This research is supported by: (1)Agreement DPC - INGV All. B, 2022-2024 - "*Sistema Unico Stromboli*".
Task 4.1: Elements for risk assessment of ballistic projectiles, pyroclastic avalanches and tsunamis at Stromboli;

(2)"*Piano di Potenziamento del monitoraggio e EW di Stromboli*" - Agreement DPC - INGV, 2022-2023.
Task ASP1: Probabilistic hazard assessment of paroxysms and major explosions;

(3)"*Reti multiparametriche - Sotto-progetto Vulcani*", INGV, 2022-2025.
Objective A7: Probability of eruptive fenomena and hazard maps of ballistics and secondary pyroclastic flows from major explosions and paroxysms with risk assessment implications.

Quantifying ballistic projectile hazards and risks due to paroxysms and major explosions at Stromboli (Italy)

A. Bevilacqua[1], A. Bertagnini[1], M. Pompilio[1], P. Landi[1], P. Del Carlo[1], A. Fornaciai[1], L. Nannipieri[1], M. Favalli[1], M. Bisson[1], A. Tadini[1], W. Aspinall[2], P. Baxter[3], G. Woo[4], A. Neri[1].

1 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa, Italy
2 School of Earth Sciences, University of Bristol, Bristol, UK
3 Institute of Public Health, University of Cambridge, UK
4 Risk Management Solutions, London, UK

Session GMPV9.1 - Advances in volcanic hazard monitoring and modeling, 27 April 2023

Motivation and objectives of the study

Stromboli (Italy) is one of the most active and most studied volcanoes of the world and therefore it is potentially well suited for a **quantitative probabilistic assessment of its hazard and risk**.

Our objective is the **statistical modeling** of the conditional **hazard of ballistic projectiles** generated by **major explosions and paroxysms**. In particular we target to quantify:

- **How much is the probability** to be in an area affected by ballistics & to be hit by a projectile (clast) as a function of the spatial location, if an explosion occurs.
- **How much is the uncertainty** affecting these estimates, due to the main epistemic uncertainty sources.

We decompose the assessment of this conditional hazard as the **product of two factors**:

Hazard (x, t) = **P** x **R**

i.e. the probability to be: in a region affected (P), hit by a projectile (R)

Assumptions and limitations of the study

- The conditional hazard is based only on the **statistical modeling of the locations and spatial density** of ballistic projectiles as reconstructed from field and remote observations. No model of the impact between a clast and a body is considered.

- We refer to the maximum distance and azimuthal dispersal reached by potentially dangerous large clasts, i.e. **lithic and spatter bombs greater than 5-10 cm** (smaller clasts and falllout pumices are not accounted for at this time).

- In this talk we illustrate a **first application** to the hazard of **paroxysms**. We are currently working on an updated version of the catalog from 1970 to 2022 to apply a similar approach to a larger dataset of **major explosions**.

Based on the conditional hazard estimates, we finally illustrate a preliminar example of "**Counterfactual Analysis**" of the afternoon paroxysm on 3 July 2019, i.e. a dynamic stochastic process of exposed/injured people as a function of **variations** of the onset time of the paroxysm.

Example maps of ballistics during major explosions

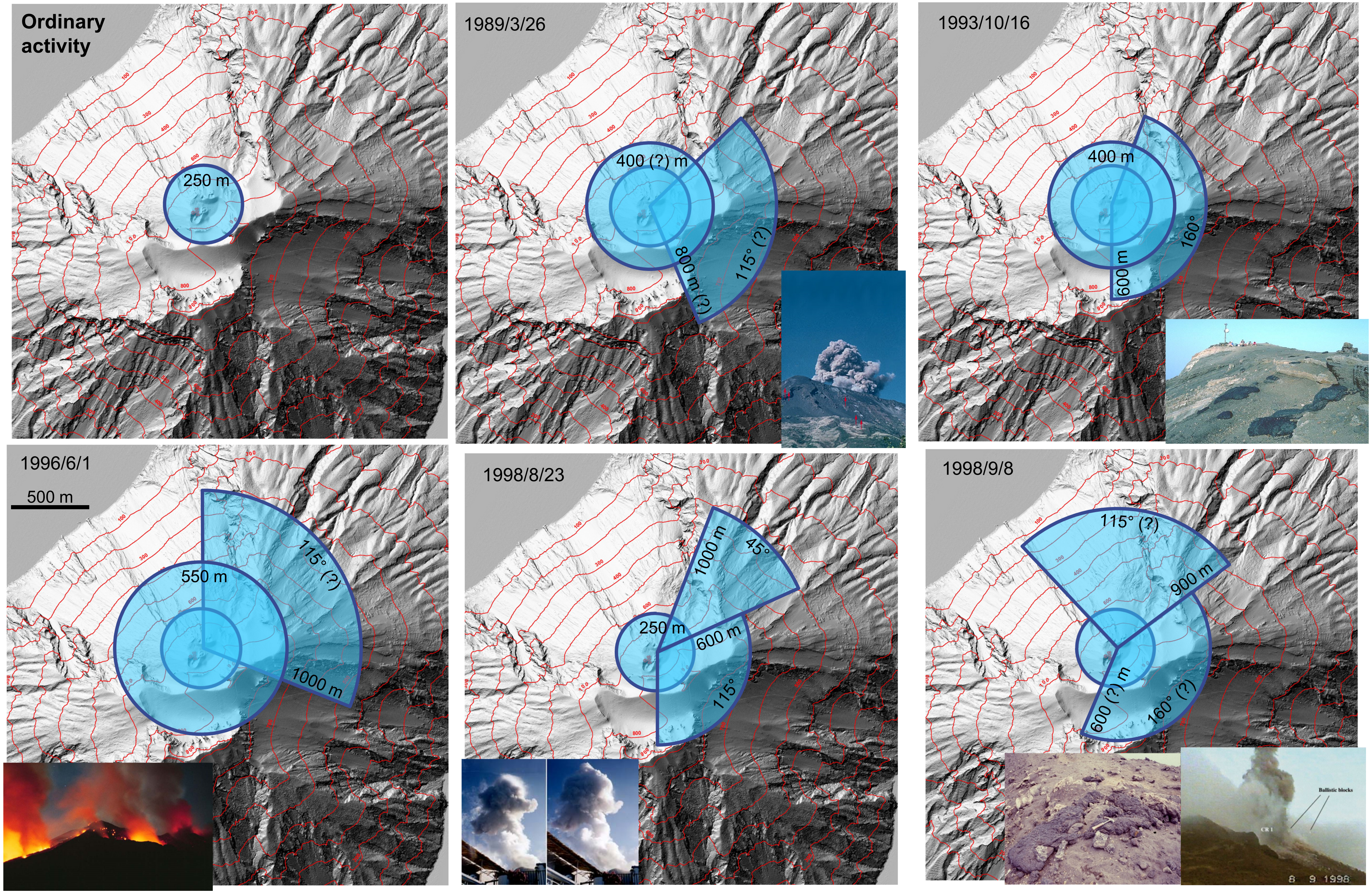
30-50 events from 2000 to 2022

A circle of ~250m radius can envelope a 200 m radius around its multiple active vents.

This region can be affected even by **ordinary activity**.

Past major explosions ejected ballistics up to ~1km distance from the vents.

We **decompose** the region affected by past major explosions by using circles and circular sectors.



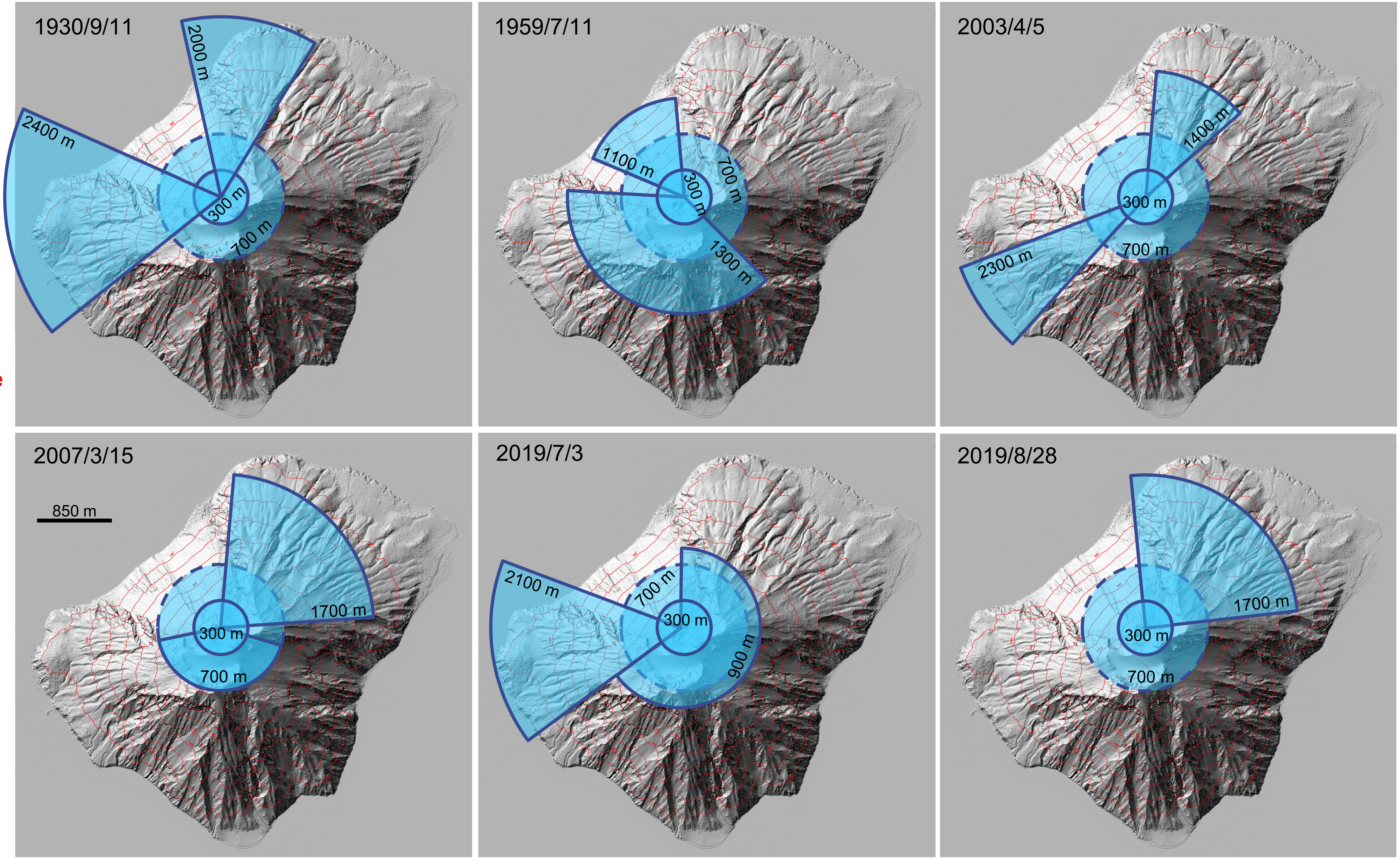
Example maps of ballistics during paroxysms

4 events from 2000 to 2022

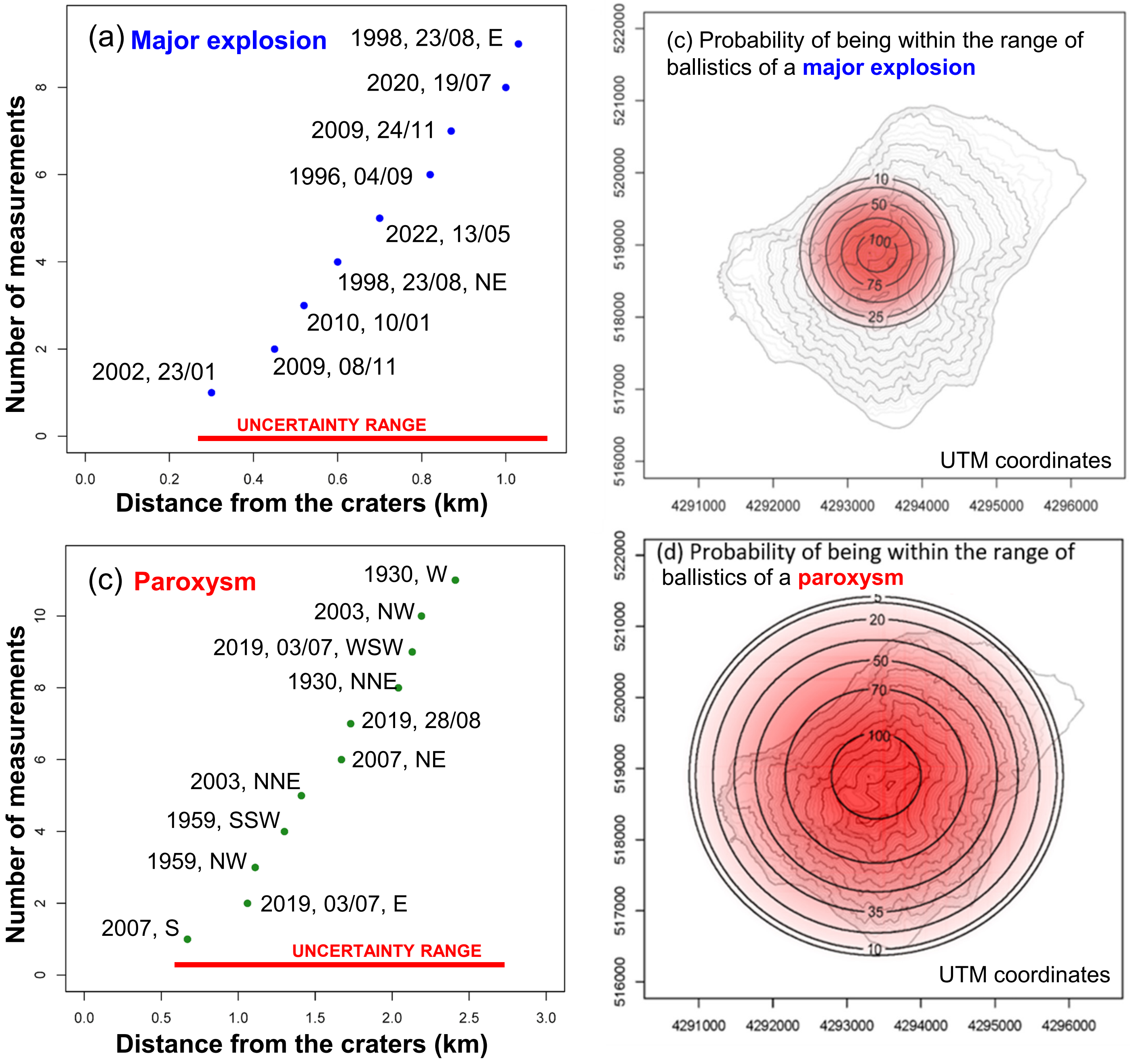
Paroxysms can affect a region up to the coastline and beyond.

We decompose it in circles and circular sectors.

A circular region up to [300, 700] m radius from the craters is assumed to be always affected.



Map of affected distance from the craters



In this example we define a **uniform** pdf over the range of observed **maximum distance** of the clasts from the craters. This includes a **±10% buffer**.

$f_0(d)$ = **Unif(270, 1100) m** major explosions

$f_1(d)$ = **Unif(600, 2600) m** paroxysms

We are going to test nonuniform PDF once our ongoing study of the historical catalog will be completed.

Figure. (a, b) **maximum range** reached by ballistics (a) of eight major explosions examples, and (b) six paroxysms examples.

(c, d) **probability maps of being within the range of ballistics** of (c) major explosions, and (d) paroxysms.

Reported values are probability percentages.

In the sequel of the talk we focus on the paroxysms.

Estimates of affected circular sectors (direction&width)

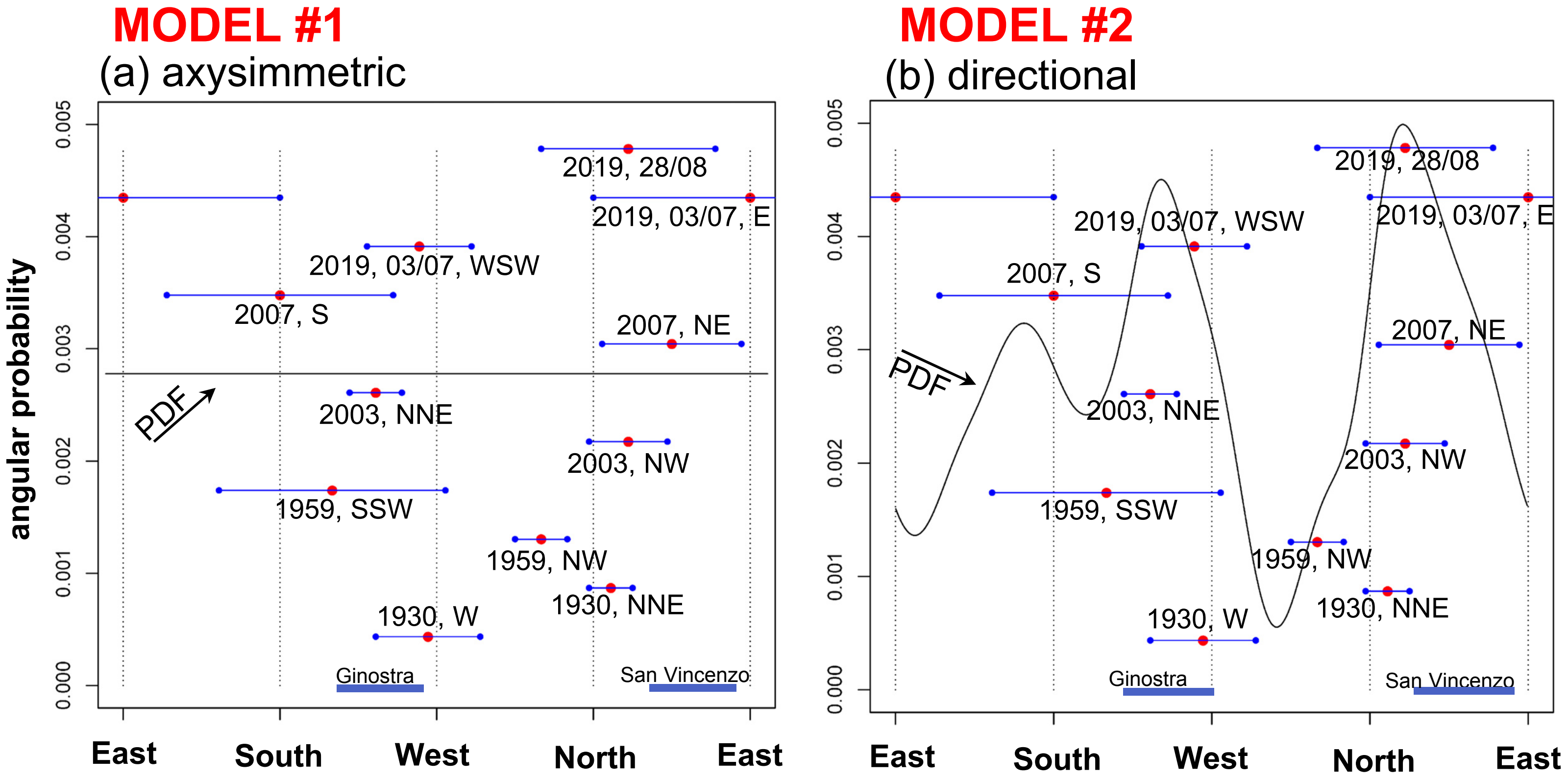


Figure. Probability density functions of the **directions of the ballistics** of **six paroxysms.**

Reported values are probabilities over degrees (angular probability).

Peaks of probability are observed in the directions SW and NNE.

Past directions may be under-recorded in Sciara del Fuoco.

The pdf is obtained through a **Monte Carlo simulation** of random directions uniformly sampled inside the sectors affected by past paroxysms. This produces a population of angle values and a **Gaussian kernel density estimator** provides the angular pdf over the circumference.

MODEL #1 is uniform axysimmetric.

MODEL #2 samples the directions in proportion with the sectors affected in the past.

Map of affected region by ballistics during the paroxysms [without epistemic uncertainty]

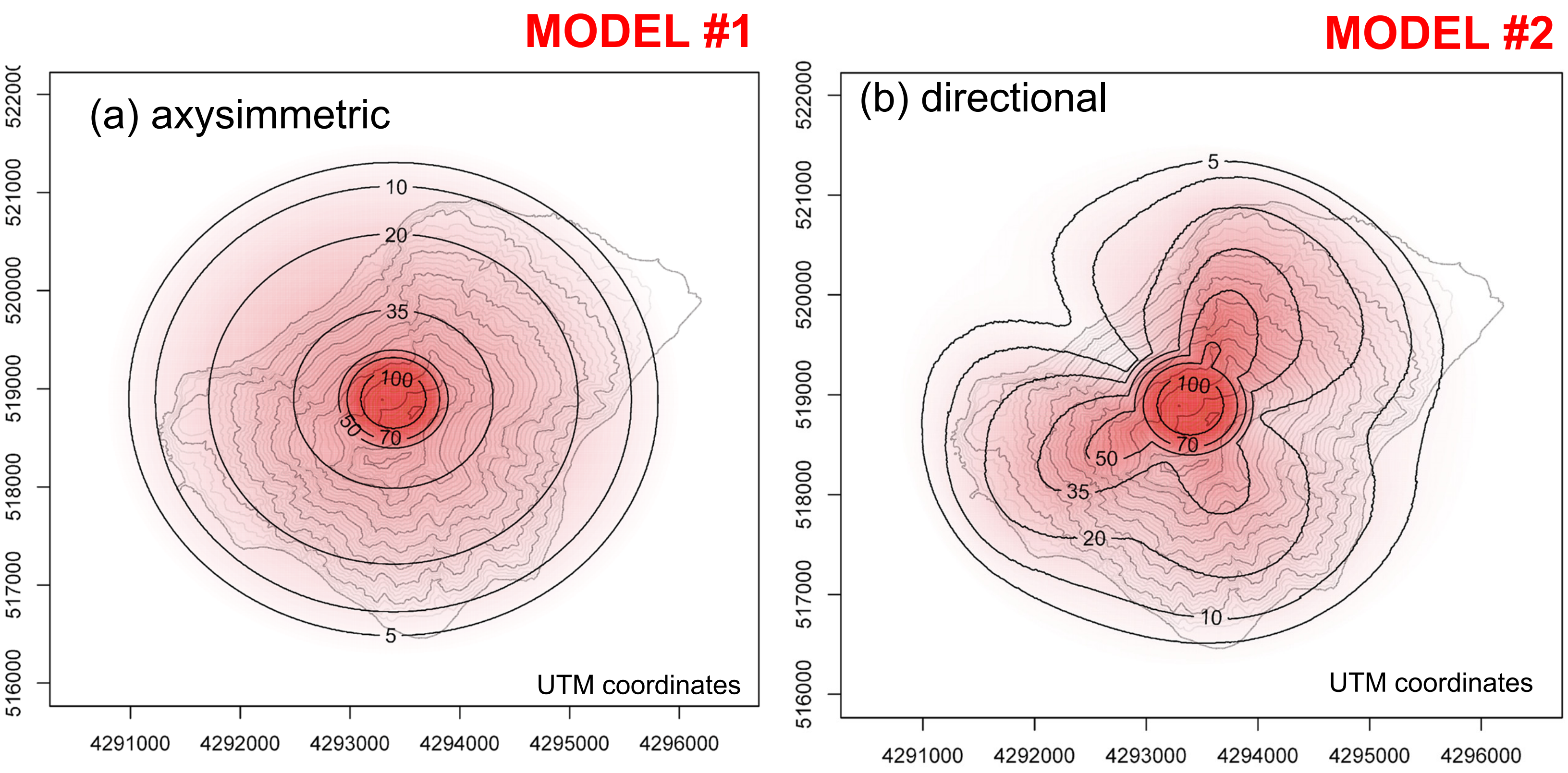


Figure. **Probability maps** of ballistics.
(a, b) assume different models.
Reported values are the probability percentages **to be in a region affected by ballistics**.

We assume that a circular region up to [300, 700] m radius from the craters is always affected.

We run a **Monte Carlo simulation** sampling both the **distance range D** from the craters and the two **angular parameters (direction θ and width α) independently.**

Both maps assume α=145° i.e. the **average** of the historically observed angles.

In each direction θ the radial interval [0, D] is affected in proportion with the sectors affected in the past.

The effects of **epistemic uncertainty** are included in the sequel.

Epistemic uncertainty (direction&width)

MODEL #2 directional

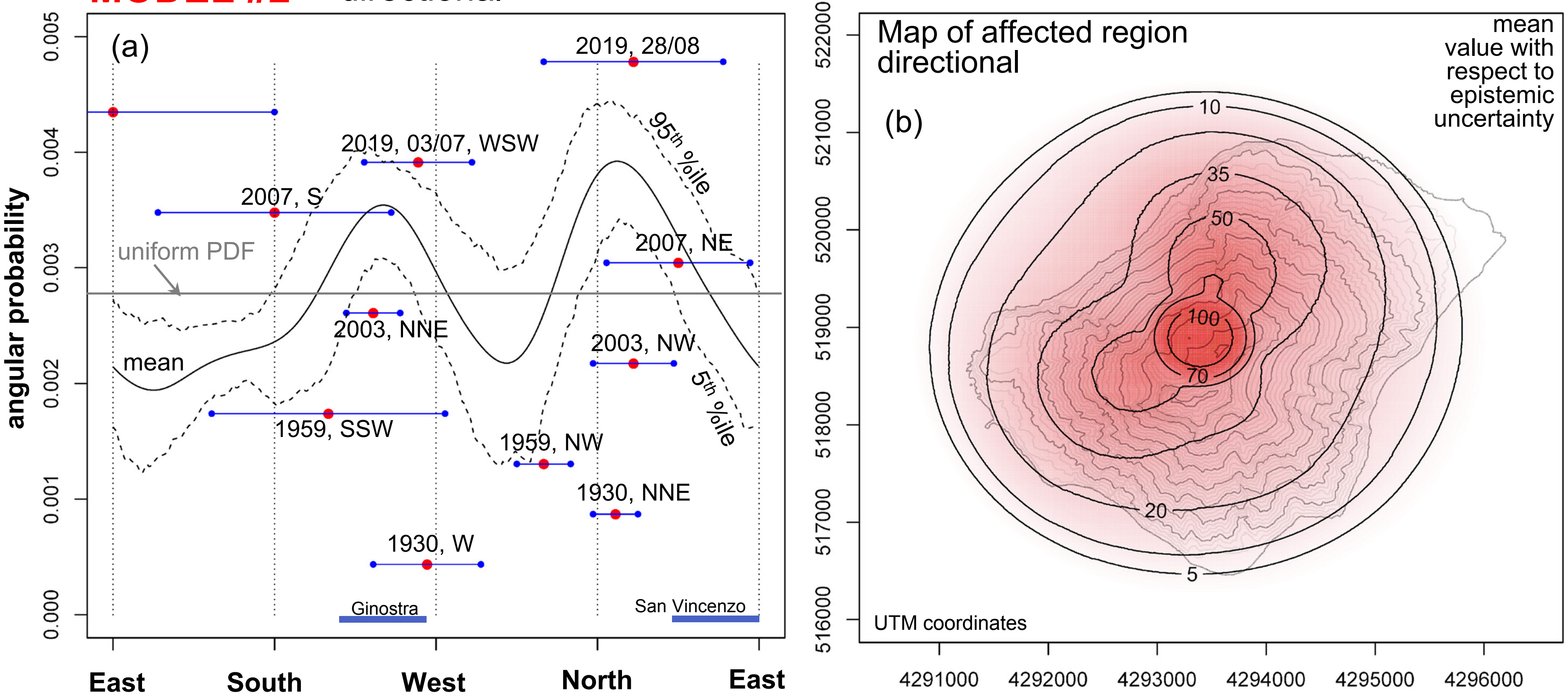


Figure. (a) Probability density functions of the directions of the ballistics of six paroxysms. We include the 5th and 95th percentiles and the mean values.

(b) Map of affected region, directional, mean value with respect to epistemic uncertainty on direction and width.

These results are obtained with a **hierarchical Monte Carlo**.

The pdf estimation of direction and width is repeated for independent perturbations of direction and width of the sectors affected by each paroxysm.

We quantify the possible effects of the **epistemic uncertainty affecting the sectors** of past paroxysms:

- Unif(-20°, +20°) samples the **uncertainty on the direction** (i.e. the bisector is rotated)
- Unif(0°, +20°) samples the **uncertainty on the half width** (i.e. the sector is symmetrically enlarged on both sides).

These values are preliminary and displayed as an example. Uniform PDF is included for comparison.

Examples of conditional hazard to be hit by a projectile at specific locations

We choose **two sites**, corresponding to two conditional probability levels to be in the affected region (5th and 95th %iles):

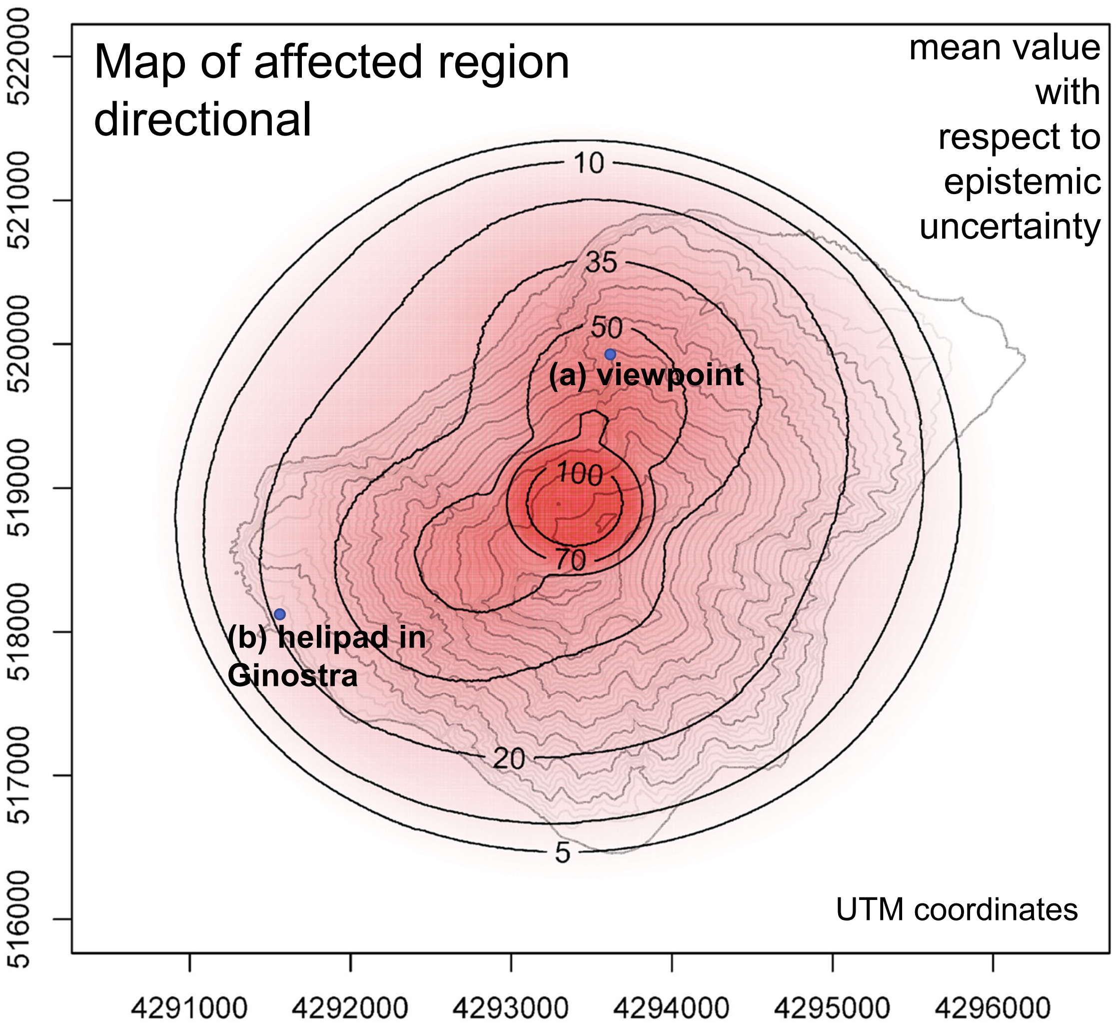
(a) viewpoint at 400 m elevation a.s.l. on the trekking path from «Punta Labronzo» → $P_a \in [50\%, 70\%]$

(b) helipad in Ginostra village → $P_b \in [15\%, 25\%]$

Note that region (a) could be also affected by the ballistics during a major explosion.

Variable estimates of clasts/meter^2 (above 10 cm diameter):

- A value of $R_1 \cong$ **25%** has been measured after the paroxysms in 2007 and 2019 at the helipad near the summit. We adopt this value as a preliminary high level of clasts areal density.
- A value of $R_2 \cong$ **1%**, has been observed after paroxysm of 3 July 2019, at low elevation over the trail of Ginostra. We adopt this value as a preliminary low level of clasts areal density.



Example of downward counterfactual analysis - the paroxysm of 3 July 2019

Location (a) VIEWPOINT 400 m	$P_a \times R_1 \in$ [12%, 17.5%]
Location (b) ELIPAD GINOSTRA	$P_b \times R_2 \in$ [0,15%, 0,25%]

The **conditional hazard estimate** is the product of $P_i \times R_j$, i.e. the chance to be in a region affected and hit by a projectile.

A conservative assumption of R_0= 100% projectiles/meter^2 could be also considered.

At the time of the paroxysm, 4.46 pm, no one was at the viewpoint 400 m asl, or above.
In summer, the visits to the summit **started at 5:00 pm**.
[*Ordinanza sindacale Comune di Lipari No.23 - 2019*].

The highest tourist exposure was around sunset, which is 8.28 pm on 3 July. A **maximum number of 80 tourists** was allowed to be above 750 m at the same time, in groups of 20 people per guide.

People waiting their turn at the viewpoint at 400 m a.s.l. or climbing towards at the shelters at 750 m a.s.l., were likely to **double this number or more**, based on the chronicles of that day,
up to N = 150 - 200 people.

If a paroxysm had started later, the number of **hit people** could have been $P_a \times R_1 \times N$,
i.e. about 20 - 35 people on average.

This is obtained by applying the estimates valid at the viewpoint 400 m a.s.l. **to all the people**,
i.e. 50-70% of being affected, 25% of being hit if affected.
However, closer to the craters the conditional hazard would have been **higher**.

Preliminary outcomes (for paroxysms)

In case a paroxysm occurs - **conditional probabilities**:

- By assuming **independence** between distance and direction, almost the **entire island is prone to a probability of 5% or higher** to be affected by ballistic projectiles (only the NE portion is below this value). Similar probabilities are estimated up to distance of more than **1 km offshore** (e.g. NW the SdF). This outcome is weakly affected by the existance or not of preferential directions of the dispersal.

- Probabilities of **about 50%** (mean value) to be affected by ballistics are computed for areas at altitudes of about **300 and 400 m in the NNE and SW directions**, respectively, if directionality is accounted for. The village of **Ginostra** is exposed to probabilities above 20% (mean value).

- If we refer to the **probability to be hit by a clast**, values approximately reduce by at least a factor of 4 at moderate altitudes and by about two orders of magnitude along the coasts.

- Downward counterfactual analysis of the events of July 3, 2019 estimated that the average number of hit people could have been P_a x R_1 x N, i.e. about **20 - 35 people on average**, if a paroxysms had occurred **later in the afternoon**.