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Exposure-based risk assessment and emergency management associated with the fallout of large clasts at Mount Etna

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Supplementary information

Historical activity

Date	Crater	Plume height [a] (km)	Lava fountain height (m)	Duration (mins)	Reference
23 May 2016	NEC	n/a	n/a	n/a	(INGV, n.d.)
21 May 2016	VOR	n/a	n/a	~ 60	(INGV, n.d.)
19 May 2016	VOR	n/a	n/a	n/a	(INGV, n.d.)
18 May 2016	VOR	3 - 3.5 av	n/a	> 60	(INGV, n.d.)
5 Dec 2015	VOR	13 12.5	1120	~ 120 115	(Bonaccorso and Calvari, 2017; Corsaro et al., 2017; Pompilio et al., 2017; Vulpiani et al., 2016)
4 Dec 2015 pm	VOR	13.3 12.5	2050	65	(Bonaccorso and Calvari, 2017; Corsaro et al., 2017; Pompilio et al., 2017; Vulpiani et al., 2016)
4 Dec 2015 am	VOR	13.4	2600	~ 140 80	(Bonaccorso and Calvari, 2017; Corsaro et al., 2017; Pompilio et al., 2017; Vulpiani et al., 2016)
3 Dec 2015	VOR	15	>1000 4100	80 90	(Bonaccorso and Calvari, 2017; Corsaro et al., 2017; INGV, n.d.; Pompilio et al., 2017; Vulpiani et al., 2016)
28 Dec 2014	NSEC	n/a	n/a	> 120 ~ 90	(Bonforte and Guglielmino, 2015; INGV, n.d.)
14 Jun 2014	NSEC	n/a	n/a	n/a	(INGV, n.d.)
2 Dec 2013	NSEC	n/a	n/a	85	(De Beni et al., 2015)
28 Nov 2013	NSEC	n/a	n/a	385	(De Beni et al., 2015)
23 Nov 2013	NSEC	> 6 av 9 +/- 1.8 10 - 12	2500 3500 1000	40 50	(Andronico et al., 2015; De Beni et al., 2015; Bonaccorso et al., 2014, 2016; Corradini et al., 2016)
17 Nov 2013	NSEC	n/a	n/a	225	(De Beni et al., 2015; INGV, n.d.)
11 Nov 2013	NSEC	n/a	n/a	420	(De Beni et al., 2015; INGV, n.d.)
26 Oct 2013	NSEC	7	500	480	(De Beni et al., 2015; Greco et al., 2016; INGV, n.d.; Sellitto et al., 2016)
27 Apr 2013	NSEC	n/a	300 - 500	~ 120 130 210	(De Beni et al., 2015; INGV, n.d.; Viccaro et al., 2016)
20 Apr 2013	NSEC	7 av	800 - 1000	55 ~ 60 85	(De Beni et al., 2015; INGV, n.d.; Viccaro et al., 2016)
18 Apr 2013	NSEC	n/a	n/a	75 135	(De Beni et al., 2015; Spampinato et al., 2015; Viccaro et al., 2016)
12 Apr 2013	NSEC	n/a	n/a	~ 60 70 480	(De Beni et al., 2015; INGV, n.d.; Spampinato et al., 2015; Viccaro et al., 2016)
3 Apr 2013	NSEC	n/a	80 - 100	60 95 135	(De Beni et al., 2015; INGV, n.d.; Viccaro et al., 2016)
16 Mar 2013	NSEC	2 av	600 - 800	25 20	(De Beni et al., 2015; INGV, n.d.; Viccaro et al., 2016)
5-6 Mar 2013	NSEC	Several km av	800	45 50	(De Beni et al., 2015; INGV, n.d.; Viccaro et al., 2016)

Date	Crater	Plume height [a] (km)	Lava fountain height (m)	Duration (mins)	Reference
28 Feb 2013	NSEC	n/a	n/a	30 50	(De Beni et al., 2015; Viccaro et al., 2016)
23 Feb 2013	NSEC	n/a	800	45 60	(De Beni et al., 2015; INGV, n.d.; Viccaro et al., 2016)
21 Feb 2013	NSEC	n/a	n/a	30	(De Beni et al., 2015; Viccaro et al., 2016)
20 Feb 2013 pm	NSEC	n/a	n/a	45 110	(De Beni et al., 2015; Spampinato et al., 2015; Viccaro et al., 2016)
20 Feb 2013 am	NSEC	n/a	n/a	40 70	(De Beni et al., 2015; Spampinato et al., 2015; Viccaro et al., 2016)
19 Feb 2013	NSEC	n/a	200	45 80	(De Beni et al., 2015; Viccaro et al., 2016)
13 Feb 2013	NSEC	n/a	n/a	57	(De Beni et al., 2015)
24 Apr 2012	NSEC	n/a	n/a	45	(Viccaro et al., 2016)
12 Apr 2012	NSEC	3 av	n/a	70	(Viccaro et al., 2016)
1 Apr 2012	NSEC	Few km av	n/a	90	(Viccaro et al., 2016)
18 Mar 2012	NSEC	4 - 5 av	100	150 165	(INGV, n.d.; Viccaro et al., 2016)
4 Mar 2012	NSEC	Several km av	n/a	120	(Viccaro et al., 2016)
9 Feb 2012	NSEC	6 av	300 - 400	300 330	(INGV, n.d.; Viccaro et al., 2016)
5 Jan 2012	NSEC	7 - 8	100-150	95 105	(INGV, n.d.; Viccaro et al., 2016)
15 Nov 2011	SEC	Several km av	300	80	(Andronico and Del Carlo, 2015; Viccaro et al., 2016)
23 Oct 2011	NSEC	6	300	155 165	(Guerrieri et al., 2015; INGV, n.d.; Viccaro et al., 2016)
8 Oct 2011	NSEC	n/a	n/a	195 ~ 20	(INGV, n.d.; Viccaro et al., 2016)
28 Sep 2011	NSEC	n/a	600 - 800	35 40	(INGV, n.d.; Viccaro et al., 2016)
19 Sep 2011	NSEC	n/a	n/a	40	(Viccaro et al., 2016)
8 Sep 2011	NSEC	n/a	n/a	120 135	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)
29 Aug 2011	NSEC	n/a	100	45	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)
20 Aug 2011	NSEC	5 - 6 av	n/a	50 55	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)
12 Aug 2011	NSEC	3 av 7 9.5 +/- 0.5	> 100 Several 100 m	115	(Carbone et al., 2015; Guerrieri et al., 2015; Scollo et al., 2015; Viccaro et al., 2016)
5 Aug 2011	NSEC	n/a	710 > 500	165	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)
30 Jul 2011	SEC	n/a	450 - 500	120	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)
25 Jul 2011	SEC	n/a	340 350	240	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)

Date	Crater	Plume height [a] (km)	Lava fountain height (m)	Duration (mins)	Reference
19 Jul 2011	SEC	1.5 - 2 av	200 - 250	150	(Carbone et al., 2015; INGV, n.d.; Viccaro et al., 2016)
9 Jul 2011	SEC	9 av	540	105	(Carbone et al., 2015; Viccaro et al., 2016)
12 May 2011	SEC	2 - 3 av	200 - 300	250	(INGV, n.d.; Viccaro et al., 2016)
10 Apr 2011	SEC	2 av	300	360	(INGV, n.d.; Viccaro et al., 2016)
18 Feb 2011	SEC	n/a	n/a	660	(Viccaro et al., 2016)
12 Jan 2011	SEC	9 > 4 av > 6 av	800 300 - 500	65 100	(Andronico et al., 2014b; Calvari et al., 2011; Donnadieu et al., 2016; INGV, n.d.; Viccaro et al., 2015)
10 May 2008	SEC	n/a	n/a	210	(Bonaccorso et al., 2011)
23 Nov 2007	SEC	n/a	n/a	300	(Acocella et al., 2016)
4 Sep 2007	SEC	5	350 - 400 400 - 600	600 640	(Acocella et al., 2016; Andronico et al., 2008)
7 May 2007	SEC	n/a	n/a	450	(Acocella et al., 2016)
29 Apr 2007	SEC	Few 100 m av	n/a	n/a	(Acocella et al., 2016)
11 Apr 2007	SEC	n/a	n/a	> 225	(Acocella et al., 2016)
29 Mar 2007	SEC	Several km av	600 - 800	70	(Acocella et al., 2016)
24 Nov 2006	SEC	1.3 - 2 av	200 - 300	n/a	(Andronico et al., 2014a)
25 Nov – 4 Dec 2002	SEC	n/a	n/a	10 days	(Spampinato et al., 2008)
14 Nov 2002	SEC	7 av 3.5 av	n/a	n/a	(Scollo et al., 2012)
13 Jul 2001	SEC	n/a	400 - 500	140	(La Spina et al., 2015)
7 Jul 2001	SEC	n/a	300 - 400	45	(La Spina et al., 2015)
4 Jul 2001	SEC	n/a	50 - 60	80	(La Spina et al., 2015)
27 Jun 2001	SEC	n/a	400 - 500	55	(La Spina et al., 2015)
22 Jun 2001	SEC	n/a	300 - 400	15	(La Spina et al., 2015)
19 Jun 2001	SEC	n/a	200 - 300	35	(La Spina et al., 2015)
17 Jun 2001	SEC	n/a	150 - 200	40	(La Spina et al., 2015)
15 Jun 2001	SEC	n/a	50 - 60	n/a	(La Spina et al., 2015)
13 Jun 2001	SEC	n/a	150 - 200	45	(La Spina et al., 2015)
9 Jun 2001	SEC	n/a	n/a	n/a	(Alparone et al., 2007)
7 Jun 2001	SEC	n/a	n/a	n/a	(Alparone et al., 2007)
24 Jun 2000	SEC	3 – 4 av	500	440	(Alparone et al., 2003)
14 Jun 2000	SEC	4.5 av	600	250	(Alparone et al., 2003)
8 Jun 2000	SEC	n/a	n/a	280	(Alparone et al., 2003)
5 Jun 2000	SEC	4 av	500 - 600	145 35	(Alparone et al., 2003, 2007)
1 Jun 2000 pm	SEC	n/a	n/a	125	(Alparone et al., 2003)
1 Jun 2000 am	SEC	5.5 av	800	500	(Alparone et al., 2003)
27 May 2000	SEC	n/a	n/a	195	(Alparone et al., 2003)
23 May 2000	SEC	n/a	n/a	115	(Alparone et al., 2003)
19 May 2000	SEC	n/a	n/a	115	(Alparone et al., 2003)
17 May 2000	SEC	Not visible	500	125	(Alparone et al., 2003)
15 May 2000 pm	SEC	Not visible	700	90	(Alparone et al., 2003)
15 May 2000 am	SEC	n/a	n/a	60	(Alparone et al., 2003)
5 May 2000	SEC	4.5 – 5 av	800	370	(Alparone et al., 2003)
26 Apr 2000	SEC	5 av	No data	80	(Alparone et al., 2003)

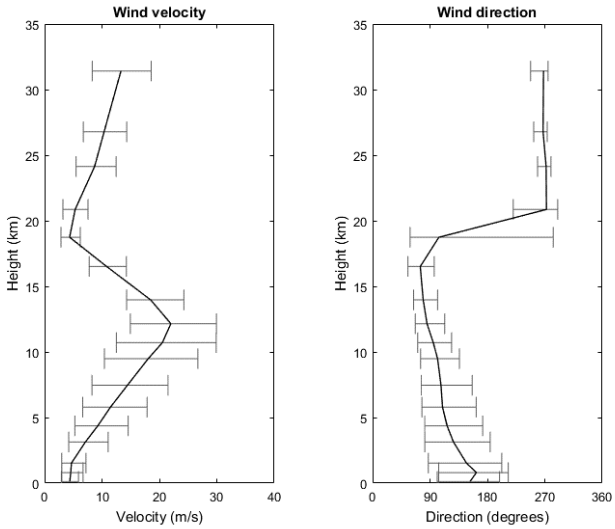
Date	Crater	Plume height [a] (km)	Lava fountain height (m)	Duration (mins)	Reference
16 Apr 2000	SEC	6 av	400	215	(Alparone et al., 2003)
6 Apr 2000	SEC	n/a	n/a	105	(Alparone et al., 2003)
3 Apr 2000	SEC	n/a	n/a	165	(Alparone et al., 2003)
1 Apr 2000	SEC	3 av	Fog	180	(Alparone et al., 2003)
29 Mar 2000	SEC	n/a	n/a	115	(Alparone et al., 2003)
24 Mar 2000	SEC	n/a	n/a	95	(Alparone et al., 2003)
22 Mar 2000	SEC	Not visible	300 - 350	125	(Alparone et al., 2003)
19 Mar 2000	SEC	n/a	n/a	115	(Alparone et al., 2003)
14 Mar 2000	SEC	Not visible	200 - 250	125	(Alparone et al., 2003)
12 Mar 2000	SEC	Not visible	80	130	(Alparone et al., 2003)
8 Mar 2000	SEC	3 av	300	145	(Alparone et al., 2003)
4 Mar 2000	SEC	n/a	n/a	120	(Alparone et al., 2003)
28 Feb 2000	SEC	n/a	n/a	100	(Alparone et al., 2003)
27 Feb 2000	SEC	n/a	n/a	165	(Alparone et al., 2003)
23 Feb 2000	SEC	n/a	n/a	105	(Alparone et al., 2003)
20 Feb 2000 pm	SEC	n/a	n/a	90	(Alparone et al., 2003)
20 Feb 2000 am	SEC	n/a	n/a	45	(Alparone et al., 2003)
19 Feb 2000	SEC	n/a	n/a	45	(Alparone et al., 2003)
18 Feb 2000 pm	SEC	n/a	n/a	20	(Alparone et al., 2003)
18 Feb 2000 am	SEC	n/a	n/a	20	(Alparone et al., 2003)
17 Feb 2000 pm	SEC	n/a	n/a	25	(Alparone et al., 2003)
17 Feb 2000 pm	SEC	n/a	n/a	25	(Alparone et al., 2003)
17 Feb 2000 am	SEC	n/a	n/a	25	(Alparone et al., 2003)
16 Feb 2000 pm	SEC	> 3 av	300 - 350	20	(Alparone et al., 2003)
16 Feb 2000 am	SEC	n/a	n/a	25	(Alparone et al., 2003)
15 Feb 2000	SEC	Not visible	>500	40	(Alparone et al., 2003)
14 Feb 2000 pm	SEC	4 av	350 - 400	30	(Alparone et al., 2003)
14 Feb 2000 am	SEC	n/a	n/a	60	(Alparone et al., 2003)
13 Feb 2000	SEC	n/a	n/a	25	(Alparone et al., 2003)
12 Feb 2000 pm	SEC	n/a	n/a	55	(Alparone et al., 2003)
12 Feb 2000 am	SEC	n/a	n/a	75	(Alparone et al., 2003)
12 Feb 2000 am	SEC	Not visible	350 - 400	70	(Alparone et al., 2003)
11 Feb 2000 pm	SEC	Not visible	250 - 300	60	(Alparone et al., 2003)
11 Feb 2000 am	SEC	n/a	n/a	55	(Alparone et al., 2003)
10 Feb 2000	SEC	n/a	n/a	55	(Alparone et al., 2003)
9 Feb 2000 pm	SEC	n/a	n/a	35	(Alparone et al., 2003)
9 Feb 2000 am	SEC	n/a	n/a	65	(Alparone et al., 2003)
8 Feb 2000 pm	SEC	n/a	n/a	70	(Alparone et al., 2003)
8 Feb 2000 am	SEC	n/a	n/a	75	(Alparone et al., 2003)
7 Feb 2000	SEC	3.2 av	200	75	(Alparone et al., 2003)
6 Feb 2000 am	SEC	n/a	n/a	65	(Alparone et al., 2003)
6 Feb 2000 pm	SEC	n/a	n/a	50	(Alparone et al., 2003)
5 Feb 2000	SEC	n/a	n/a	85	(Alparone et al., 2003)
4 Feb 2000 am	SEC	n/a	n/a	70	(Alparone et al., 2003)
4 Feb 2000 pm	SEC	n/a	n/a	50	(Alparone et al., 2003)
3 Feb 2000	SEC	n/a	n/a	85	(Alparone et al., 2003)
2 Feb 2000	SEC	n/a	n/a	65	(Alparone et al., 2003)
1 Feb 2000	SEC	n/a	n/a	100	(Alparone et al., 2003)
29 Jan 2000	SEC	n/a	n/a	95	(Alparone et al., 2003)
26 Jan 2000	SEC	n/a	n/a	565	(Alparone et al., 2003)
4 Nov 1999	BN	n/a	n/a	190	(Cannata et al., 2008)
27 Oct 1999	BN	n/a	n/a	415	(Cannata et al., 2008)

Date	Crater	Plume height [a] (km)	Lava fountain height (m)	Duration (mins)	Reference
21 Oct 1999	BN	n/a	n/a	110	(Cannata et al., 2008)
16 Oct 1999	BN	n/a	n/a	n/a	(Cannata et al., 2008)
14 Oct 1999	BN	n/a	n/a	n/a	(Cannata et al., 2008)
12 Oct 1999	BN	n/a	n/a	n/a	(Cannata et al., 2008)
20 Sep 1999	BN	n/a	n/a	130	(Cannata et al., 2008)
4 Sep 1999	SEC	n/a	n/a	10	(Cannata et al., 2008)
4 Sep 1999	VOR	n/a	1500	65	(Cannata et al., 2008; La Delfa et al., 2001)
4 Feb 1999	SEC	9	n/a	90 25	(Cannata et al., 2008; La Delfa et al., 2001)
23 Jan 1999	SEC	n/a	n/a	45	(Cannata et al., 2008)
20 Jan 1999	SEC	n/a	n/a	35	(Cannata et al., 2008)
18 Jan 1999	SEC	n/a	n/a	30	(Cannata et al., 2008)
16 Jan 1999	SEC	n/a	n/a	25	(Cannata et al., 2008)
13 Jan 1999	SEC	n/a	n/a	50	(Cannata et al., 2008)
10 Jan 1999	SEC	n/a	n/a	40	(Cannata et al., 2008)
5 Jan 1999	SEC	n/a	n/a	60	(Cannata et al., 2008)
11 Oct 1998	SEC	>10	Few 100 m	60	(Dubosclard et al., 1999)
15 Sep 1998	SEC	n/a	n/a	n/a	(Corsaro and Pompilio, 2004)
6 Aug 1998	VOR	n/a	n/a	n/a	(Corsaro and Pompilio, 2004)
22 Jul 1998	VOR	>10	n/a	6	(Andronico et al., 2015; Corsaro and Pompilio, 2004; La Delfa et al., 2001)
27 Mar 1998	NEC	n/a	n/a	120	(Corsaro and Pompilio, 2004; La Delfa et al., 2001)

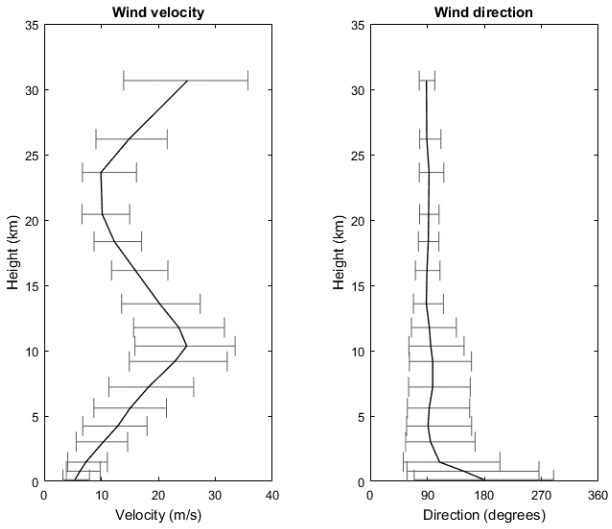
Table S1 Lava fountains at Mount Etna. Craters: BN (Bocca Nuova); NEC (Northeast Crater); NSEC (New Southeast Crater); SEC (Southeast Crater); VOR (Voragine). n/a = not available. [a] Plume height is above sea level, except av = above vent.

Wind analysis

Summer



Winter



All

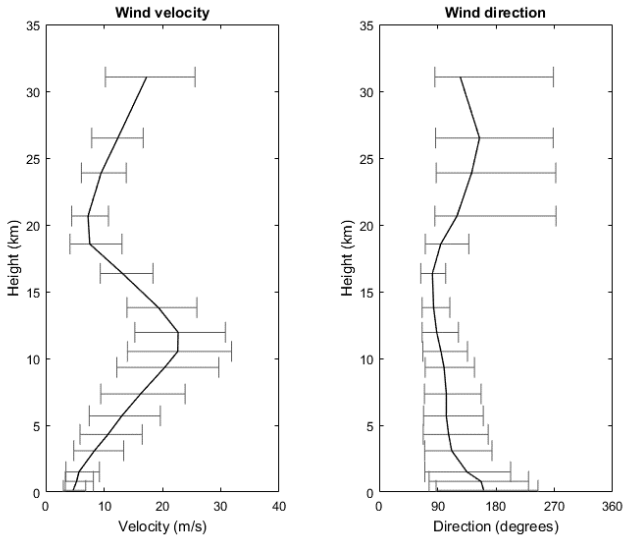


Fig. S1 Median wind speed and direction profiles, showing 25th and 75th percentile (error bars), for 2013 for summer (April to September), winter (October to March) and the whole period, produced from TephraProb (Biass et al., 2016; NOAA, 2017)**.** Wind direction is the direction towards which the wind blows, measured in degrees from north.

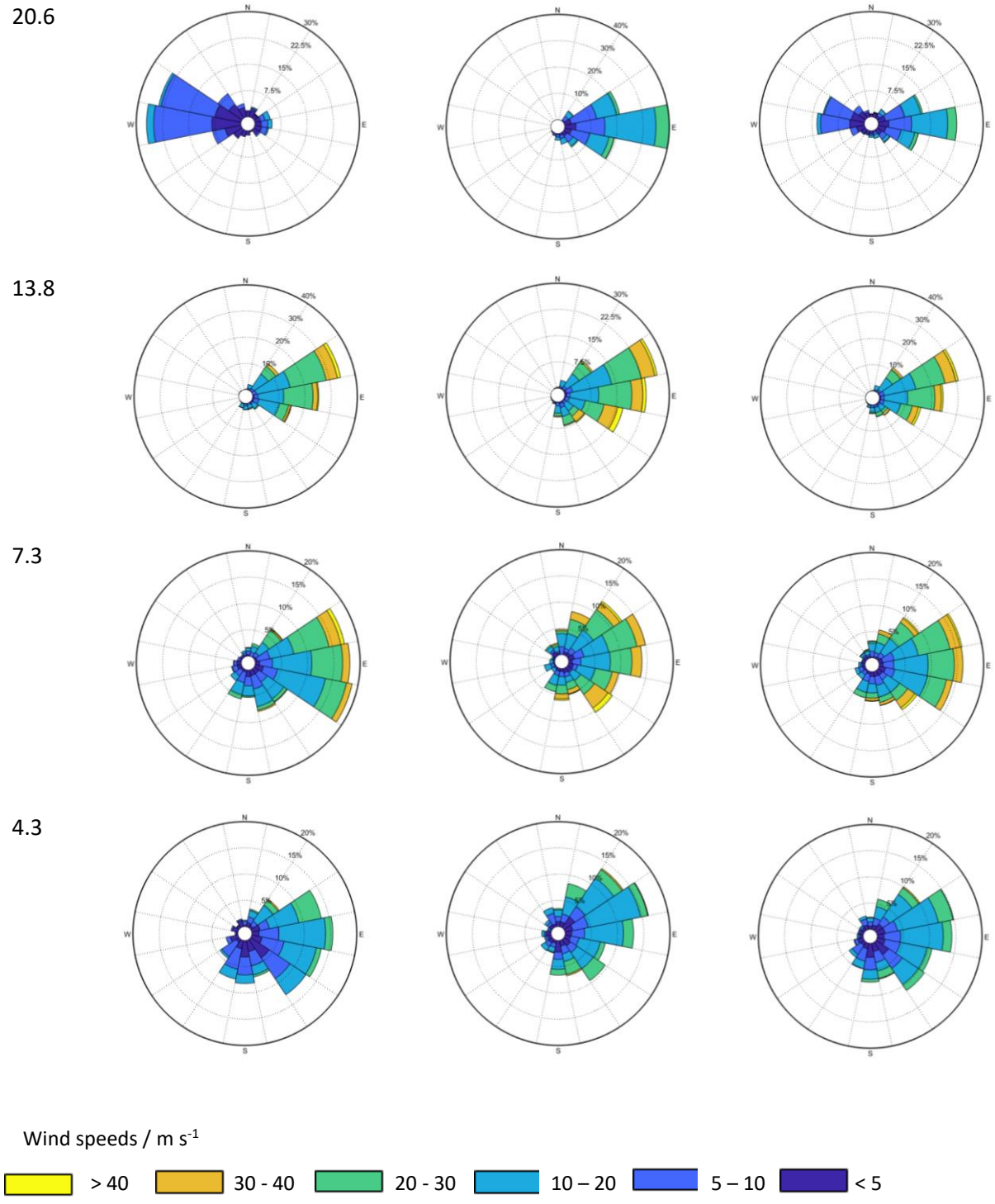
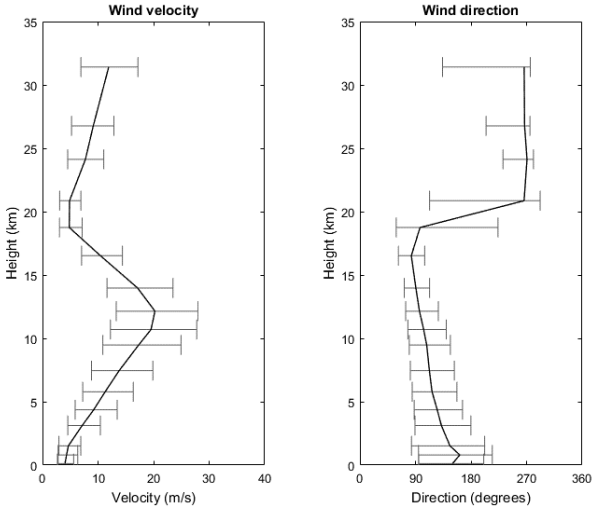
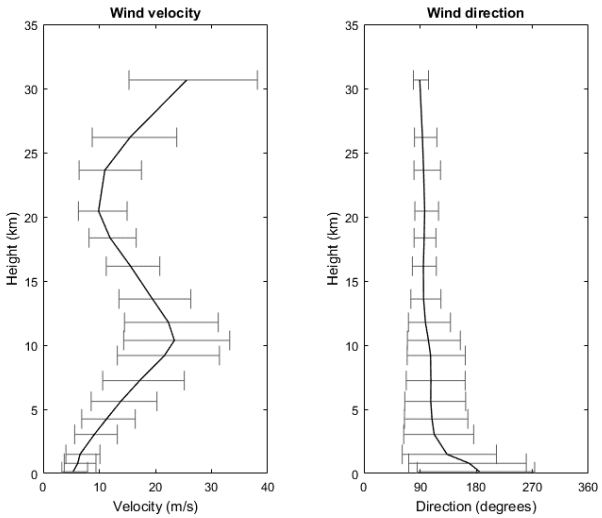


Fig. S2 Median wind roses for 2013 for summer (April to September), winter (October to March) and the whole period, produced from TephraProb (Biass et al., 2016; NOAA, 2017)**.** Wind direction is the direction towards which the wind blows.

Summer



Winter



All

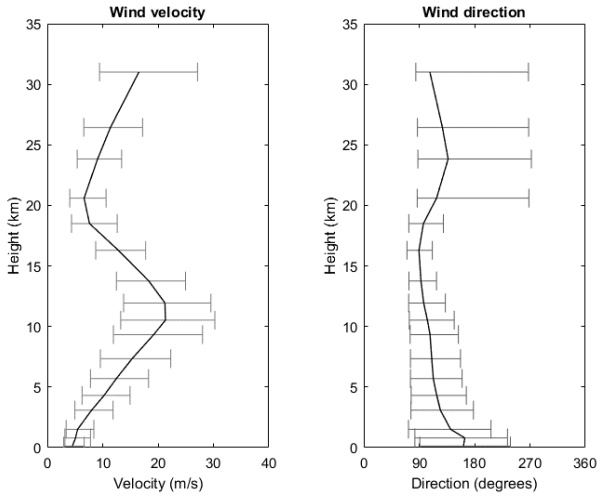


Fig. S3 Median wind speed and direction profiles, showing 25th and 75th percentile (error bars), for 2006 to 2015 for summer (April to September), winter (October to March) and the whole period, produced from TephraProb (Biass et al., 2016; NOAA, 2017)**.** Wind direction is the direction towards which the wind blows, measured in degrees from north.

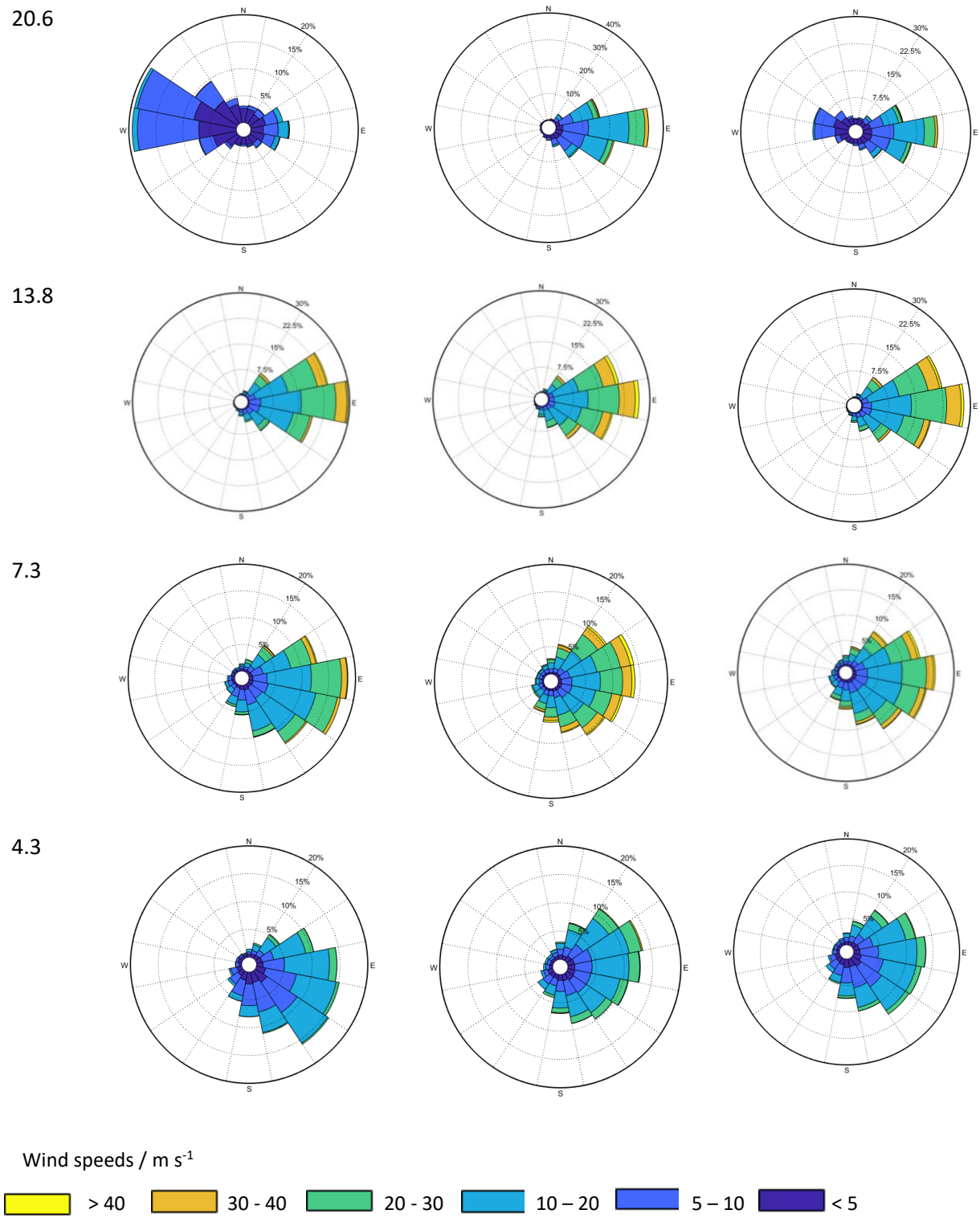
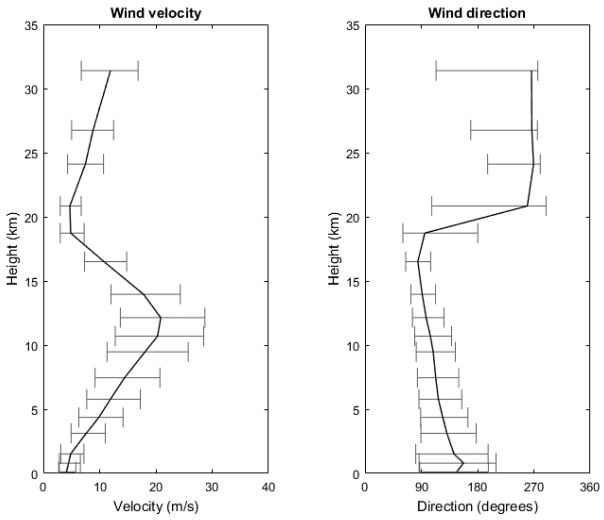
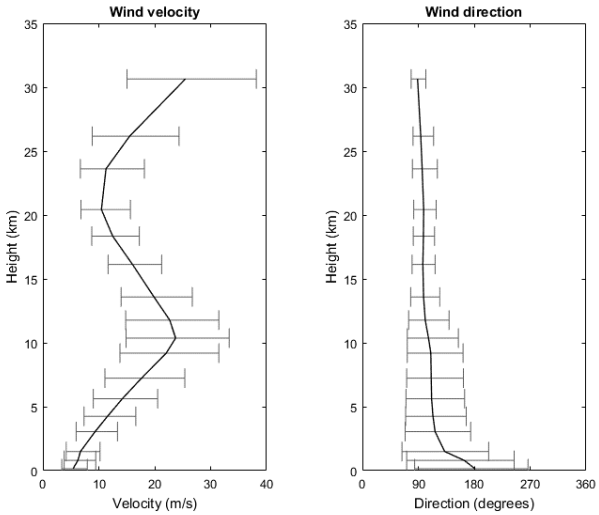


Fig. S4 Wind roses for 2006 to 2015 for summer (April to September), winter (October to March) and the whole period, produced from TephraProb (Biass et al., 2016; NOAA, 2017)**.** Wind direction is the direction towards which the wind blows.

Summer



Winter



All

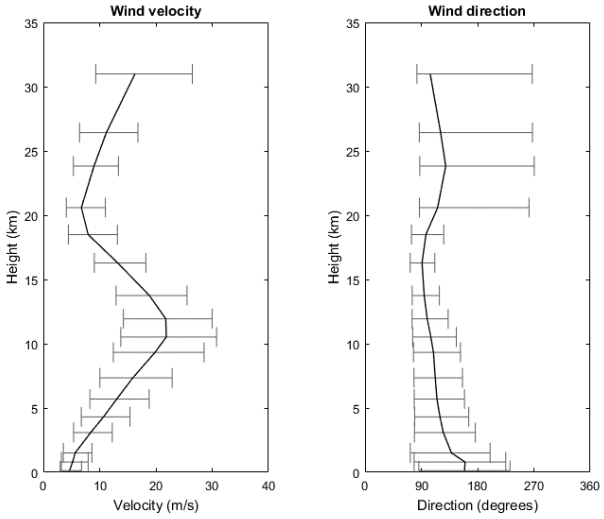


Fig. S5 Median wind speed and direction profiles, showing 25th and 75th percentile (error bars), for 1997 to 2015 for summer (April to September), winter (October to March) and the whole period, produced from TephraProb (Biass et al., 2016; NOAA, 2017)**.** Wind direction is the direction towards which the wind blows, measured in degrees from north.

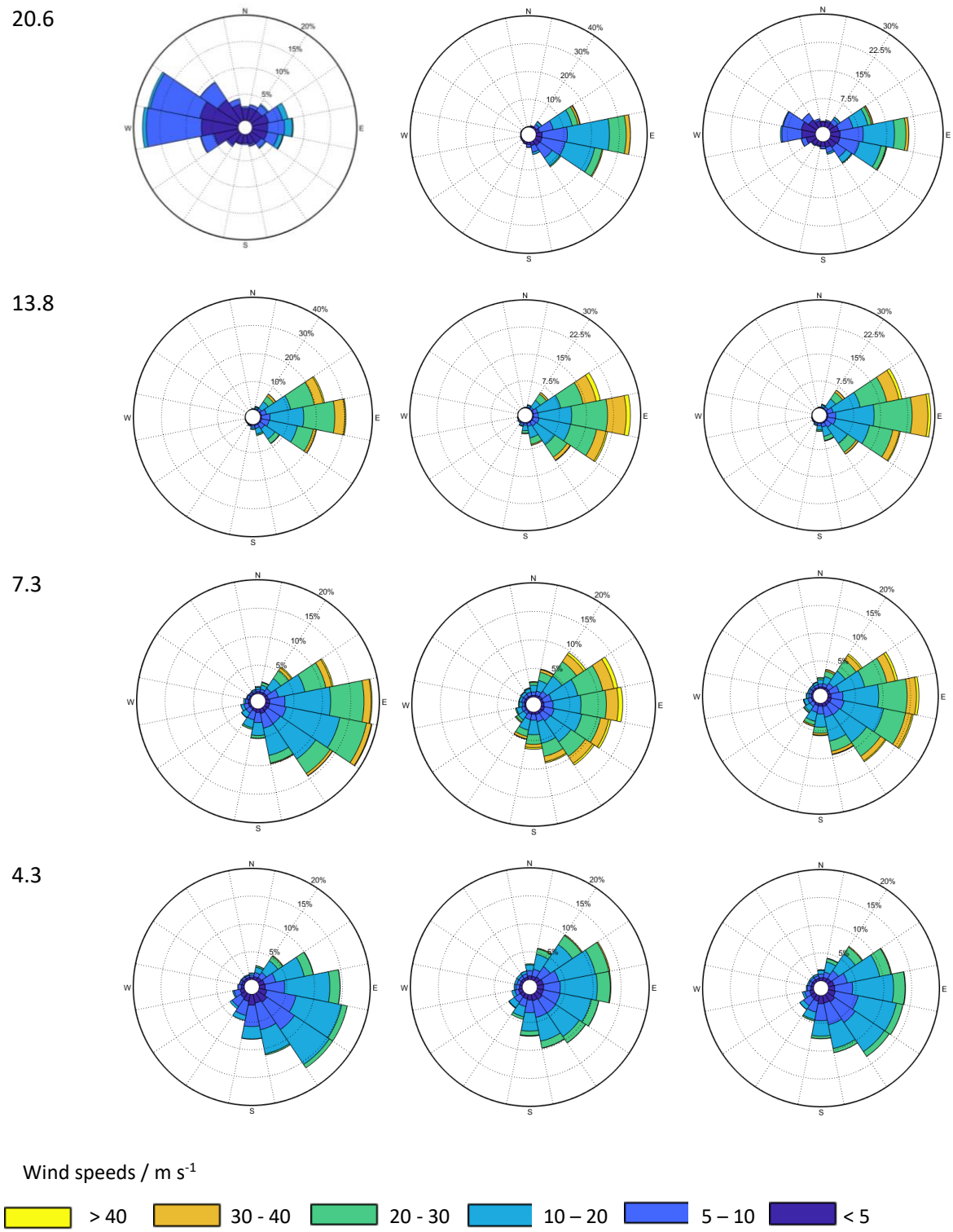


Fig. S6 Wind roses for 1997 to 2015 for summer (April to September), winter (October to March) and the whole period, produced from TephraProb (Biass et al., 2016; NOAA, 2017)**.** Wind direction is the direction towards which the wind blows.

Sensitivity analysis

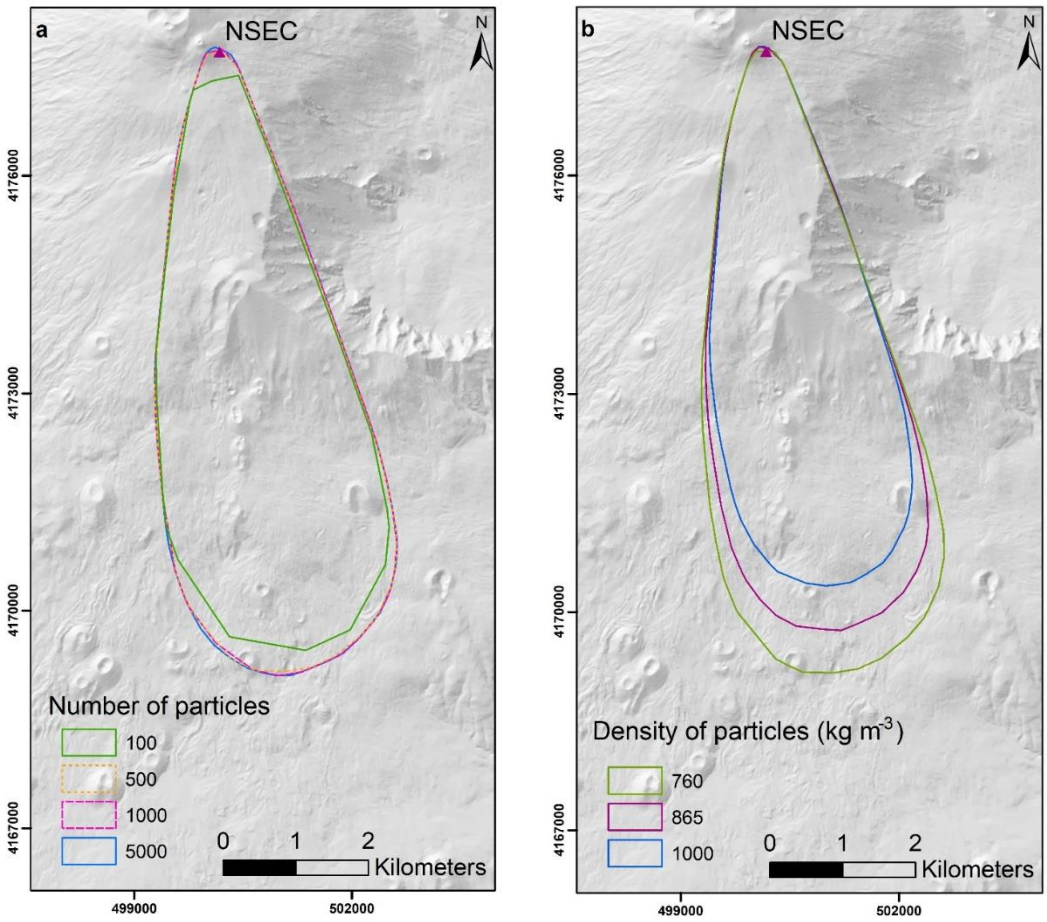


Fig. S7 For contours showing the furthest extent of sedimentation of 5 cm particles, impact of varying a) the number of particles used in each simulation, b) the particle density. NSEC = New Southeast Crater.

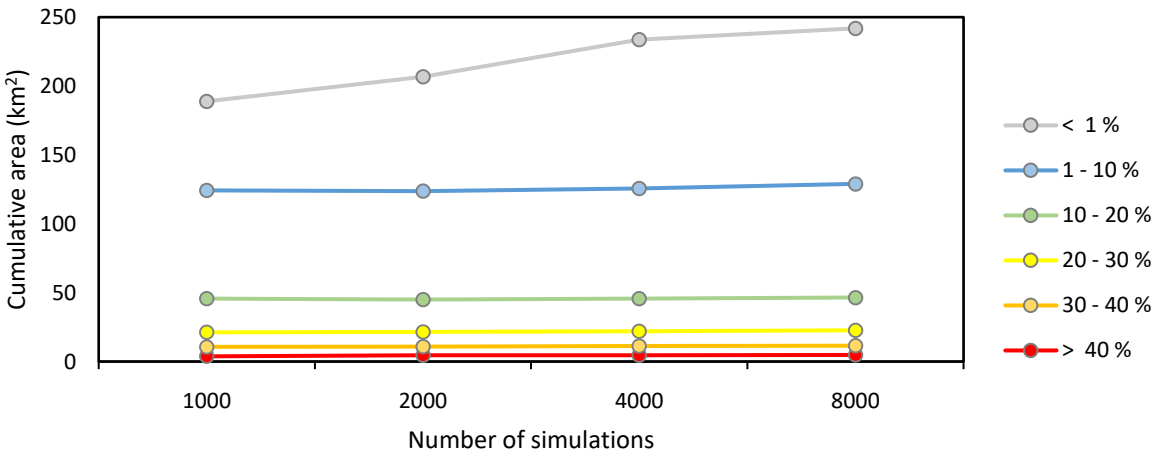


Fig. S8 Cumulative hazard zone, showing area where probability of impact from a 5 cm clast is > 40 %, 30 – 40 %, 20 – 30 %, 10 – 20 %, 1 – 10 % and < 1 %, for 1000, 2000, 4000 and 8000 simulations.

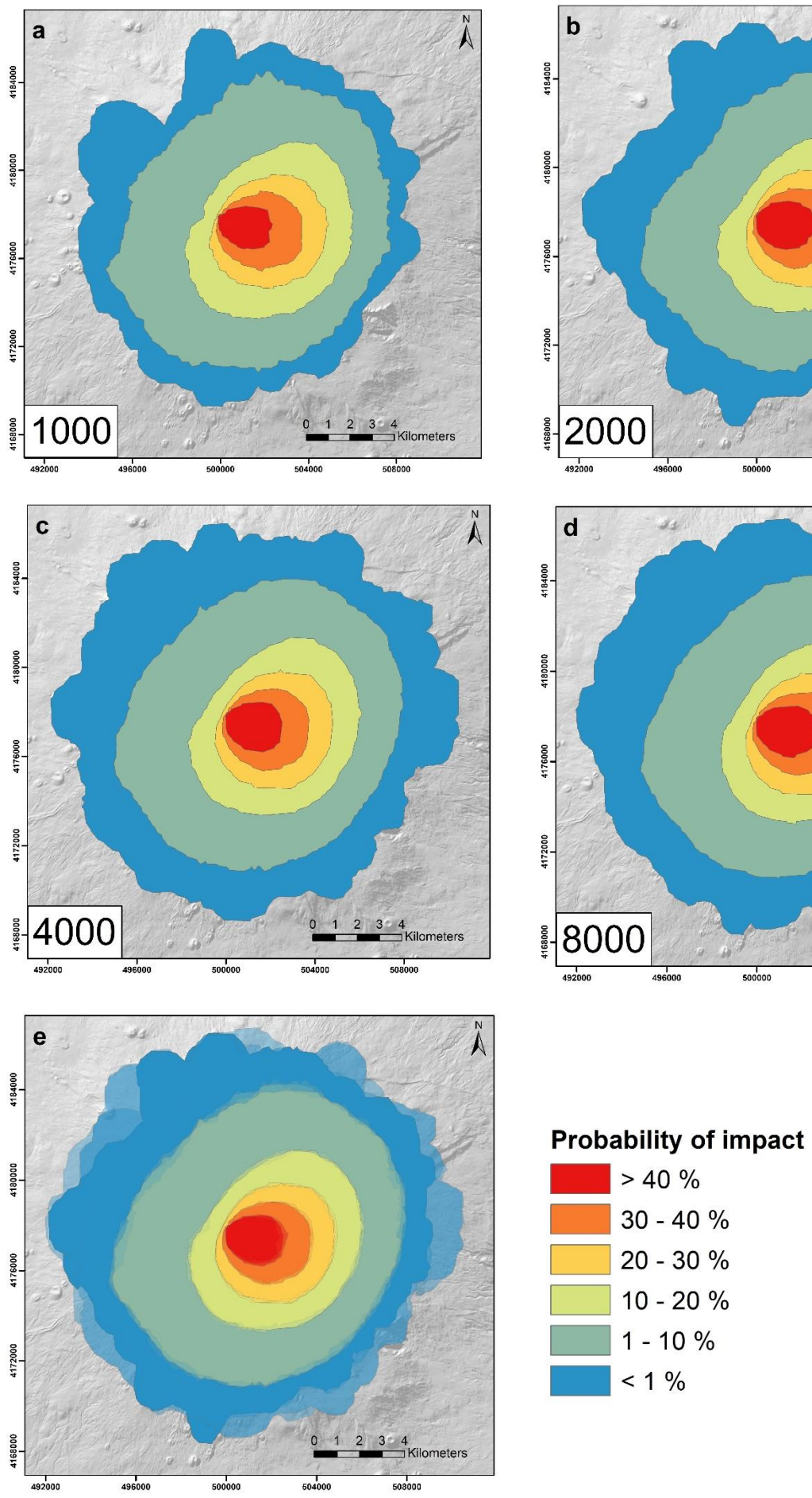


Fig. S9 Modelled probability of impact of a 5 cm clast. a) 1000 simulations, b) 2000 simulations, c) 4000 simulations, d) 8000 simulations, e) overlap of maps for 1000, 2000, 4000 and 8000 simulations.

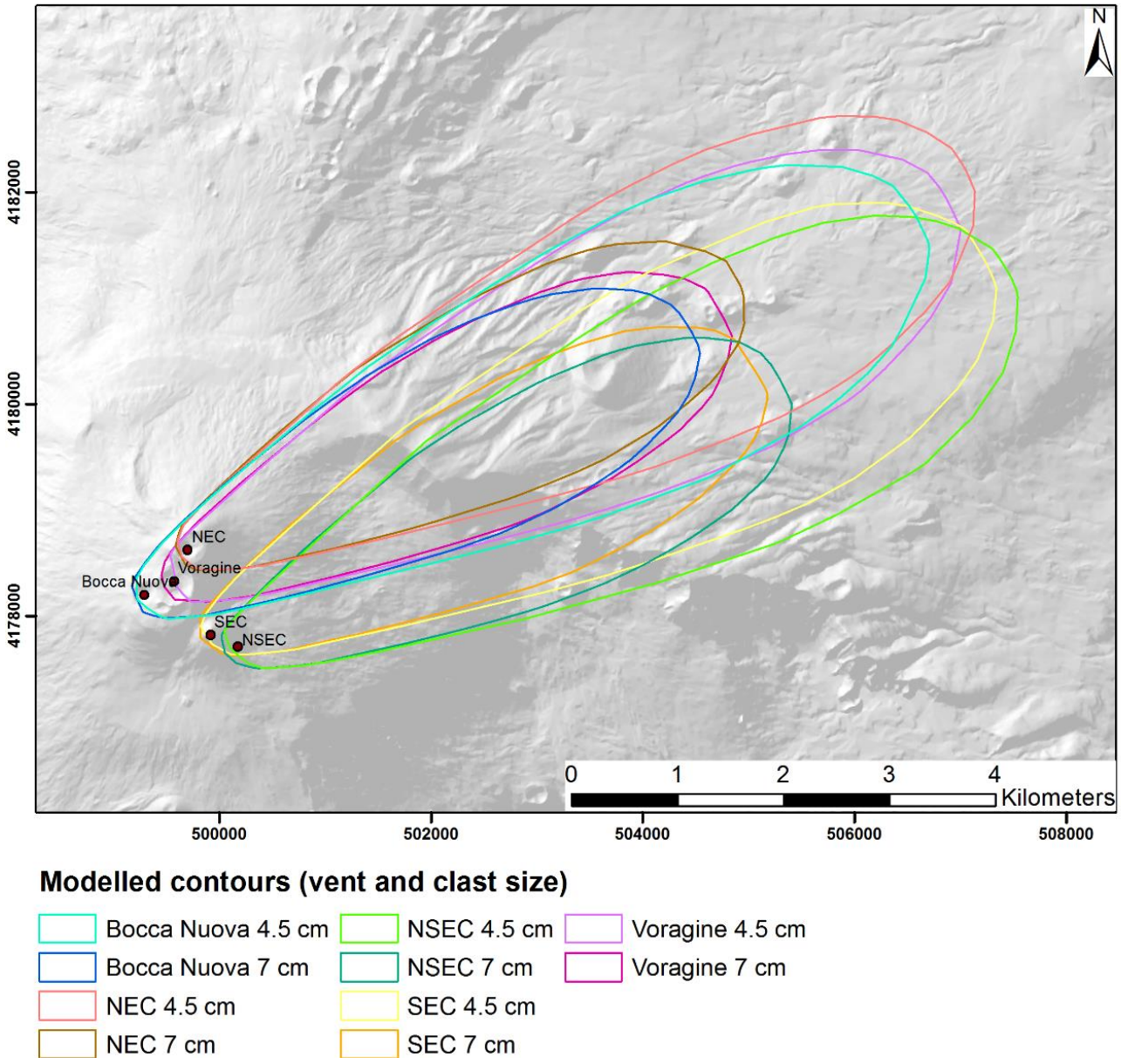


Fig. S10 Modelled 4.5 and 7 cm clast size isopleths for 23 November 2013 lava fountain from each of the five summit craters. NEC = Northeast Crater, NSEC = New Southeast Crater, SEC = Southeast Crater.

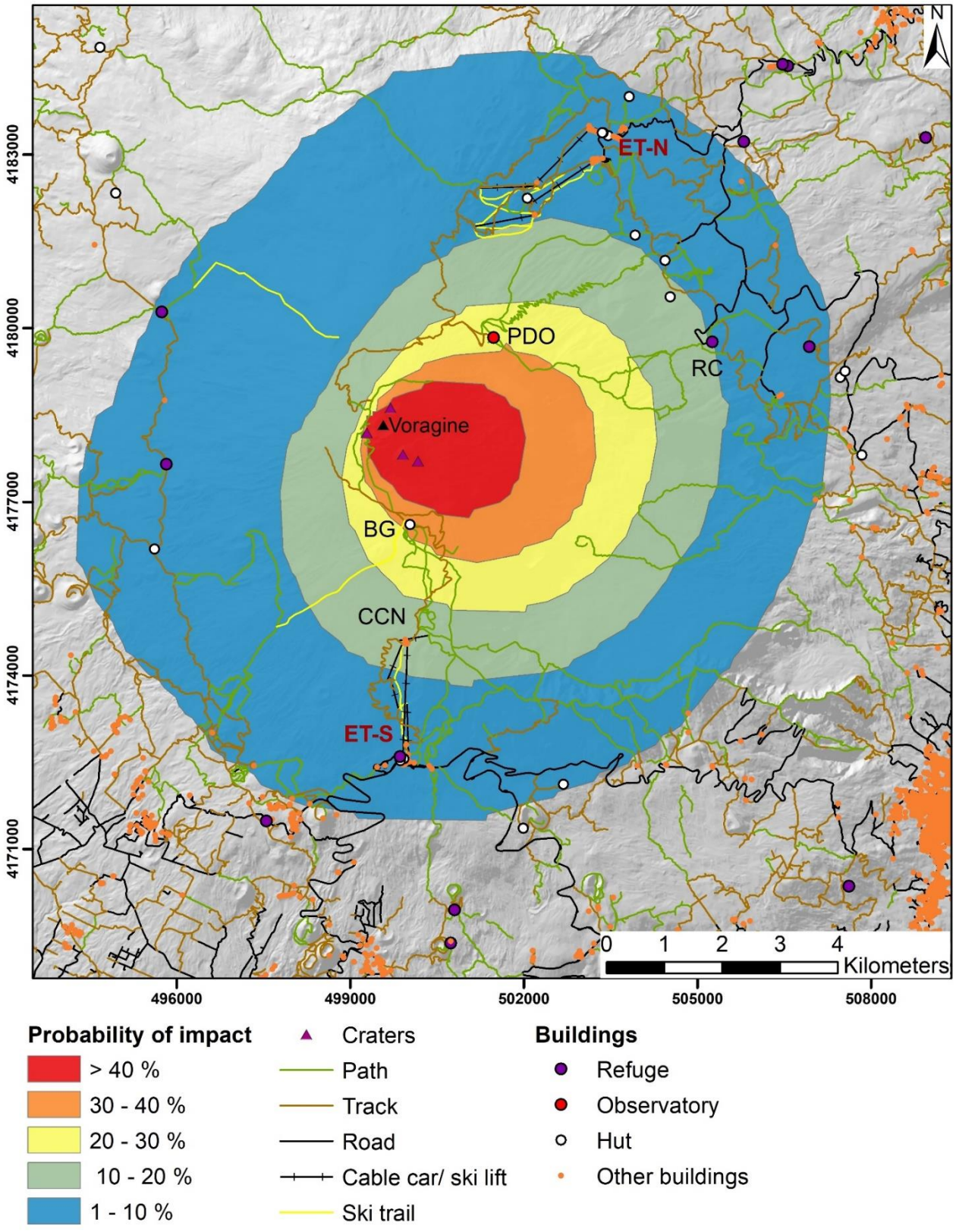


Fig. S11 Probability map showing exposure of infrastructure to impact from a 5 cm clast for the One Eruption Scenario – high mass eruption rate from Voragine. Ski areas: ET-N = Etna Nord, ET-S = Etna Sud. BG = Baita delle Guide, CCN = Top station of the Funivia dell'Etna cable car, PDO = INGV Pizzi Deneri Observatory, RC = Rifugio Citelli.

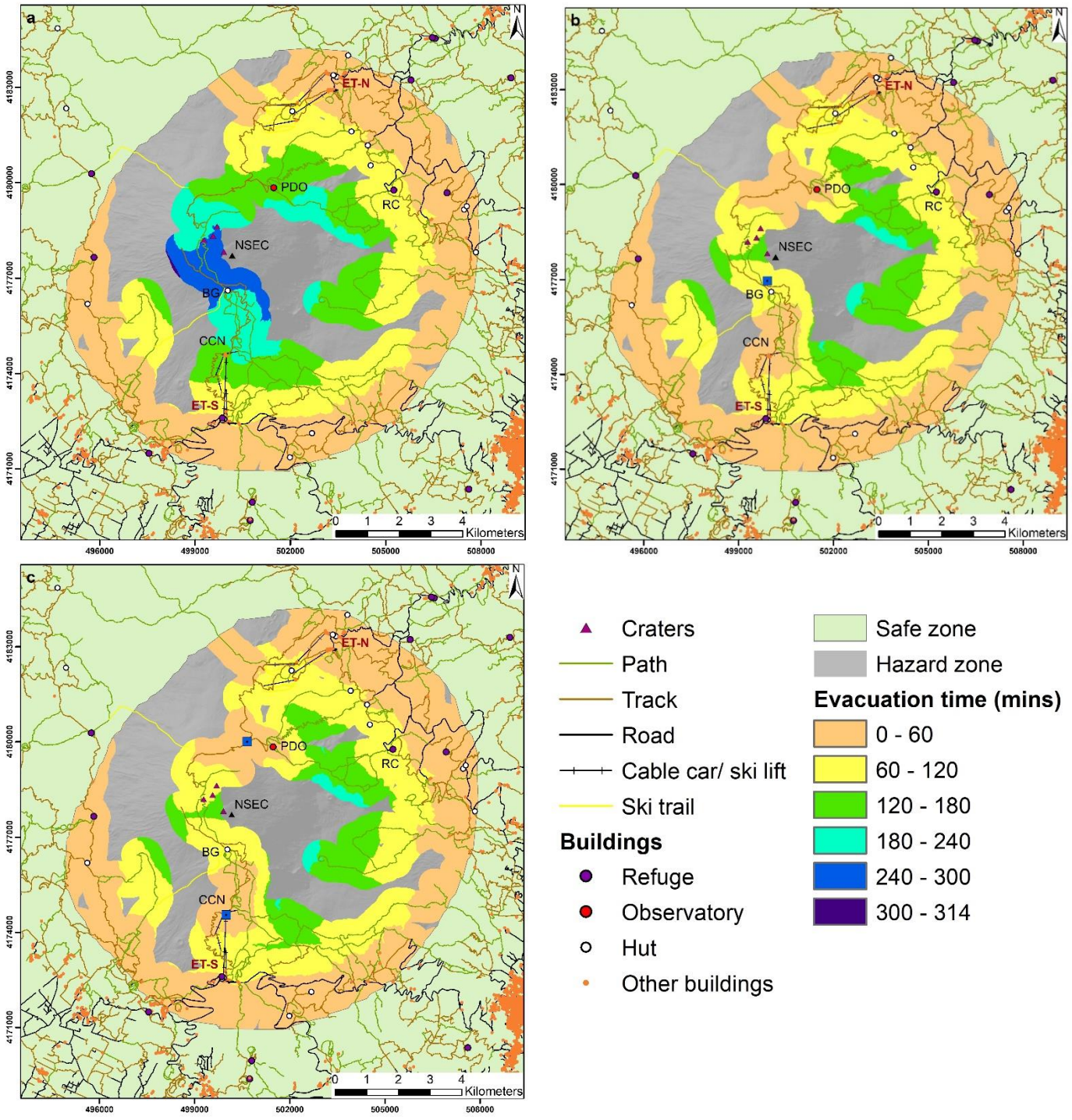


Fig. S12 Evacuation times to reach the safe zone (for One Eruption Scenario – high mass eruption rate from NSEC) based on walking speed of 3.3 km h^{-1}, assuming people start a maximum of 500 m from any path with a) no shelters, b) one shelter and c) two shelters. Hazard zone is the area with probability of impact from 5 cm clast ≥ 1 %. Safe zone includes area with probability of impact < 1 %. NSEC = New Southeast Crater. Ski areas: ET-N = Etna Nord, ET-S = Etna Sud. BG = Baita delle Guide, CCN = Top station of the Funivia dell'Etna cable car, PDO = INGV Pizzi Deneri Observatory, RC = Rifugio Citelli.

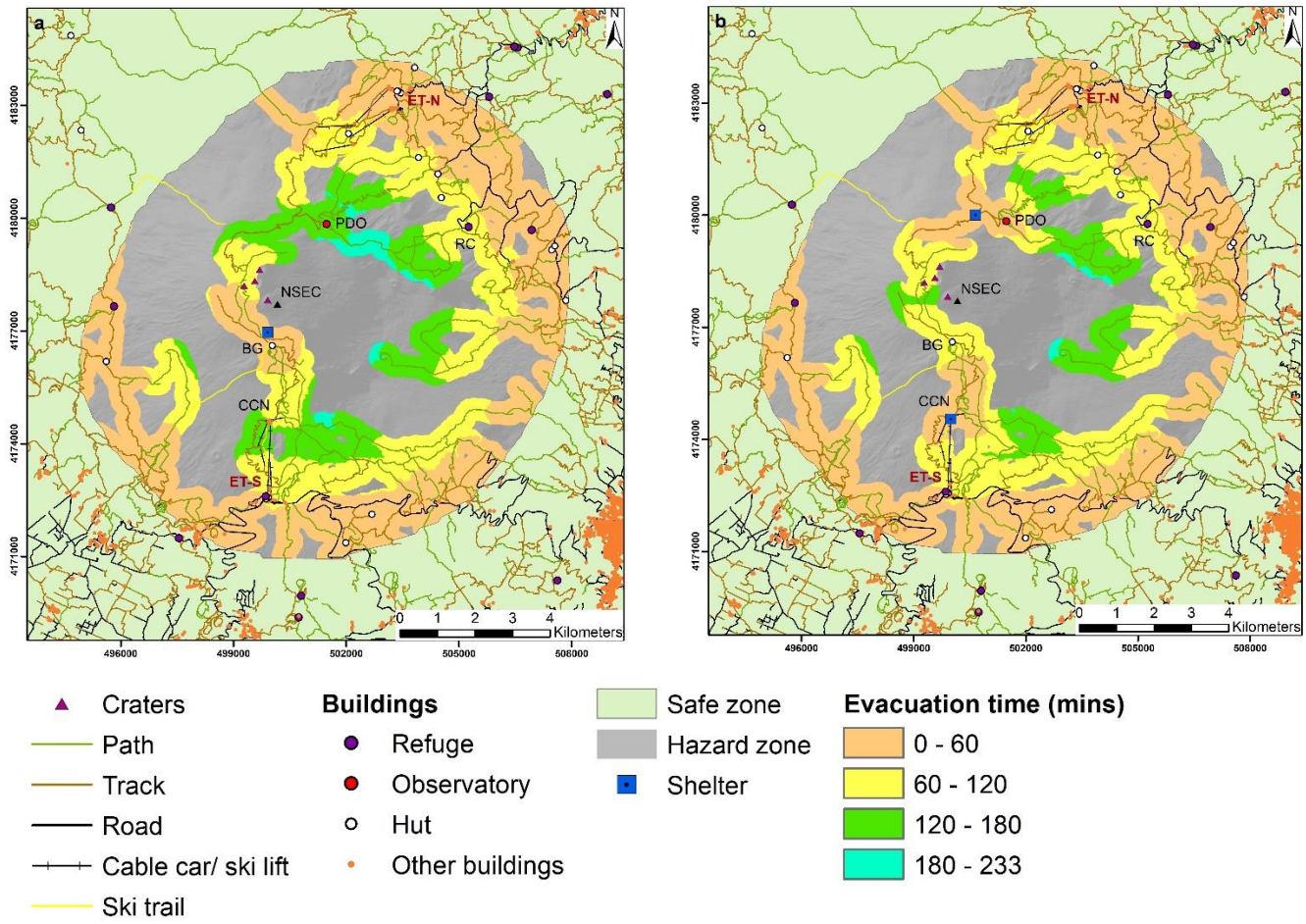


Fig. S13 Evacuation times to reach the safe zone (for One Eruption Scenario – high mass eruption rate from NSEC) based on walking speed of 3.3 km h^{-1}, assuming people start a maximum of 300 m from any path, with a) one shelter and b) two shelters. Hazard zone is the area with probability of impact from 5 cm clast ≥ 1 %. Safe zone includes area with probability of impact < 1%. NSEC = New Southeast Crater. Ski areas: ET-N = Etna Nord, ET-S = Etna Sud. BG = Baita delle Guide, CCN = Top station of the Funivia dell'Etna cable car, PDO = INGV Pizzi Deneri Observatory, RC = Rifugio Citelli.

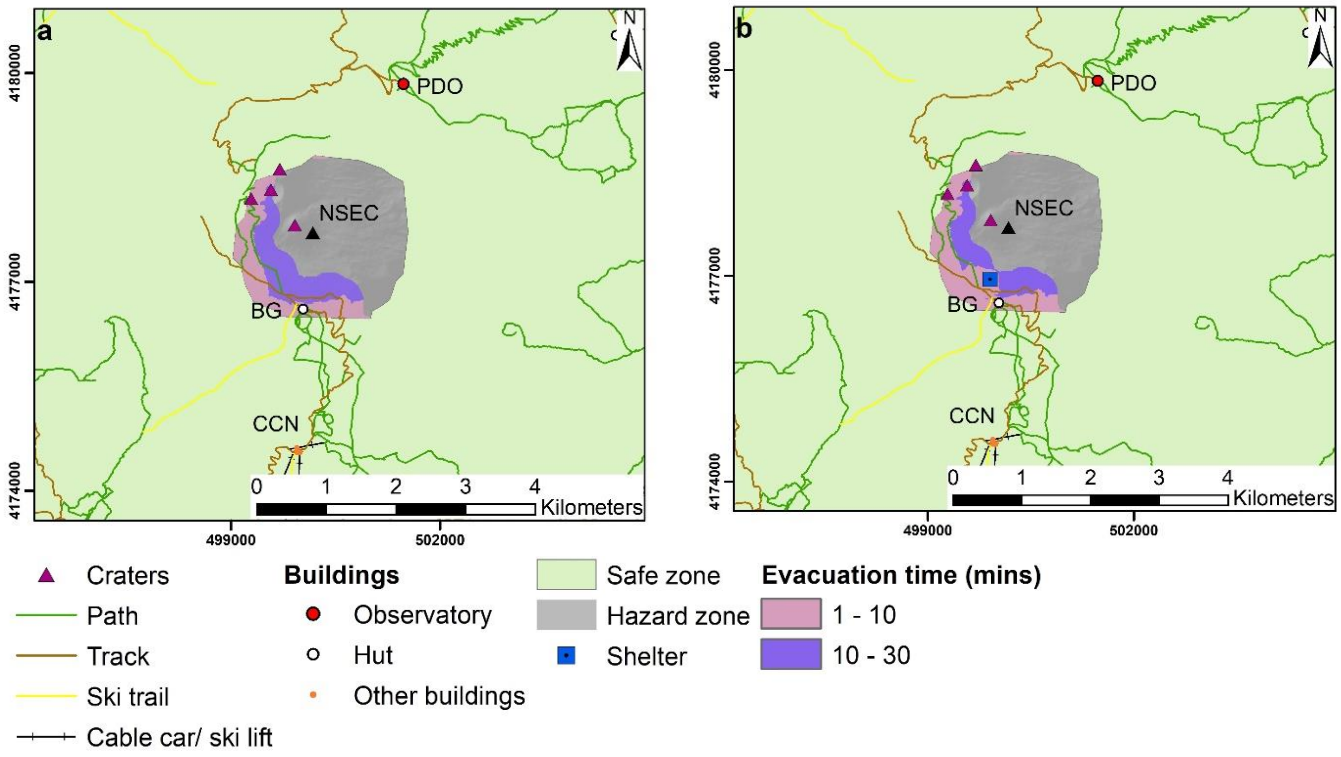


Fig. S14 Evacuation times to reach the safe zone (for One Eruption Scenario – low mass eruption rate) based on walking speed of 3.3 km h^{-1}, with a) no shelter and b) one shelter. Hazard zone is the area with probability of impact from 5cm clast ≥ 1 %. Safe zone includes area with probability of impact < 1 %. NSEC = New Southeast Crater. BG = Baita delle Guide, CCN = Top station of the Funivia dell'Etna cable car, PDO = INGV Pizzi Deneri Observatory.

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