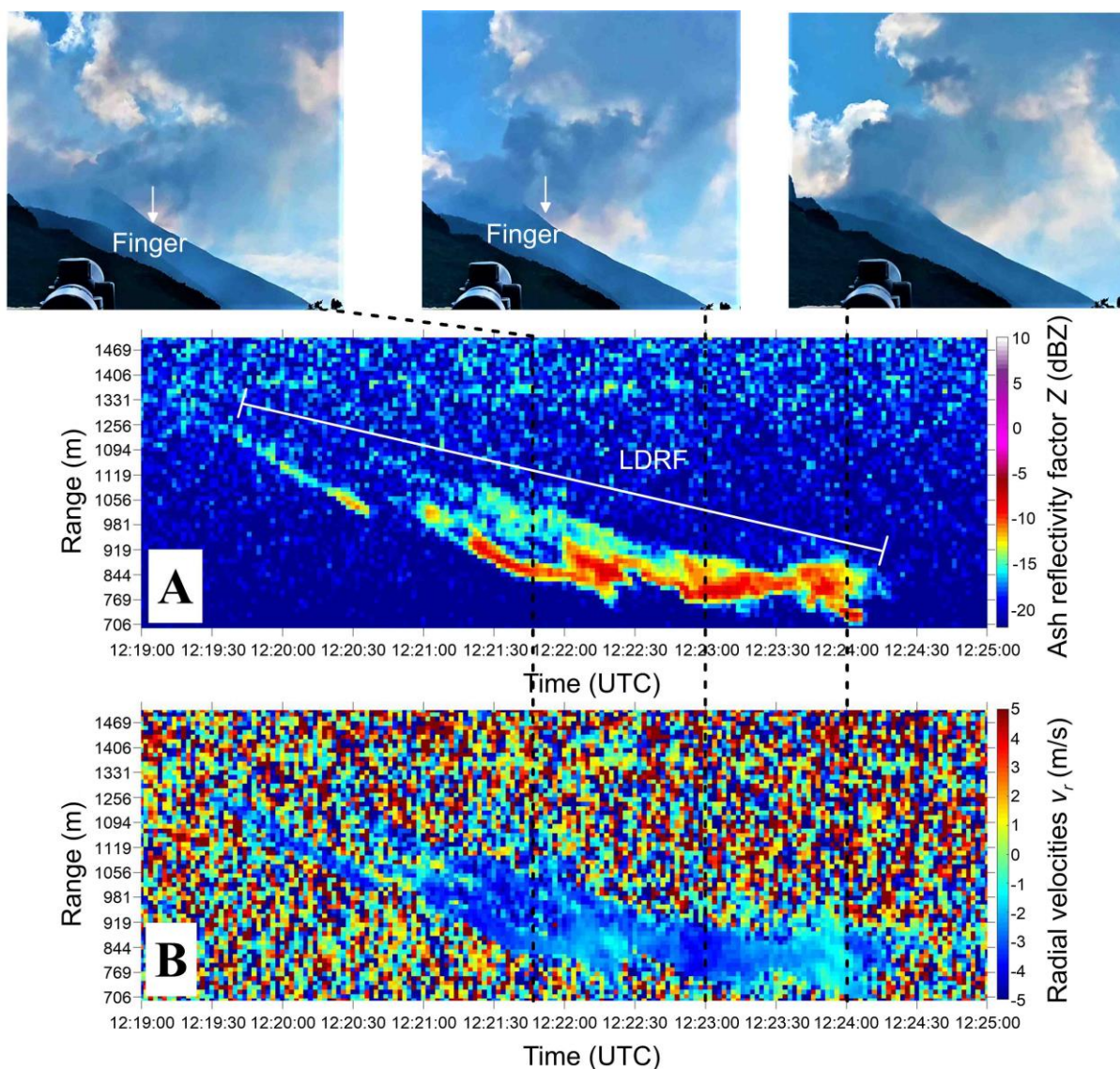


327
 328 **Figure 7: A)** Range-time profile of measured radar reflectivity factor, Z , of a single ash plume emission
 329 and subsequent LDRF. Red arrows indicate the small-scale reflectivity trends inside the LDRF. Inset:
 330 sketch of the wind direction according to the visually observed trajectory of the ash plume relative to
 331 the radar beam (at 2100 m and about 14:26 UTC on Oct. 2 2015). **B)** Range-time profiles of radial
 332 velocities of the same eruption. White arrows indicate the pattern of positive Doppler velocities in the
 333 emission. Inset: Histogram of Doppler (along-beam) velocities (filtered with threshold $Z > -13$ dBZ)
 334 inside the whole LDRF pattern. Doppler velocities mainly range between -5.5 to 1.5 m/s with a mode
 335 between -3 and -2.5 m/s. **C)** Z -profile across the three main small-scale range-time trends (peaks marked
 336 by crosses) at 1506 m from the radar between 14:32:30 and 14:38:30 UTC (black dashed line in A). **D)**

337 *Log-Log plot of the normalized reflectivity ratio (Z^*/Z_0^*) as a function of the normalized time scale for*
338 *wind-driven overturning of rolls observed within the ash cloud $t/(H_0/v_w)$ (see text). Here, H_0 is the width*
339 *of the parent plumes where the maximum reflectivity is detected in Figure 6 and 7A, and v_w is the*
340 *horizontal wind velocity. The three events recorded by the radar on 2 October at 14:26 UTC (black*
341 *dots), 15:17 UTC (green dots) and 15:44 UTC (red dots) show a decrease in normalized reflectivity*
342 *factor.*

343 In total, 93% of the Doppler velocities within the LDRF in **Figure 7** are marked by
344 negative values within $-1 < v_r < -5$ m/s (inset in **Figure 7B**). They show an abrupt increase in
345 overall v_r from ≤ -3 m/s to -0.7 m/s around 14:34:00 UTC and a return to ≤ -3 m/s closer to the
346 radar around 14:36:30. The horizontal component of the LDRF's range-time slope in **Figure**
347 **7A** corresponds to a horizontal wind velocity, $v_w = 2.47$ m/s. From the LDRF's internal modal
348 v_r , $-2.5 < v_r \leq -3$ m/s (inset in **Figure 7B**), a modal radial velocity $v_{r,a}$ between -0.2 and -0.7 m/s
349 is found. The corresponding V_T ranges from 0.55 to 1.92 m/s (**Equation 3**), indicating detected
350 particle sizes between 0.1 and 0.3 mm (Ganser, 1993; Freret-Lorgeril *et al.*, 2019).

351 A final observation was done on October 2, from 12:19 to 12:25 UTC, when LDRFs
352 emerging in the radar data were accompanied by simultaneous visual observation of the
353 formation of ash fingers under a dilute weak plume (**Figure 8; Supplemental information S2**
354 **and video S2**). The same features observed in **Figures 6 and 7** are highlighted in **Figure 8**.
355 Small-scale reflectivity trends are detected within a LDRF over a distance of 550 m (i.e. from
356 1256 m to 706 m along the radar beam) and during 284 s (**Figure 8**). The small-scale features
357 show reflectivity ranging from -16 to -7 dBZ (**Figure 8A**). Finally, the LDRF is characterized
358 by negative Doppler velocities alternating between -4 and -1 m/s (**Figure 8B**).



359
 360 *Figure 8: Simultaneous observation of ash fingering (black arrows) at Stromboli from visible*
 361 *(snapshots) and radar imagery on October 2, 2015 between 12:19 and 12:25 UTC. A) Range-time*
 362 *profile of ash reflectivity factor Z. The white dashed line indicates the detected LDRF. B) Range-time*
 363 *profile of radial velocities v_r .*

364 **4 Discussion**

365 The LDRFs detected by the radar over a range of 150 to 2000 m downwind from the
 366 vent (**Figures 6, 7 and 8**) are interpreted as ash sedimentation from the October 2015 eruption

367 clouds. We interpret the temporal correlations between pulses in the sedimentation rate
368 recorded proximally on the ground by the disdrometer (**Figures 4** and **5**) and the small-scale
369 radar reflectivity trends (**Figures 6A** and **7A**) as evidence that the ash sedimentation is pulsed
370 and quasi-periodic with recurrence intervals of 20-60 s in the disdrometer data and 30-50 s in
371 the radar reflectivity data. On the basis of this consistency, the observations of finger-like
372 structures in **Figure 1B**, **Figure 8** and the observations of ash curtains below Strombolian
373 plumes in Patrick *et al.* (2007), we hypothesize that the sedimentation pulses are ash fingers
374 arising from the same mechanism, which we now explore in detail.

375 *4.1 A hypothesis for the origin, geometry and evolution of the ash fingers: Wind-driven rolls,*
376 *convective fingering and sediment thermals*

377 Before comparing the PSD measured by the disdrometer to that detected in the
378 sedimentation targeted by the radar, several challenges must be addressed. First, the local PSD
379 measured by the disdrometer only represents the fraction of the PSD falling at the location of
380 the disdrometer (**Figure 2**). The largest pyroclastic particles are likely to fall out of the ash
381 cloud before reaching the disdrometer. The disdrometer has also a lower detection limit of 0.230
382 mm and thus records a local PSD that is not only biased against the largest particles but also
383 biased against fine ash, the dynamics of which probably control finger formation (Carazzo &
384 Jellinek, 2012). Nevertheless, Freret-Lorgeril *et al.* (2019) have shown that the disdrometer
385 local PSDs matched 75-94% (*i.e.*, in vol%) of the ground PSDs sampled at the same location.
386 The total concentration measured by the disdrometer consequently sets a lower limit for the
387 total ash concentration settling at its location. Additionally, transient non-dilute mixture effects
388 such as enhanced or hindered settling (Del Bello *et al.*, 2017), potentially complicate V_T derived

389 from v_r . Bearing this in mind, we proceed with caution, to investigate the origin of the
390 sedimentation features.

391 Processes that drive the formation of fingers must explain four principal observations
392 from the combined disdrometer and radar data:

- 393 1. Quasi-periodic sedimentation pulses with wavelengths of 80-95 m and periods of 30-50 s
394 (**Figure 7A**).
- 395 2. An increase in size over time of the initial sedimentation pulses detected (**Figures 6A** and
396 **7A**)
- 397 3. The 120 - 360 s time scale for fingers to emerge (**Figure 6A** and **7A**) after initial detection
398 of ash sedimentation.
- 399 4. The overall increase of v_r within the sedimentation after 14:33:30 and 12:15:00 in **Figure**
400 **7B** and **Figure 8B**, respectively (after 15:28:00 for the first LDRF in **Figure 6B**).

401 Explosive volcanic eruptions, no matter their size and nature, are commonly
402 characterized by unsteady mass fluxes at the vent (Ripepe *et al.*, 1993; Donnadieu, 2012;
403 Scharff *et al.*, 2015; Chevalier & Donnadieu, 2015). If the source mass flux fluctuates
404 significantly over time, we would expect to see such fluctuations in the radar data acquired
405 above the vent. However, the reflectivity of the ascending ash plume detected by the radar
406 (**Figure 7A**) does not show such time-dependent behavior during the emission. Nonetheless,
407 the radar data do show an alternating pattern of positive and negative Doppler velocities (see
408 white arrows top left of this **Figure 7B**), which we interpret as internal motions within the
409 plume.

410 With an approximately constant mass eruption rate (at least over the time scale for
411 sediment fingers to form in our data), one mechanism for the quasi-periodic formation of the

412 fingers evident in **Figure 1B** and **Figure 8** is the intermittent growth and detachment of ash-
413 rich particle boundary layers (Carazzo & Jellinek, 2012; Scollo *et al.*, 2017). If sufficiently
414 strong, the wind will influence the timing of these convective effects in the Stromboli ash cloud
415 in **Figure 1** and **Figure 8**. If we assume that the wind is horizontal, from the crater to the radar
416 site, consistent with qualitative observations made in the field, we estimate the wind speed as
417 the horizontal component of the overall range-time slope for the sedimentation in radar
418 reflectivity data as $v_w = 2.47$ m/s (**Figure 7A**). This background wind is larger than the
419 maximum inferred settling speeds for particles forming the median grain size in the PSD
420 (**Figure 5C**) and will consequently affect their dynamics at leading order. For a cloud width H_0
421 (*i.e.* where the maximum reflectivity is detected), wind-driven organization of the ash plume
422 will occur over a time scale $t_w = H_0/v_w$. Because this time scale is comparable to or smaller than
423 the time scale for particle settling $t_p = H_0/V_T$ for much of our inferred PSD, an initial prediction
424 for particle buoyancy-driven sedimentation is that it will begin approximately at or shortly after
425 $\sim 1 t_w$, which is consistent with **Figure 7D**. We consequently infer that there is strong particle-
426 fluid coupling and these mixture buoyancy effects are more important than particle loss by their
427 ejection from the rolls (*i.e.*, so-called Stokes number effects). Moreover, if this inference is
428 incorrect, the change in concentration in **Figure 7D** would begin at a different part of the
429 evolution than where $t/(H_0/v_w) = 1$.

430 Although consistent with **Figure 7D**, this heuristic expectation provides little insight
431 into the underlying mechanisms governing how particles become concentrated into mixtures
432 sufficiently dense to form fingers (Carazzo & Jellinek, 2012). **Figure 7D** shows only that
433 progressive particle loss occurs after $\sim 1 t_w$. Nonetheless, observations of fingers in the images
434 of the wind-advected plume taken on October 2, 2015 (**Figure 1B**) indicate that the small-scale
435 reflectivity trends in **Figure 6A** and **Figure 7A** represent ash fingers. If ash sedimentation is

436 only controlled by individual particle settling, we would expect to see an LDRF with no small-
437 scale reflectivity features within.

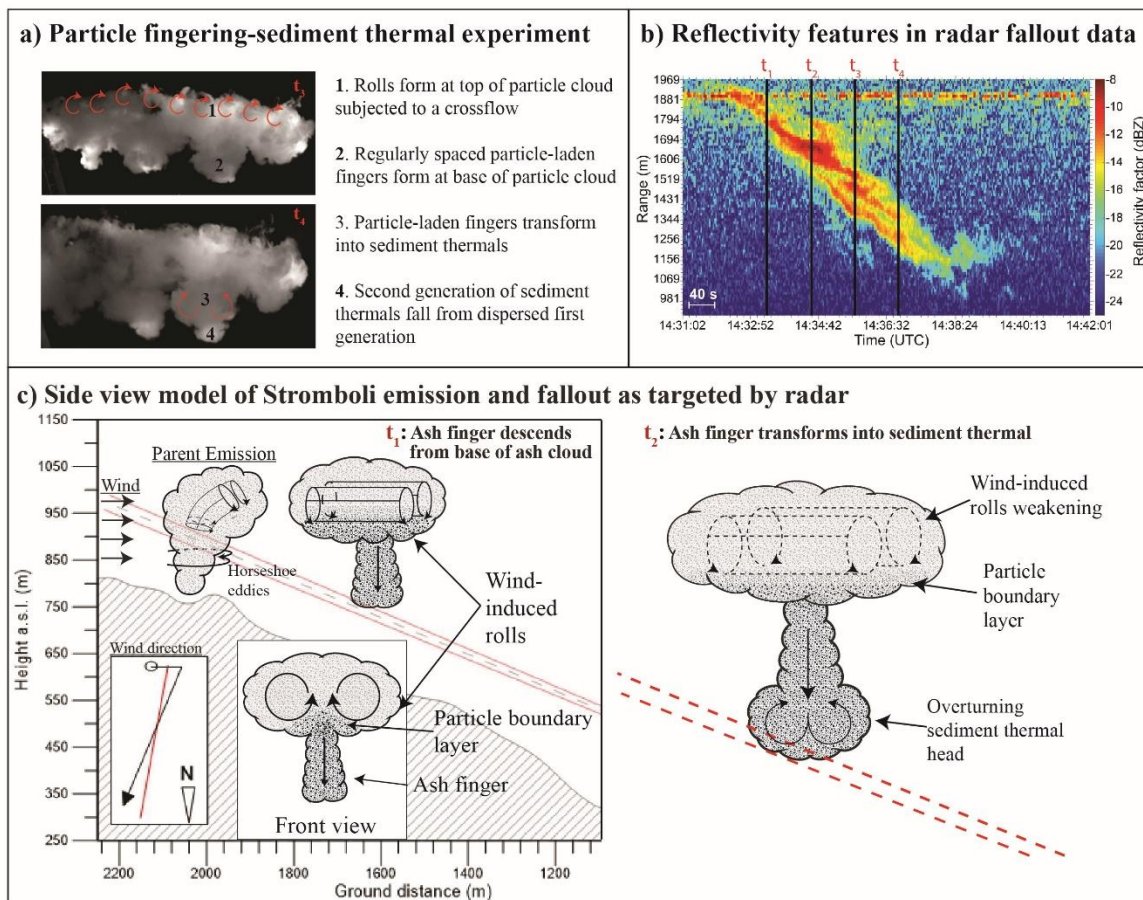
438 The maximum finger length, h_f below the parent ash cloud is $h_f = t_w V_f$, where V_f is the
439 finger fall velocity (see Equation 23 in Carazzo & Jellinek, 2012). If we assume that particle-
440 fluid mixtures forming fingers descend faster than individual particles (*i.e.*, a condition for
441 fingers to form in the first place) then we can take $V_f \approx V_T$ detected in the LDRFs in **Figure 7B**.
442 With $H_0 = 100$ m we find $189 < h_f < 300$ m, in agreement with estimates from visual
443 observations of fingers in **Figure 1B** and **Figure 8**. Additionally, the initial increase in width
444 followed by a decrease in overall v_r of the LDRFs in **Figure 6A**, **Figure 7A** and **Figure 8B**
445 indicate that the volume of the fingers increases as they fall, which is followed by a decrease in
446 settling velocity soon after, consistent with the dynamics of sediment thermals (Bush *et al.*,
447 2003). On this basis, we propose that these are observations of fingers evolving into sediment
448 thermals (Ernst *et al.*, 1994; Bush *et al.*, 2003; Carazzo & Jellinek, 2012; Suzuki & Koyaguchi,
449 2013; Del Bello *et al.*, 2017; Scollo *et al.*, 2017

450 4.2 A conceptual model for the generation of fingers forming sediment thermals

451 To build qualitative understanding of the sedimentation dynamics below wind-affected
452 volcanic plumes, we conduct simple experiments (described in the **Supplemental Information**
453 **S3**) in which we introduce dilute warm mixtures of 0.030, 0.190, 0.225 and 2 mm diameter
454 silica particles into water with an imposed constant crossflow velocity to form an advected
455 analog for the cloud shown in **Figure 1**. We choose ad hoc properties in the experiments to
456 capture the range in t_w/t_p inferred for our PSD for a wind speed of 2.47 m/s, and to explore
457 sensitivity of the cloud structure to this ratio of time scales (**Figure 9**). In **Figure 9A**, counter-
458 rotating rolls induced by the experimental crossflow develop along with regularly spaced

459 sedimentation features in the form of particle-laden fingers. They detach to form sediment
460 thermals but retain the regular spacing of the features. Descending sediment thermals entrain
461 ambient water and their buoyancy increases. This entrainment causes them to slow such that
462 entrained particles sediment from their basal edges to form a second generation of smaller
463 sediment thermals. The second generation of sediment thermals disperses and the dispersed
464 clouds of both generations continue to settle to the tank floor at the terminal settling velocity of
465 the modal particle size (0.03 m/s and 0.200 mm respectively) (Bush *et. al.*, 2003; Carazzo &
466 Jellinek, 2012).

467 Guided by the experimental observations from **Figure 9A**, previous studies (Ernst *et al.*,
468 1994; Bush *et al.*, 2003; Carazzo & Jellinek, 2012; Scollo *et al.*, 2017), and the field
469 observations presented in this study we present the conceptual model. We key the main features
470 of this model to 4 time slices (t_1 - t_4 in **Figure 9B**), which indicate the sedimentation pulses in
471 **Figure 7A** and those inferred in **Figure 9A**. The sketches of **Figure 9C** depict the formation of
472 ash fingers over a time $\sim t_w$ evolving, in turn, into sediment thermals at the base of the volcanic
473 ash cloud, as seen by the radar. The development of counter-rotating rolls in the particle cloud
474 enhances the delivery of particles to its base, particularly where the flow in the rolls converge
475 (Front view in **Figure 9C**). This relatively dense mixture undergoes gravitational instabilities
476 to form fingers, in turn (Carazzo & Jellinek, 2012, 2013; Scollo *et al.*, 2017) (t_2 in **Figure 9C**;
477 see also figures 3, 5, 6 and 9 in Scollo *et al.*, 2017). Fingers descend, entrain ambient fluid and
478 decelerate (**Figure 9A**, t_3). This basic evolution agrees with the increase in cloud width (point
479 2 in section 4.1) and overall decrease of cloud settling velocity (point 4 in section 4.1) occurring
480 simultaneously around 14:33:30. However, **Figure 7B** shows that the overall settling velocity
481 increases after 14:36:30, which could imply that a second generation of sediment thermals has
482 formed, similar to that observed at t_4 in the **Figure 9A**.



483

484 **Figure 9:** A) Photo of polydisperse particle cloud experiment exhibiting regularly spaced particle-laden
 485 fingers transforming into sediment thermals. Crossflow is from left to right, nearside counter-rotating
 486 roll indicated by number 1 with red arrows showing fluid motion and sediment thermals are marked by
 487 numbers 2 and 3 with red arrows showing overturning head fluid motion. t_4 corresponds to instance in
 488 A), which represents the second generation of sediment thermals. B) Zoomed view of sedimentation
 489 pulses in Figure 7A with black bars representing four instances in time (t_1 - t_4). C) Model sketches of
 490 parent ash emission with crosswind generating horseshoe eddies that induce counter-rotating rolls in
 491 resulting ash cloud. t_1 and t_2 show sedimentation behavior at instances in time corresponding to t_1 and
 492 t_2 in A), with radar beam in red. t_1 shows side and front views of ash cloud with arrows indicating flow
 493 direction for counter-rotating rolls and initial finger instability. Darker particles at base of ash cloud
 494 in Front View and t_2 highlight the Particle Boundary Layer formation enhanced by counter-rotating
 495 rolls above. t_2 shows overturning motions at head of finger as it evolves into a sediment thermal (Ernst

496 *et al., 1994; Bush et. al, 2003; Carazzo & Jellinek, 2012, 2013; Suzuki & Koyaguchi, 2013; Del Bello*
497 *et al., 2016; Scollo et al., 2017).*

498 Predictions from the conceptual model in **Figure 9** satisfy the list of observations we
499 identify in section 4.1 and make additional predictions, in line with our observations:

- 500 1. Fingers transitioning into sediment thermals: Periodic structure of the sedimentation
501 pulses in space and time (**Figures 4, 5, 6, 7 and 9**).
- 502 2. Entrainment and finger/thermal dilution: The volumetric growth of sediment thermals
503 through entrainment is consistent with observed increases in size in **Figures 6 and 7A**,
504 and the decrease in reflectivity density of the initially detected sedimentation pulses in
505 **Figure 7D**. Dilution through entrainment is also consistent with the overall increase of
506 v_r within the sedimentation, indicating a decrease in settling velocity, occurring after
507 14:34:30 in **Figure 7B** and after 12:22:00 and 12:23:30 in **Figure 8B**, respectively.
- 508 3. Multiple generations: The entrance of later forming fingers into the radar beam, after
509 the initial finger enters the radar beam, explains the emergence of periodic
510 sedimentation structure after the first sedimentation pulse is detected (**Figure 7A**). In
511 particular, the particle loading supplied by a second generation of sediment thermals
512 may explain the curious decrease of v_r (between 15:26:00 and 15:28:00 in **Figure 6B**;
513 after 14:36:30 in **Figure 7B**), which indicates an increase in settling velocity, later in
514 the sedimentation.
- 515 4. Sediment thermals, entrainment and individual particle settling: The dispersal of sediment
516 thermals leads to individual particle settling, which is captured by the radar and can
517 explain the modal v_r in the sedimentation corresponding to a smaller size range of
518 particles than that detected by the disdrometer. The faster fall velocity of sediment

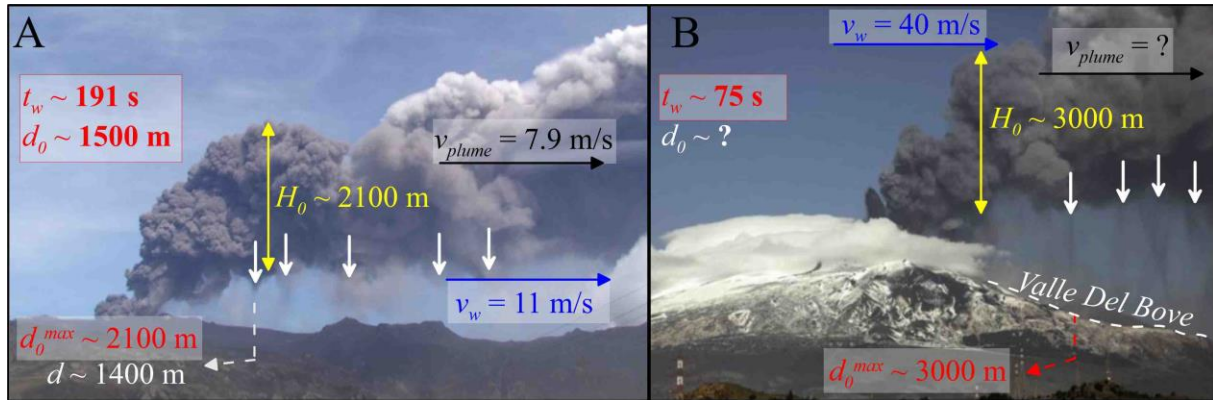
519 thermal mixtures *vs* the terminal settling velocity of the particles that compose them can
520 explain the extreme values of $v_r, \leq -3$ m/s detected in the sedimentation (**Figure 7B**).

521 5. Theoretical plausibility of sediment fingers: The modal value of the local PSD measured
522 at the disdrometer (0.345-0.460 mm) and the modal value derived from v_r (0.100-0.300
523 mm) are both consistent with theoretical constraints indicating a 0.060-0.250 mm particle
524 size limit for the formation of fingers for plausible ash concentrations (Carazzo & Jellinek,
525 2012, Figure 8). Moreover, the maximum ash concentration derived from the disdrometer
526 measurements, 0.681 g/m^3 , is comparable to the minimum concentration required (1 g m^{-3})
527 ³) for the development of gravitational instabilities determined from scaling arguments.
528 (Carazzo & Jellinek, 2012; Manzella *et al.*, 2015). Furthermore, radar measurements of
529 ash cloud thickness, finger fall and ambient wind velocity predict a finger length, $189 < h_f$
530 < 300 m, which is consistent with the observations in **Figure 1B**.

531 4.3 Wind-affected ash finger sedimentation

532 Ash fingering requires the formation of PBLs, which are expected to govern ash
533 sedimentation in highly explosive eruptions (Carazzo & Jellinek, 2012), as well as the relatively
534 weak events at Stromboli in 2015 (*i.e.*, type 2 explosions of Patrick *et al.*, 2007; **section 2.1**). It
535 is important to note that the ash clouds observed in this study are not related to large MERs or
536 high concentrations of particles, *i.e.* two mandatory conditions for the formation of gravitational
537 instabilities in addition to the presence of fine ash, after Scollo *et al.*, 2017. Hence, our new
538 finding at Stromboli that will enter in consideration for how and when ash fingers form
539 generally is that wind-driven stirring can modulate the growth and timing of PBLs. In particular,
540 unsteady wind-driven motions can form spatially local zones of fine-grained ash concentration
541 where counter-rotating vortices meet (**section 4.2**). We expect the occurrence of these wind
542 effects on sedimentation to be common features of any ash cloud for which $t_w \sim t_p$ (**section 4.1**).

543 Furthermore, these effects will be enhanced in clouds with higher particle concentration and a
 544 greater proclivity for PBL formation (Carazzo & Jellinek, 2012).



545
 546 **Figure 10:** Ash plume snapshots of **A)** the Eyjafjallajökull long-lasting plume on 4 May 2010 (figure
 547 modified from Manzella *et al.*, 2015) and **B)** the 23 November 2013 paroxysmal tephra plume at Mount
 548 Etna (Figure modified from Scollo *et al.*, 2017, source: [www.tboeckel.de/EFSF/efsf_etna/Etna2013/
 549 Etna_11_13/volcano_etna_11_2013_e.htm](http://www.tboeckel.de/EFSF/efsf_etna/Etna2013/Etna_11_13/volcano_etna_11_2013_e.htm)). White arrows indicate ash finger location. Are reported on
 550 both figures the horizontal plume and wind speed (v_{plume} and v_w), the plume width (H_0), the distance from
 551 the vent where the first finger is observed (d) or is expected due to wind-driven organization (d_0) and
 552 the maximum distance d_0^{max} assuming $v_w = v_{plume}$.

553 However, among the studies relating to ash finger formation (Carazzo & Jellinek, 2012,
 554 2013; Manzella *et al.*, 2016; Scollo *et al.*, 2017; and reference therein), the potential for wind-
 555 driven dynamics of ash finger sedimentation and potential impact on ground in a natural system
 556 have only been explored by Manzella *et al.* (2015) during the Eyjafjallajökull eruption in 2010.
 557 This study provides detailed observations of a long-lasting plume emitted on 4 May 2010. The
 558 plume horizontal velocity v_{plume} was ~ 7.9 m/s with a horizontal v_w at its base of 11 m/s (**Figure**
 559 **10A**). Considering a plume width H_0 of ~ 2100 m obtained from **Figure 10A**, we derive a wind-
 560 driven organization time (see **section 4.1**) t_w of 191 s. This value, multiplied by v_{plume} , leads to
 561 a distance d_0 of ~ 1500 m being similar to the ~ 1400 m from which fingers are continuously

562 observed (Manzella *et al.*, 2015). Therefore, our results for transient weak Strombolian plumes
563 help to reconcile key observations of sedimentation from the relatively continuous
564 Eyjafjallajökull event: Fingers appear approximatively or shortly after ~ 1 wind-driven
565 organization time t_w . Also, if we take $v_{plume}=v_w$, we obtain a maximum distance at which the
566 first finger should form with $d_0^{max}= 2100$ m, approximately the width of the plume. Hence,
567 evidence of ash fingers on ground deposit should emerge at a distance greater than d_0^{max} ,
568 depending on the horizontal speeds of the fingers and their settling velocity (Manzella *et al.*,
569 2015).

570 We have applied the same reasoning for a weak plume emitted during the 23 November
571 2013 paroxysm at Mount Etna (**Figure 10B**). For this eruption, less information (*e.g.* distance
572 of finger formation and plume horizontal speed) is available except for a wind speed of ~ 40 m/s
573 and a plume width of ~ 3000 m (Corradini *et al.*, 2016; Montopoli, 2016). Considering the
574 maximum plume velocity to be equal to v_w leads to $d_0^{max}=3000$ m. Although less precise than
575 the previous calculation for Eyjafjallajökull, this simple estimate seems reasonable at Etna
576 regarding the visually observed location of the first fingers inside La Valle del Bove from
577 **Figure 10B**.

578 Predictions based on our observations and conceptual model constitute a step forward
579 in understanding the location, timing and overall character of ash sedimentation driven by wind-
580 affected PBL convective dynamics. Nevertheless, quantitative observations of ash finger
581 formation remain poorly constrained for most eruptive events. Future field observations should
582 include high space-time resolution instruments similar to our Doppler radar to more precisely
583 constrain ash finger dynamics from transient and weak volcanic plumes *in situ*. Finally, given
584 the major control of wind on the 3-dimensional structure and dynamics of PBLs, future

585 experiments should address finger formation in the presence of background wind velocity fields
586 with varying strength and direction.

587 **5 Conclusions**

588 Quantifying the processes leading to ash finger formation *in situ* is a key challenge to
589 understand their impacts on ground deposits and how fine ash is dispersed in the atmosphere.
590 Our joint radar-disdrometer study aims to characterize, quantitatively, the behavior of
591 heterogeneous ash sedimentation from volcanic plumes at high spatial and temporal resolution.
592 As a case study, the campaign carried out at Stromboli in 2015 demonstrates an effective
593 approach for monitoring volcanic ash plumes and for characterizing the internal dynamics of
594 their sedimentation.

595 Our observations of ash sedimentation show that ash sedimentation is time dependent,
596 potentially periodic, and well explained as a consequence of wind-affected gravitational
597 instabilities to ash-air mixtures in the form of ash fingers. Our results support a hypothesis that
598 wind-induced counter-rotating rolls may concentrate ash particles such that the formation and
599 release of relatively dense ash-air mixtures occurs over a time scale that is small in comparison
600 to individual particle settling.

601 In more detail, we have provided evidence that the maximum particle size and minimum
602 concentration favoring fingering dynamics at the base of volcanic plumes (Carazzo & Jellinek,
603 2012, Scollo *et al.*, 2017) may be influenced by ambient wind. Estimates of the *in-situ* ash size
604 distribution and concentration across the fingers are, however, required for a more thorough
605 comparison of these data with existing theoretical constraints on the basis of laboratory
606 experiments. Time-dependent wind-induced counter-rotating rolls in ash plumes are not a new
607 phenomenon and have been observed for a wide spectrum of eruptive activity (Ernst *et al.*,

608 1994; Suzuki & Koyaguchi, 2013). However, their role in ash finger formation was not
609 previously quantified. Accordingly, we show that ash fingers may form approximatively at or
610 shortly after one wind-driven organization time. Finally, if counter-rotating rolls, fingering and
611 sediment thermal dynamics emerge even for very dilute and short-lived ash plumes observed
612 in this study, we expect these physical processes to be common features of wind-affected
613 explosive volcanic plumes with higher fine ash concentrations that have a greater proclivity for
614 particle boundary layer-related dynamics to occur (Carazzo & Jellinek, 2012). Our newly
615 proposed model for the effect of wind on ash finger formation can be tested with future
616 experimental studies and may need to be parameterized for ash cloud dispersal and fallout
617 modelling in the framework of ash hazard assessment following explosive eruptions.

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