Reconstruction of Azorean eruptive scenarios through the correlation of proximal and distal tephras

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1. INTRODUCTION

Explosive volcanic eruptions are amongst the most hazardous natural phenomena due to their potential to affect large areas of land, ocean, and airspace. The resulting tephra fallout can threat human and animal health, crops, vegetation, water resources, and critical infrastructure, among many others. Thus, understanding how volcanic ash clouds disperse is of crucial importance for the mitigation of volcanic hazard. However, on small volcanic islands determining eruption source parameters of past volcanic eruptions is difficult due to limited area of deposition, which may lead to large uncertainties. São Miguel Island, located in the Azores archipelago (Figure 1), in the middle of the North Atlantic, is a small and active volcanic island with an extensive geological record of explosive eruptions from several trachytic central volcanoes. Previous studies have reported distal occurrences of Azorean tephra as far as North Africa or the British Isles, but to date there are no reconstructions of tephra dispersal patterns.

In the present work, proximal trachytic tephra layers from Sete Cidades and Furnas volcanoes on São Miguel Island are correlated with cryptotephras found in Morocco and Ireland, respectively, based on volcanic glass compositions (Figure 2) and age constraints (Table 2). To reconstruct possible volcanic ash clouds trajectories from Sete Cidades and Furnas volcanoes to Morocco and Ireland, we used the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1997) from NOAA (National Oceanic and Atmospheric Administration) and, performed simulations of hundreds of eruptive scenarios based on Santa Bárbara, Furnas C, Furnas I, and Furnas 1630 AD eruptions, and daily atmospheric conditions between 2014 and 2021.

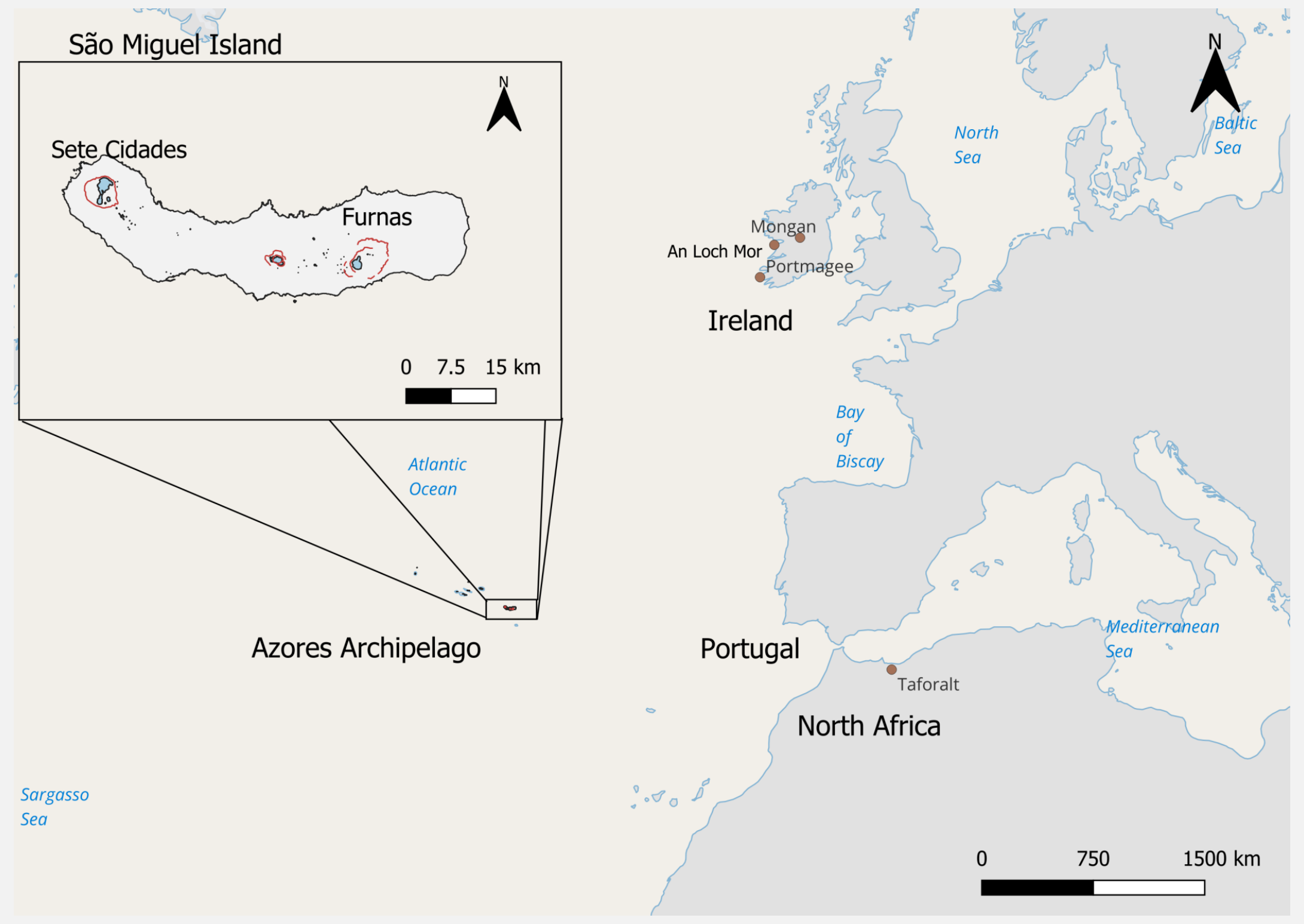

Figure 1. Map with Azores Arquipelago location and distribution of study sites in São Miguel Island, North Africa and Ireland. Location of distal tephras marked with a brown point, namely, in North Africa and Ireland.

2. ERUPTIONS DATA AND DEPOSITS CHARACTERISTICS

Eruptions from São Miguel Island

- 1 Magmatic Eruption from Sete Cidades volcano (Smithsonian volcano number 382080):
  - Santa Bárbara
- 3 Hydromagmatic Eruptions from Furnas volcano (Smithsonian volcano number 382100):
  - Furnas C
  - Furnas I
  - Furnas 1630 AD/ Furnas J

Table 1. Eruptive Source Parameters

Eruption	Latitude	Longitude	Summit Height (m)	Column Height (m)
Santa Bárbara	37.87 N	25.79 W	842	17,000 (Kueppers et al., 2019)
Furnas C	37.77 N	25.32 W	805	17,000 (Cole et al., 1999)
Furnas I	37.76 N	25.32 W	805	13,000 (Cole et al., 1999)
Furnas 1630 AD/J	37.77 N	25.32 W	805	14,000 (Cole et al., 1995)

3. PROXIMAL AND DISTAL TEPHRA AGE CORRELATION AND GEOCHEMISTRY COMPILATION RESULTS

Table 2. Age calibration and correspondence of the chosen proximal and distal tephras.

Proximal Tephras	Age Cal BC – AD*	Distal Tephras
Santa Bárbara 15,740 ± 200 yr BP (Queiroz, 1997)	18,688 – 19,505 Cal yr BP	TAF_S1_R2 18 - 30 ka (Barton et al., 2015)
Furnas C 1870 ± 120 yr BP (Guest et al., 1999)	154 Cal BC - 422 Cal AD	MOR-T7 (c. 280 AD) MOR-T8 (c. 150 AD) MOR-T9 (c. 35 AD) (Chambers et al., 2004)
Furnas I c. 1439 - 1443 AD (Guest et al.,1999)	-	MOR-T2 c. 1400 AD (Chambers et al., 2004)
Furnas 1630 AD/J 1630 AD (Guest et al.,1999)	-	PMG-5 c. 1600 AD (Hall and Pilcher, 2002)

*CALIB rev. 8; Stuiver, M., and Reimer, P.J., 1993, Radiocarbon, 35, 215-230.

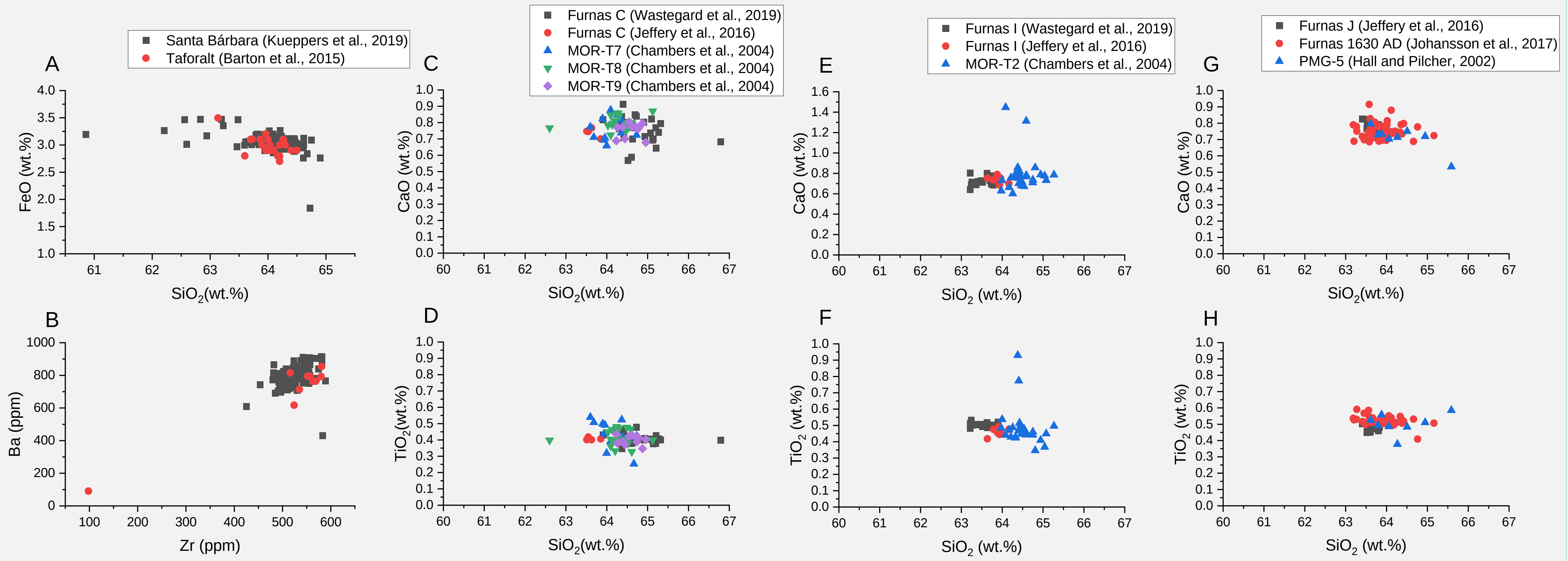

Figure 2. Geochemistry diagrams of major, minor and trace elements for tephra layers from Santa Bárbara eruption/ Taforalt site (A and B). Major and minor elements for tephra layers from Furnas eruptions/ Ireland sites (C - H).

4. HYSPLIT MODEL INPUTS

Meteorology data

- ✓ NCEP/NCAR Reanalysis database (Kalnay et al., 1996)

Eruptive Source Parameters

- ✓ Volcanic ash cloud microphysical properties are introduced by default within the HYSPLIT model, specific for Volcanic Ash (Stein et al., 2015)
- ✓ PSD following Dare, 2015
- ✓ Density of trachyte particles
- ✓ MER equation (Mastin et al., 2009)

↓

Scenarios simulations for conditions with particles reaching North Africa and Ireland

Table 3. HYSPLIT Input PSD for Sete Cidades Eruption

Santa Bárbara Eruption	Diameter (μm)	PSD-65 Mass Fraction (%)	Emission Rate (μg/h)	Emission Time (h)*	Simulation Days
Particle Group 1	0.65	1	3.105×10^{17}	4	03/01/2016 and 03/06/2016
Particle Group 2	2	6	1.863×10^{18}		
Particle Group 3	6.5	20	6.209×10^{18}		
Particle Group 4	20	34	1.056×10^{19}		
Particle Group 5	65	39	1.211×10^{19}		

* Estimated from column height based on Mastin et al. (2019)

Table 4. HYSPLIT Input PSD for Furnas Eruptions

Furnas C	Diameter (μm)	PSD-20 Mass Fraction (%)	Emission Rate (μg/h)	Emission Time (h)*	Simulation Days
Particle Group 1	0.65	1	3.105×10^{17}	22	19/02/2019 and 11/05/2019
Particle Group 2	2	5	1.552×10^{18}		
Particle Group 3	6.5	20	6.209×10^{18}		
Particle Group 4	20	70	2.173×10^{19}		
Particle Group 5	65	4	1.242×10^{18}		
Furnas I					
Particle Group 1	0.65	1	1.020×10^{17}	4	19/02/2019 and 11/05/2019
Particle Group 2	2	5	5.100×10^{17}		
Particle Group 3	6.5	20	2.040×10^{18}		
Particle Group 4	20	70	7.139×10^{18}		
Particle Group 5	65	4	4.080×10^{17}		
Furnas 1630 AD/J					
Particle Group 1	0.65	1	1.387×10^{17}	7	19/02/2019 and 11/05/2019
Particle Group 2	2	5	6.936×10^{17}		
Particle Group 3	6.5	20	2.774×10^{18}		
Particle Group 4	20	70	9.710×10^{18}		
Particle Group 5	65	4	5.548×10^{17}		

* Estimated from column height based on Mastin et al. (2019)

5. SIMULATIONS RESULTS AND ERUPTIVE SCENARIOS

Table 5. Number of simulations that reach the indicated locations, performed with HYSPLIT model.

Simulation Year	Locations				
	North Africa	Ireland	North Africa + Ireland	Other locations	Total of simulations per year*
2014	101 (58%)	11 (6%)	12 (7%)	51 (29%)	175
2015	85 (49%)	15 (9%)	14 (8%)	60 (34%)	174
2016	95 (54%)	18 (10%)	13 (7%)	49 (28%)	175
2017	72 (41%)	18 (10%)	20 (11%)	64 (37%)	174
2018	100 (57%)	11 (6%)	15 (9%)	48 (28%)	174
2019	85 (49%)	20 (11%)	13 (7%)	56 (32%)	174
2020	99 (57%)	12 (7%)	12 (7%)	51 (29%)	174
2021	91 (52%)	10 (6%)	21 (12%)	52 (30%)	174

* % is calculated relative each year.

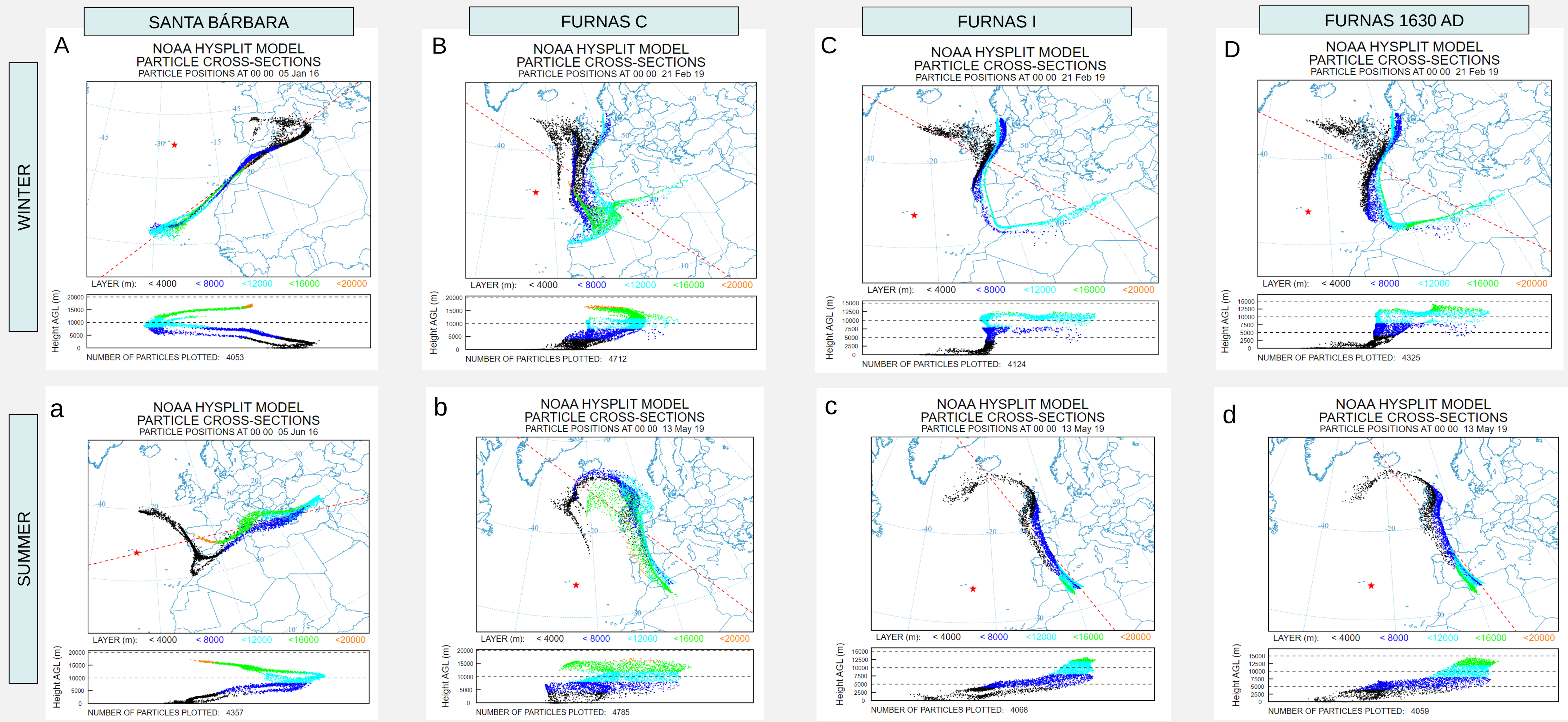

Figure 3. HYSPLIT simulations of ash particles dispersion with an output after 48 hours of run time. Eruptions of (A) Santa Bárbara in "winter" with 4 hours of emission (a) "summer"; (B) Furnas C "winter" with 22 hours emission (b) "summer"; (C) Furnas I "winter" with a 4 hours emission (c) "summer" and (D) Furnas 1630 AD "winter" with 7h emission (d) "summer".

★ represents the source volcano.

6. CONCLUSIONS AND REMARKS

The pumice fall deposit of Santa Bárbara eruption from Sete Cidades volcano has been geochemically correlated with cryptotephras in layer TAF_S1_R2 of Taforalt archaeological site, Morocco. Likewise, the deposits of three hydromagmatic eruptions of Furnas volcano showed good geochemical correlations with cryptotephras found in lacustrine sediments in Ireland, confirming previous studies: Furnas C compositionally matched cryptotephra layers MOR-T7, -T8, and -T9; Furnas I has been correlated with MOR-T2; and Furnas 1630 AD with PMG-5 cryptotephra.

Simulations results show that in 52% of the cases tephra disperses towards North Africa and in 8% towards the British Isles. Also, in 9% of the cases tephra heads to both North Africa and the British Isles in the same simulation and in the other 31% of the cases tephra disperses in different directions.

Although the frequency of explosive eruptions in the Azores is relatively low, a future explosive event may have tremendous economic consequences not only to the archipelago, but also to the entire North Atlantic airspace, as the predominant westerly atmospheric circulation pattern will most probably disperse volcanic ash clouds across some of the world's busiest air routes. Therefore, eruptive scenario modelling based on past eruptions is a fundamental tool to improve the assessment of volcanic hazard.

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