Pyroclastic density current hazard maps at Campi Flegrei caldera (Italy): the effects of event scale, vent location and time forecasts

Andrea Bevilacqua(1), Augusto Neri(1), Tomaso Esposti Ongaro(1), Roberto Isaia(2), Franco Flandoli(3), Marina Bisson(1)

(1) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa
(2) Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli
(3) Università di Pisa, Dipartimento di Matematica, Pisa.

INGV

European Geosciences Union, General Assembly 2016
Vienna, 17 - 22 April 2016

EGU

The volcanological problem

Campi Flegrei is an active volcanic area in the Campanian Plain, dominated by a 12 km large caldera.

A few hundreds of thousand people live inside the caldera, and more than **1 million people** live in the nearby city of Naples.

This study concerns Campi Flegrei **long-term hazard assessments** about pyroclastic density currents (PDC), primarily based on past eruption data and on the structural features of the volcanic system.

The PDC invasion hazard mapping in Campi Flegrei caldera is very challenging because must include:

1) the large uncertainty on **future vent location**,

2) the unpredictable **scale of future activity**,

3) the complexity of the long-term **temporal forecasts.**

Mosaic of orthophotos of Campi Flegrei caldera and surrounding areas.

A yellow line separates western and eastern sectors of the caldera characterized by different history of activity.

Research objective and methodology

This study is aimed at further developing the results of Bevilacqua et al. [2015] and Neri et al. [2015], by **including temporal models** into the spatial hazard assessment produced, and by exploring the effects of a **dependency of eruption scale** on the spatial location.

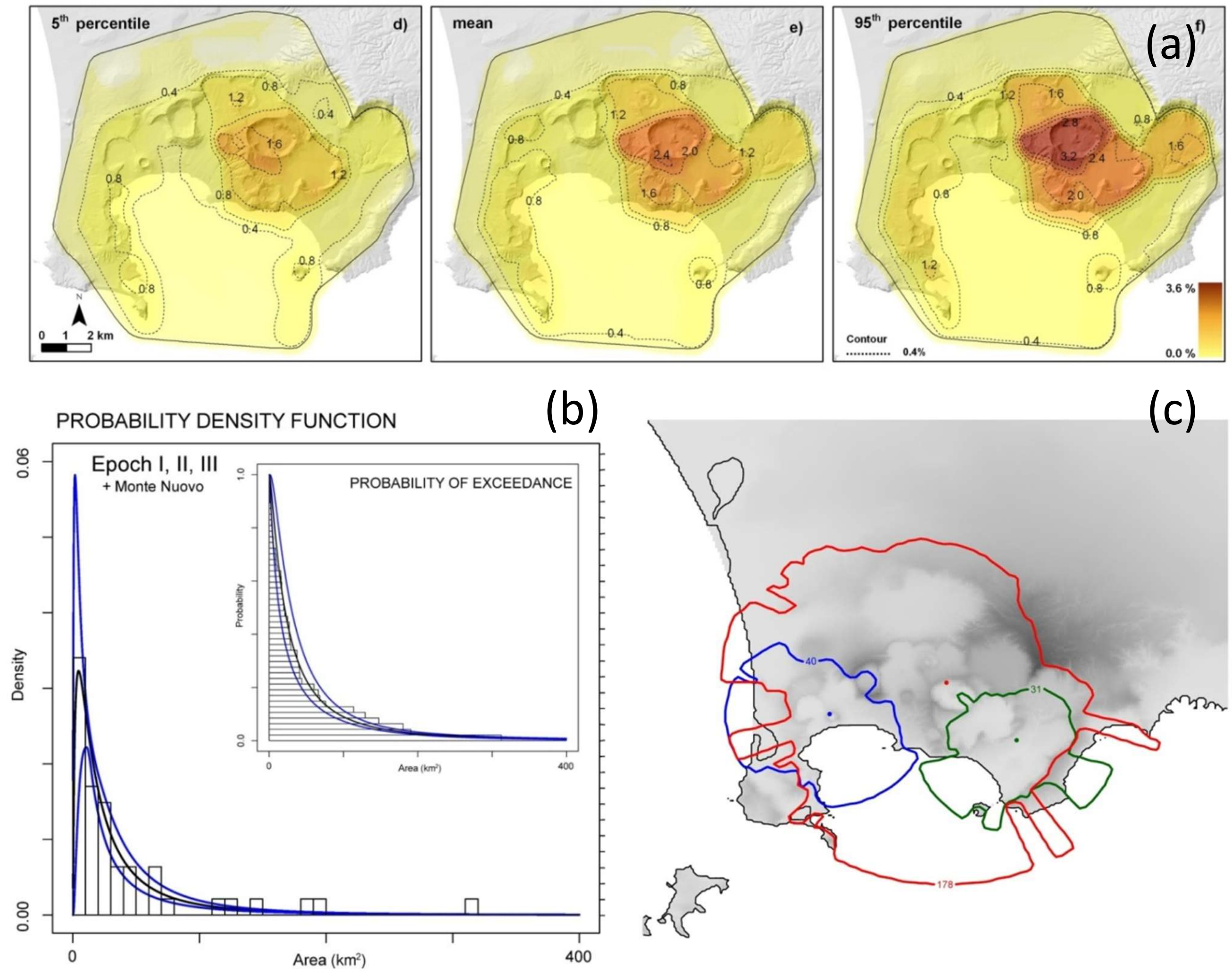
We combined three types of data and associated distributions:

I. a probability map for **the location** of the next eruptive vent

II. a probability distribution for **the size** of the next PDC, i.e. without selecting a reference scenario

III. a time-space probability model for **the time** of the next eruption, able to describe the vent clustering.

With a **simplified PDC invasion model** (*box model*)**,** we repeated a large number of PDC invasion samples, changing vent location, scale and time.



Examples of probability density functions modeling (a) vent opening location [Bevilacqua et al. 2015], (b) areal size of PDC [Neri et al. 2015], (c) examples of single PDC propagations, assuming different vent locations and areal sizes in km^2.

Doubly stochastic approach and uncertainty propagation

The volcano was assumed as a **random system** that had to be assessed with incomplete and **uncertain information**.

Adopting a **doubly stochastic approach,** the ill-constrained parameters of the probability models were themselves represented as additional random variables.

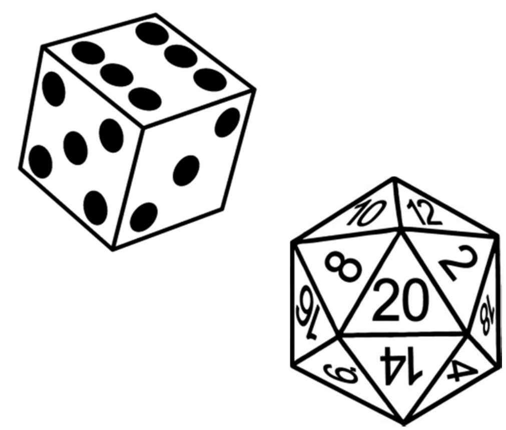
Uncertainty quantification assumed a great importance, and we distinguished:

I. the **physical variability,** i.e. the intrinsic randomness of the system under study,
II. the **epistemic uncertainty** due to the imperfect knowledge of the system.

As a consequence of this approach, all the probability estimates have their own confidence intervals.

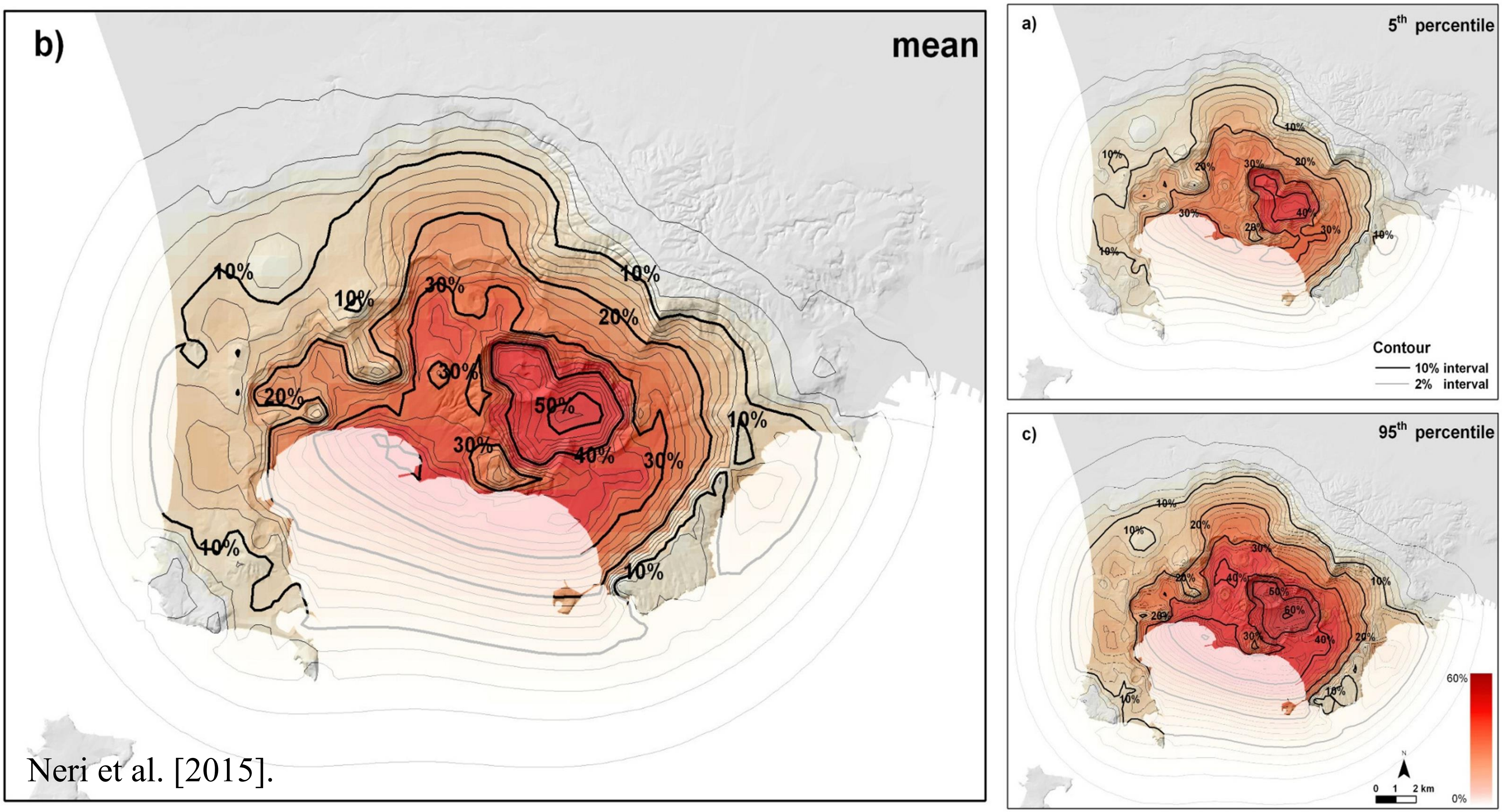
Example*: define X as the random result of an unknown dice, which could have 6 or 20 faces with equal chances.*

Following a doubly stochastic approach, we will say that the probability P of the event {X>3} is 67.5% in mean, with an uncertainty range from 50% to 85%.



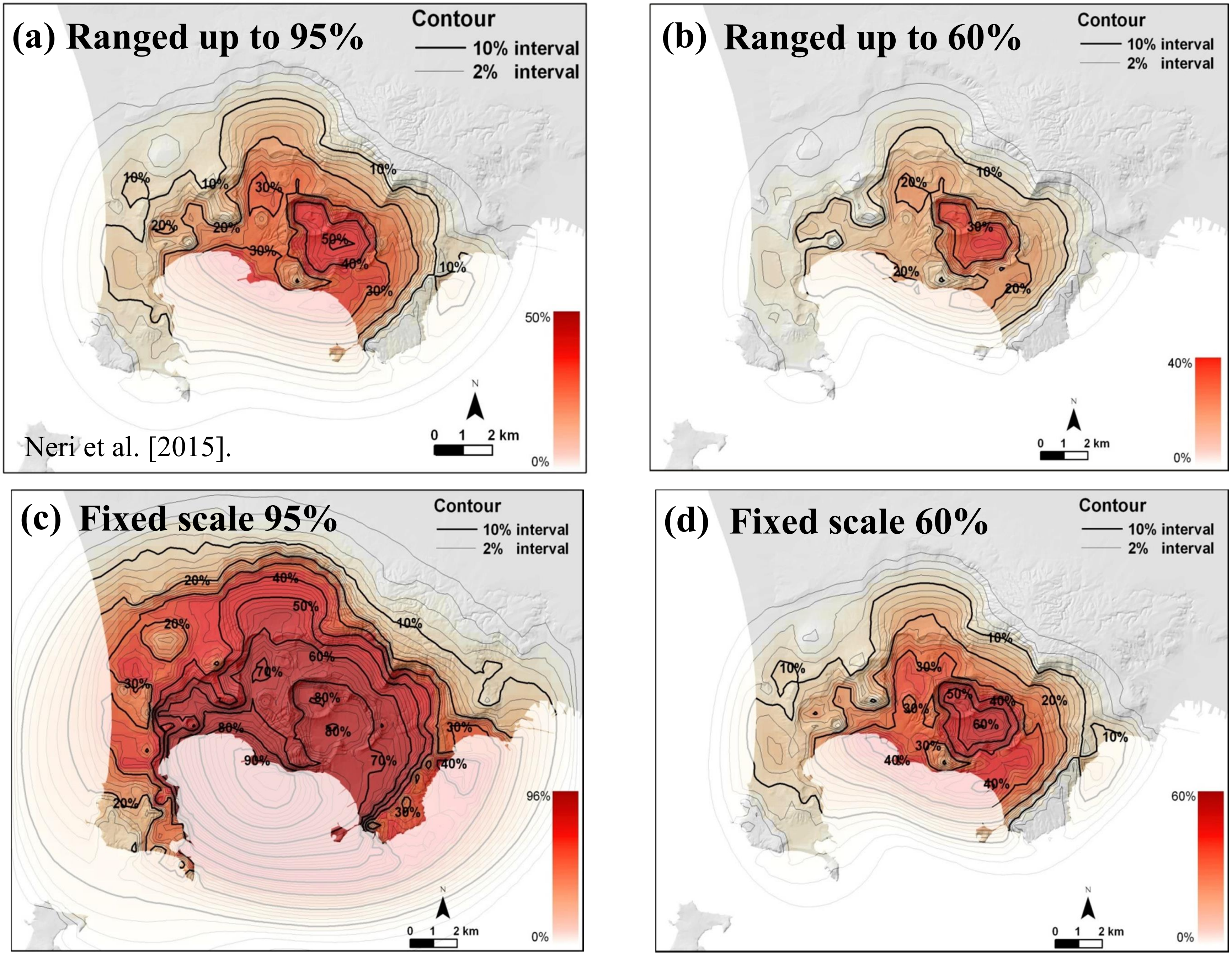
The three probability distributions for vent location, PDC size and time were convolved through a multivariate **Monte Carlo simulation**, propagating the effects of the uncertainty to the hazard estimates.

PDC invasion hazard map conditional to an explosive event - not including time



PDC invasion hazard map assuming a single vent located onland. Contours and colours indicate the percentage probability of PDC invasion **conditional on the occurrence** of an explosive eruption.

PDC invasion hazard maps – Ranged vs fixed scales



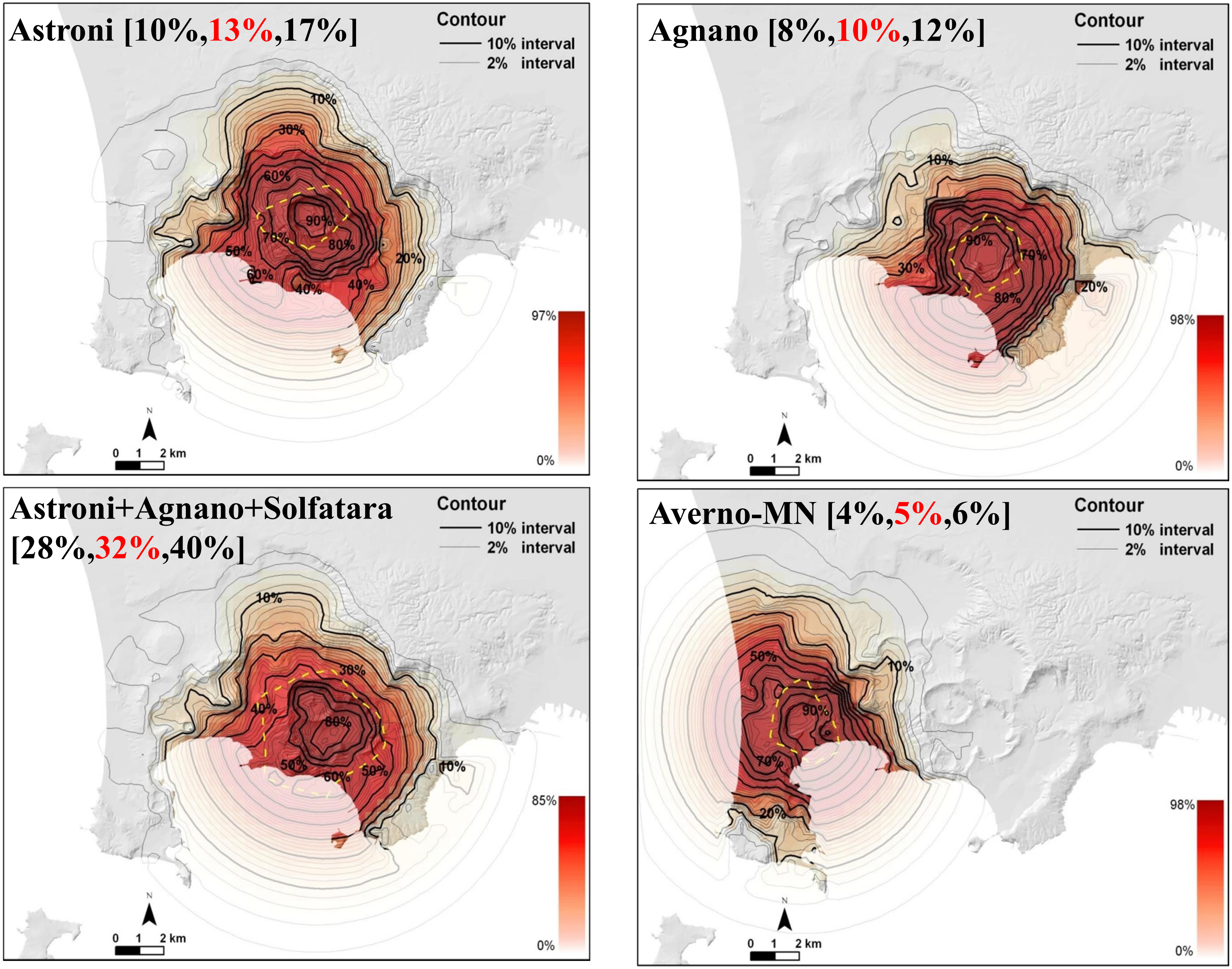
Percentages reported are:

(a) -(b) **bounding limits** for invasion areal size probability distribution;

(c) - (d) **fixed areal sizes**, assumed as reference scenarios varying only vent location.

Mean PDC hazard maps computed under different assumptions concerning the scale.

PDC invasion hazard maps – Vent opening in specific zones of the caldera



Percentages reported in bold are the **vent opening probabilities** inside each selected zone (bounded with a yellow dashed line).

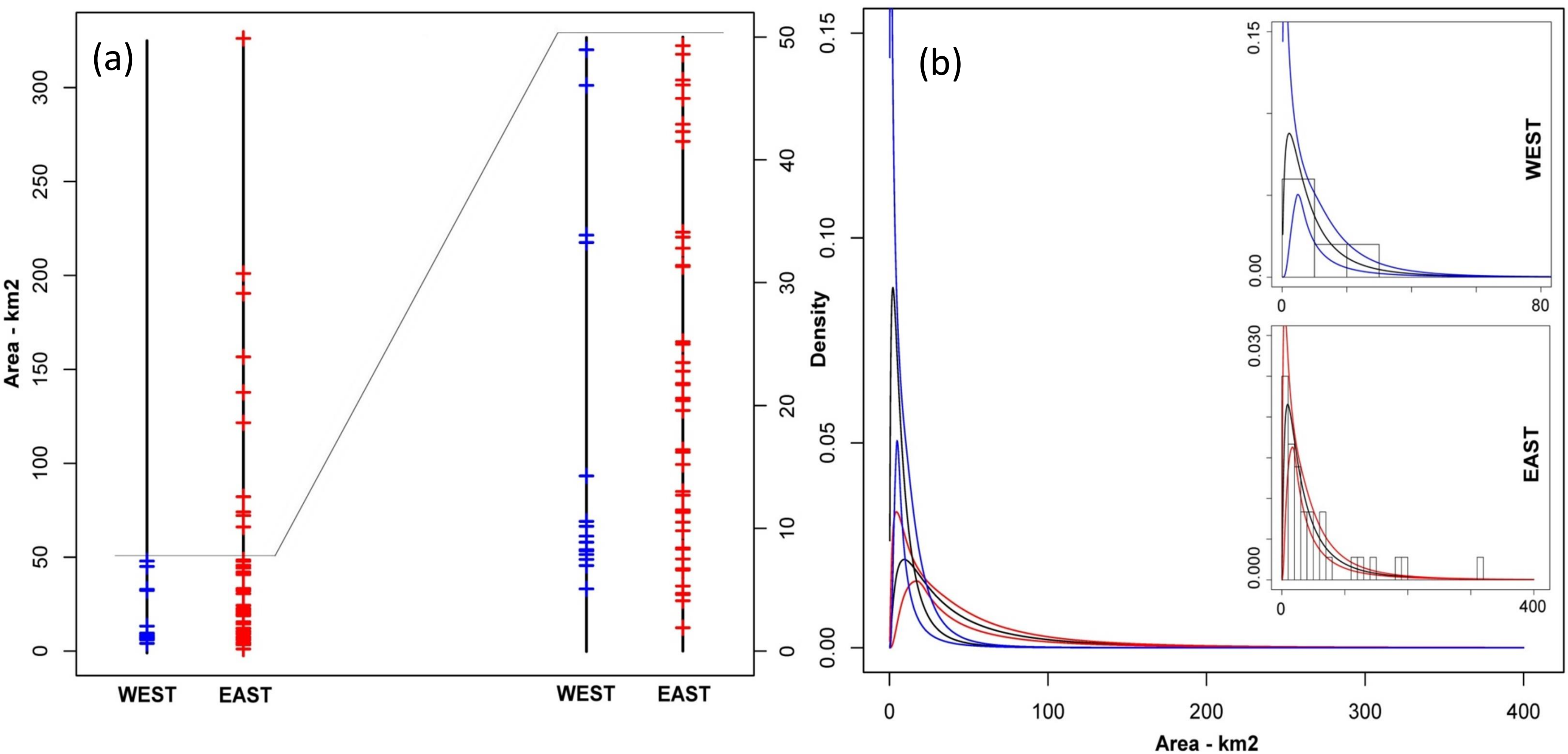
The three values are the 5th percentile, the mean and the 95th percentile according to the **vent opening maps** of Bevilacqua et al. [2015].

Mean PDC invasion hazard maps conditional on an explosive eruption in originating in a **specific zone of the caldera**.

Eastern vs Western sectors of the caldera

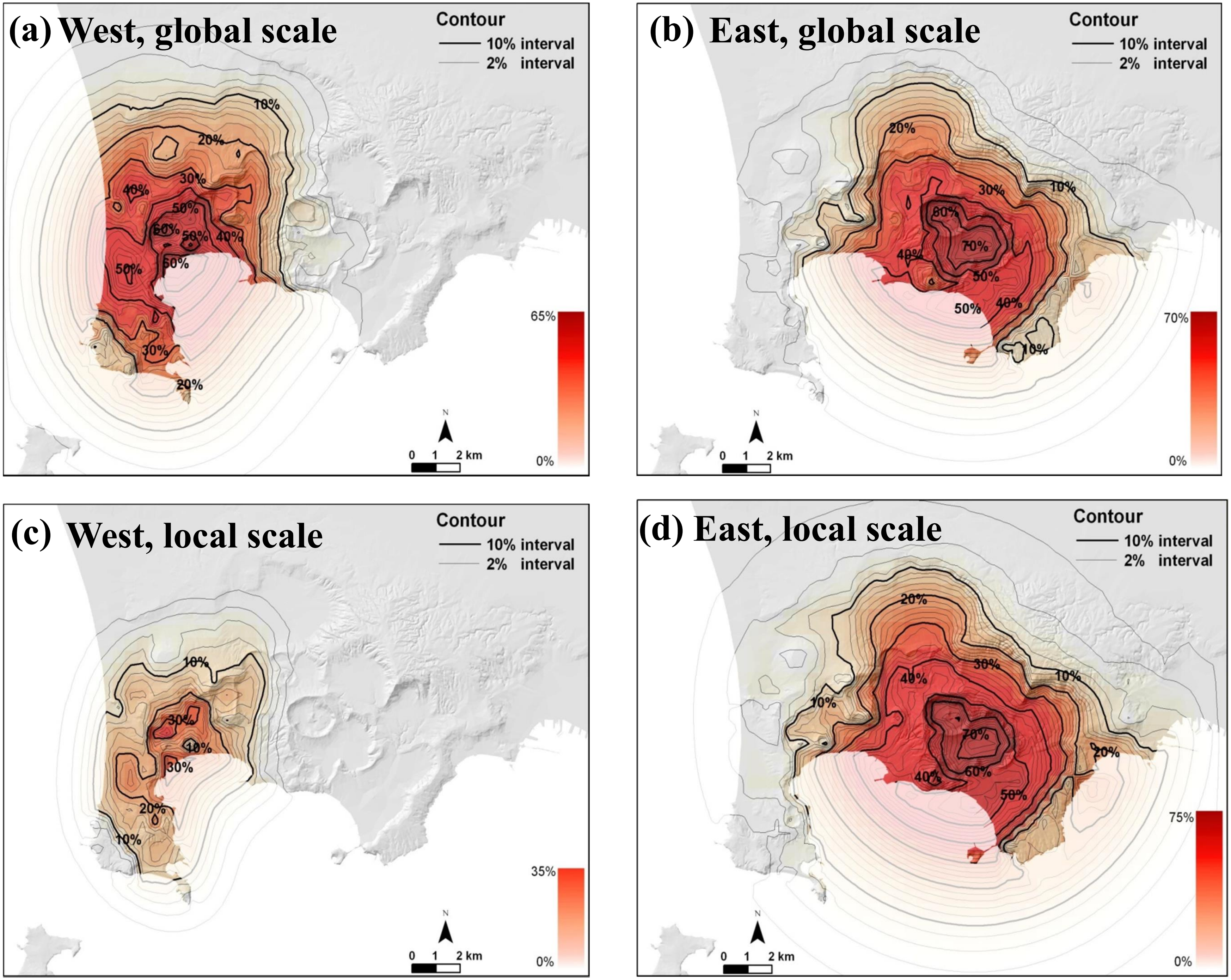
Significant **differences between the eastern and western sectors** of the caldera were found in terms of the past PDC areal sizes over the last 15 ka.

In particular the **eastern sector** is characterized by a **significantly greater number of eruptive events** and **larger eruptive scales**.



(a) **Areas invaded by past PDC**, comparison between eastern and western sectors. Each coloured line is an event. Zoom of small scales on the right of the frame. (b) PDC invasion areas and **probability density functions for the invasion areas**. The black curve is the mean and the coloured curves are the 5*th* and 95*th* uncertainty percentiles.

PDC invasion hazard maps – Vent opening in specific sectors (East/West)



Percentages of **vent opening probabilities** inside the sectors are **34% West, 66% East**, with uncertainty ranges ±4%.

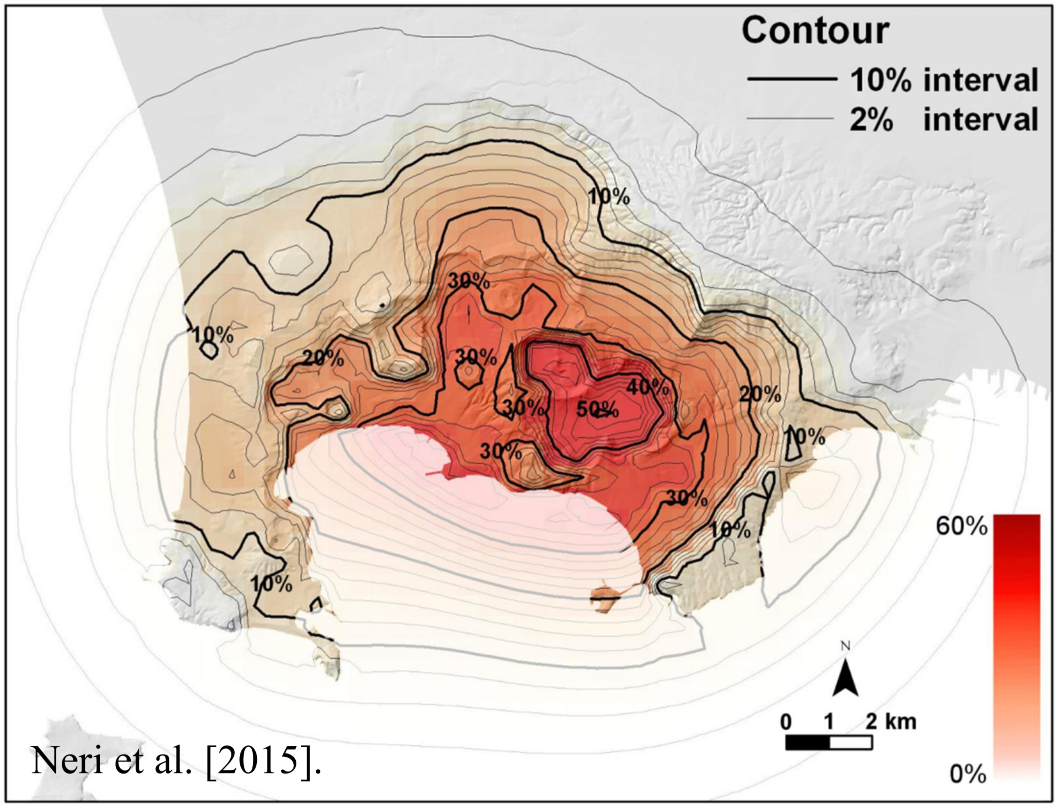
(a) - (b) assume the global PDC areal size distribution;

(c) - (d) assume specific PDC areal sizes distributions for the different sectors.

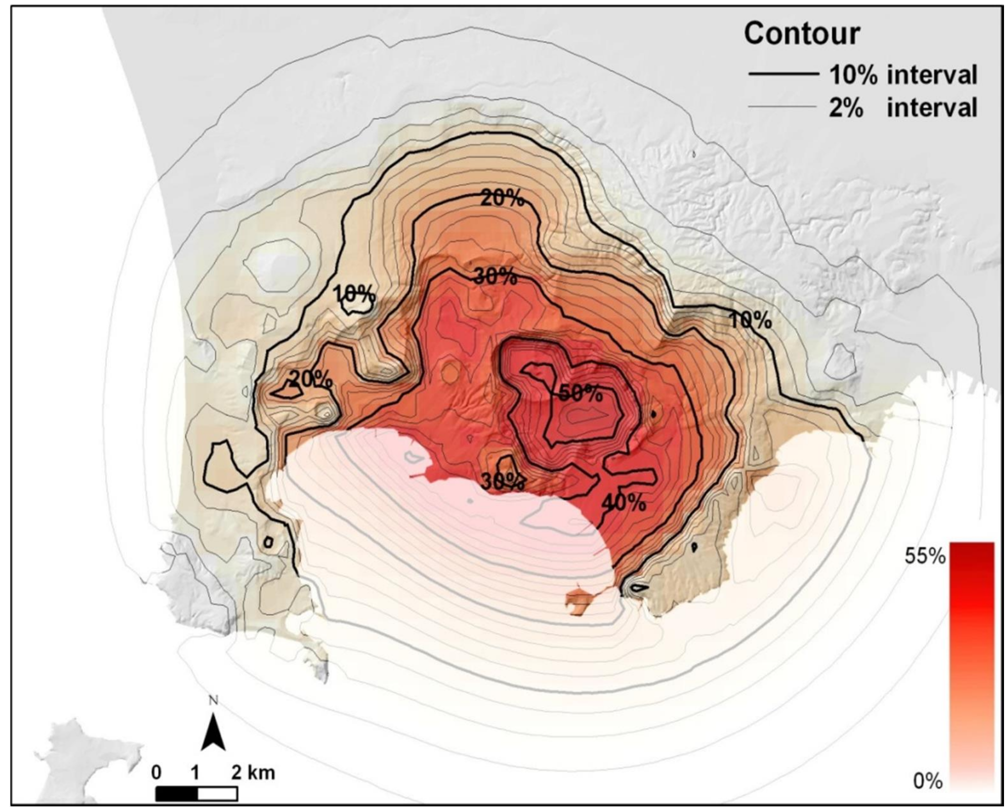
Mean PDC invasion hazard maps computed under different assumptions.

PDC invasion hazard maps - West/East scales estimated separately

PDC invasion hazard map with the same scale for West and East



PDC invasion hazard map with separate scales for West and East



Comparison between two mean maps assuming the **same scale** (left) and **separate scales** (right) between the eastern and western sectors of the caldera.

The second assumption produced a **shift** of the PDC invasion hazard towards East.

Probability model for the representation of the eruptive pattern

For representing the eruptive events as a function of time we defined a stochastic process Z in the class of **Cox-Hawkes multivariate counting processes**.

Each component Z^l counts the number of events occurred in a specific zone of the caldera [see Bevilacqua et al. 2015].

Cox-Hawkes generalize the class of **Poisson processes**, which sample the waiting times between events as independent identically distributed exponential random variables.

In general the intensity function λ of a counting process has the meaning of the **average density** of new events occurring in the selected time interval. Indeed the integral $\int \lambda dt$ gives the average number of events in the selected time interval.

The **Cox processes** assume their intensity function λ affected by uncertainty. They are doubly stochastic [e.g. Jaquet et al. 2000; Jaquet et al. 2008].

Hawkes processes assume that their intensity function increases with a jump whenever an event occurs and decreases as time passes without any event occurring. They naturally **generate clusters** [e.g. Bebbington and Cronin 2011].

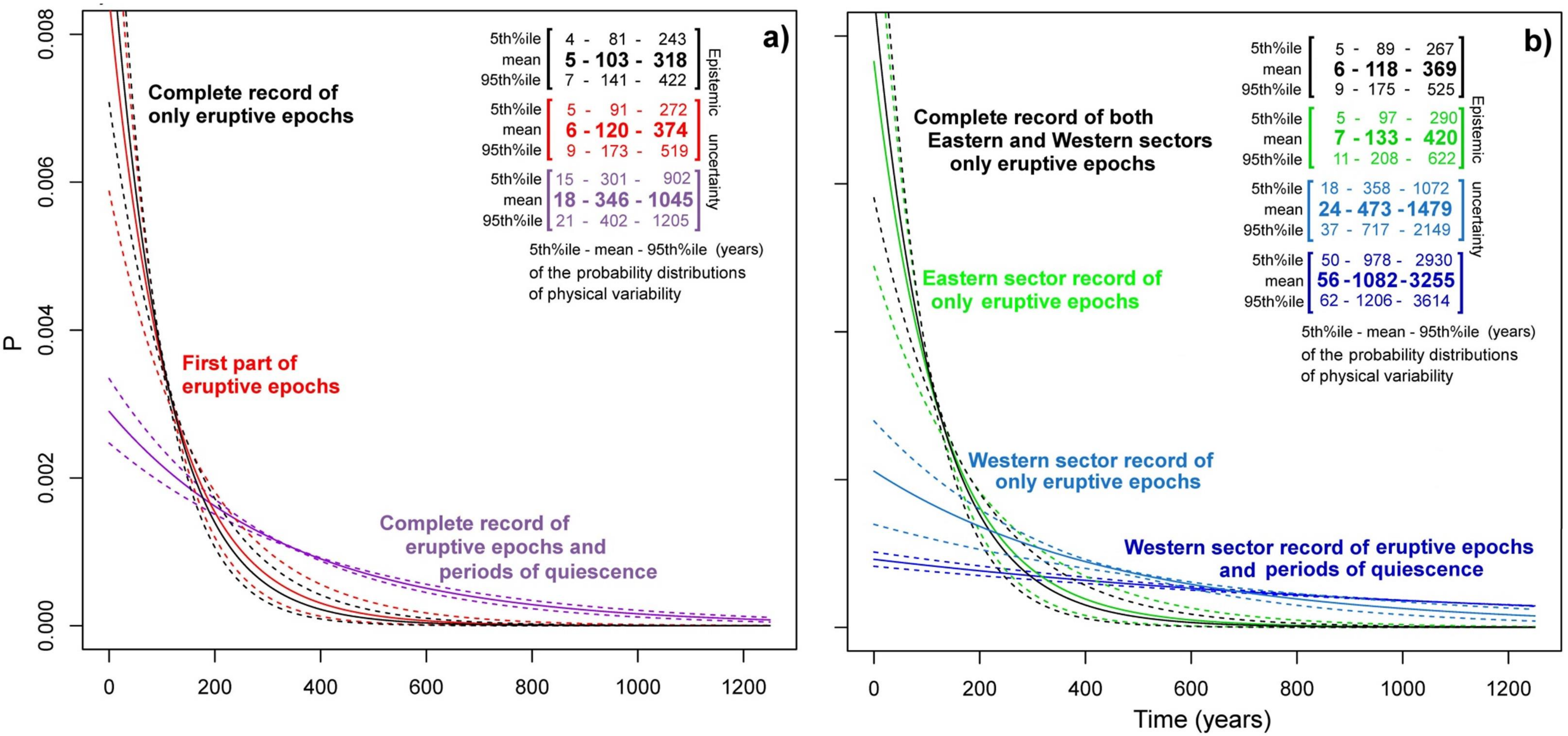
The **Cox-Hawkes processes** are both doubly-stochastic and self-exciting.

Probability forecasts of the next eruption time

A probability density function for the **remaining time** before the next eruption has been calculated.

We assumed a process Z_{mn} starting without excitement except for the residual additional intensity from Monte Nuovo event.

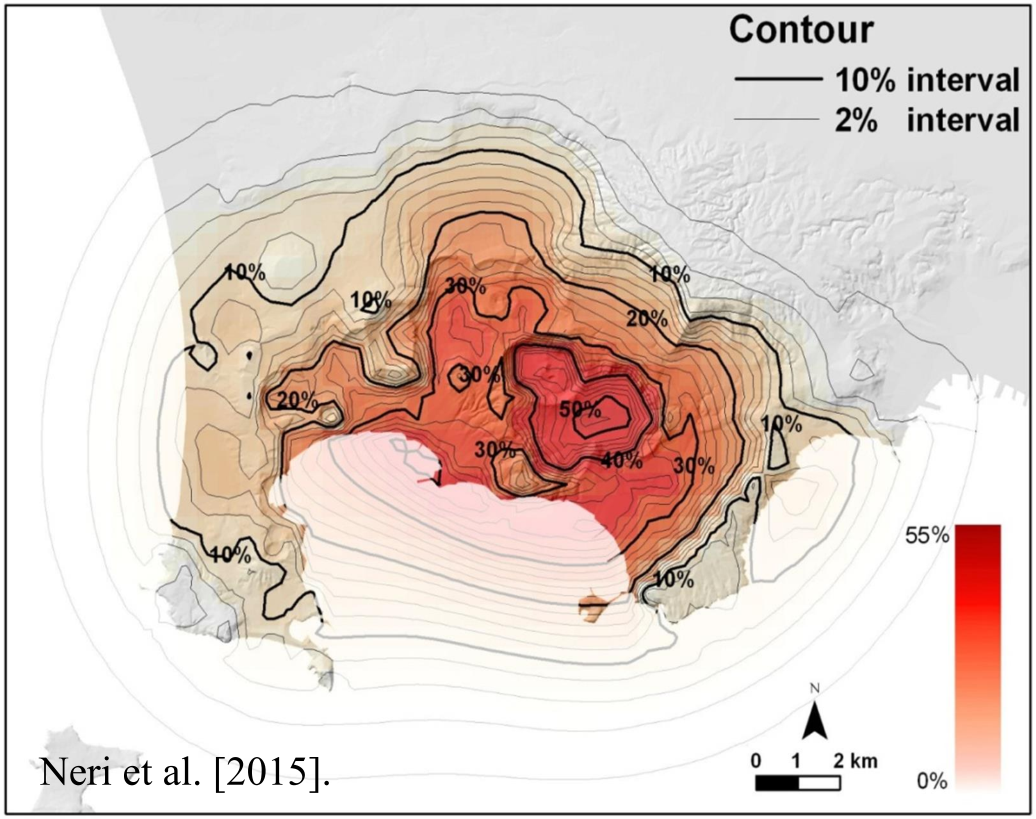
The mean and **uncertainty percentiles** of each probability density values were reported, as a function of the epistemic uncertainty affecting the stratigraphic record (see Bevilacqua [2016] – PhD thesis).



Probability density functions for the **remaining time before the next eruption**, assuming maximum likelihood exponential distributions. Different colours correspond to alternative geological assumptions. The bold lines indicate the mean probability density functions per year, and the dashed lines are composed of the 5*th* and 95*th e*pistemic uncertainty percentiles.

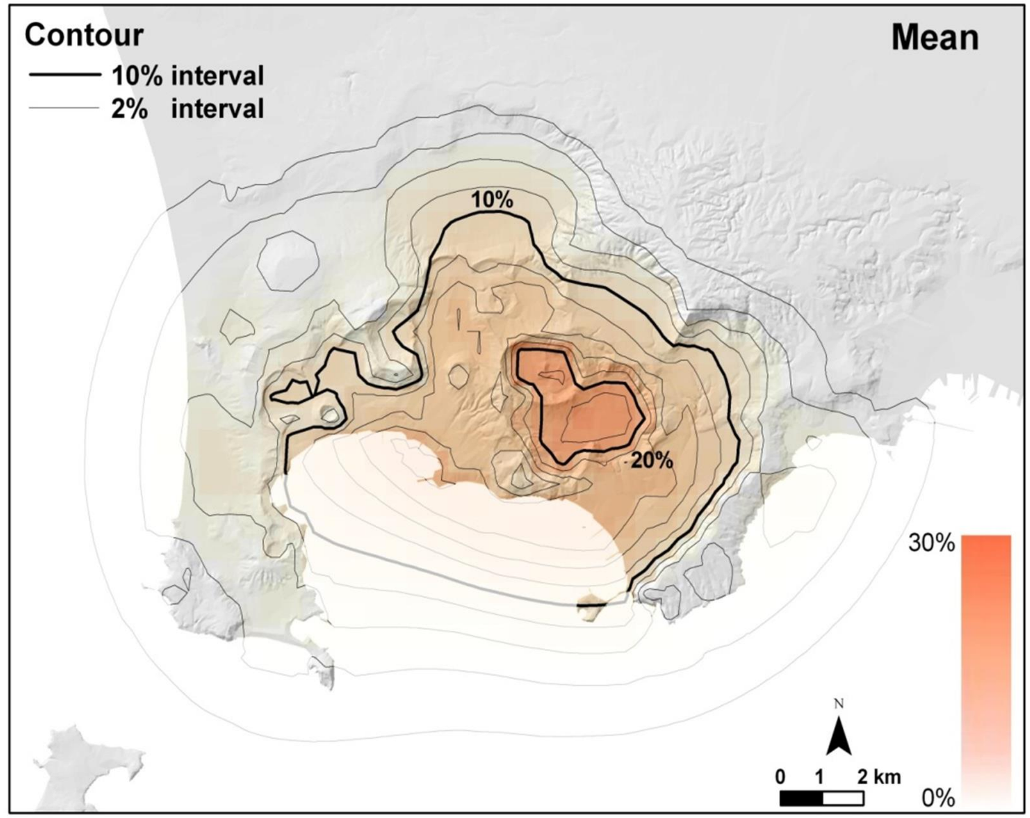
Preliminary PDC invasion hazard maps including time

PDC invasion hazard map conditional on the occurrence of a PDC - not including time



Neri et al. [2015].

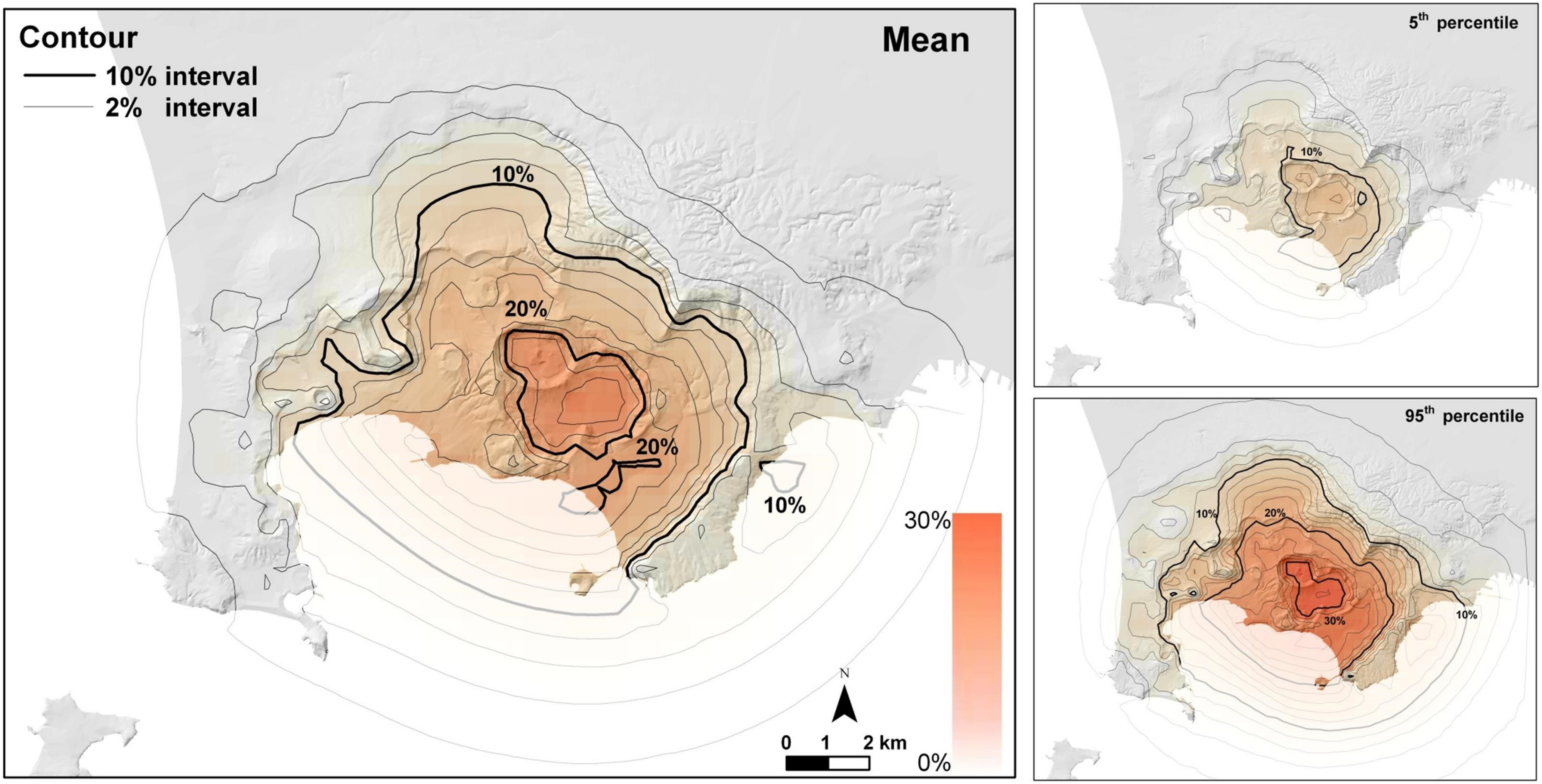
Preliminary PDC invasion hazard map with <u>50 years</u> temporal scale



The map on the right includes the possibility of a self-excited sequence of events, according to the Cox-Hawkes process.

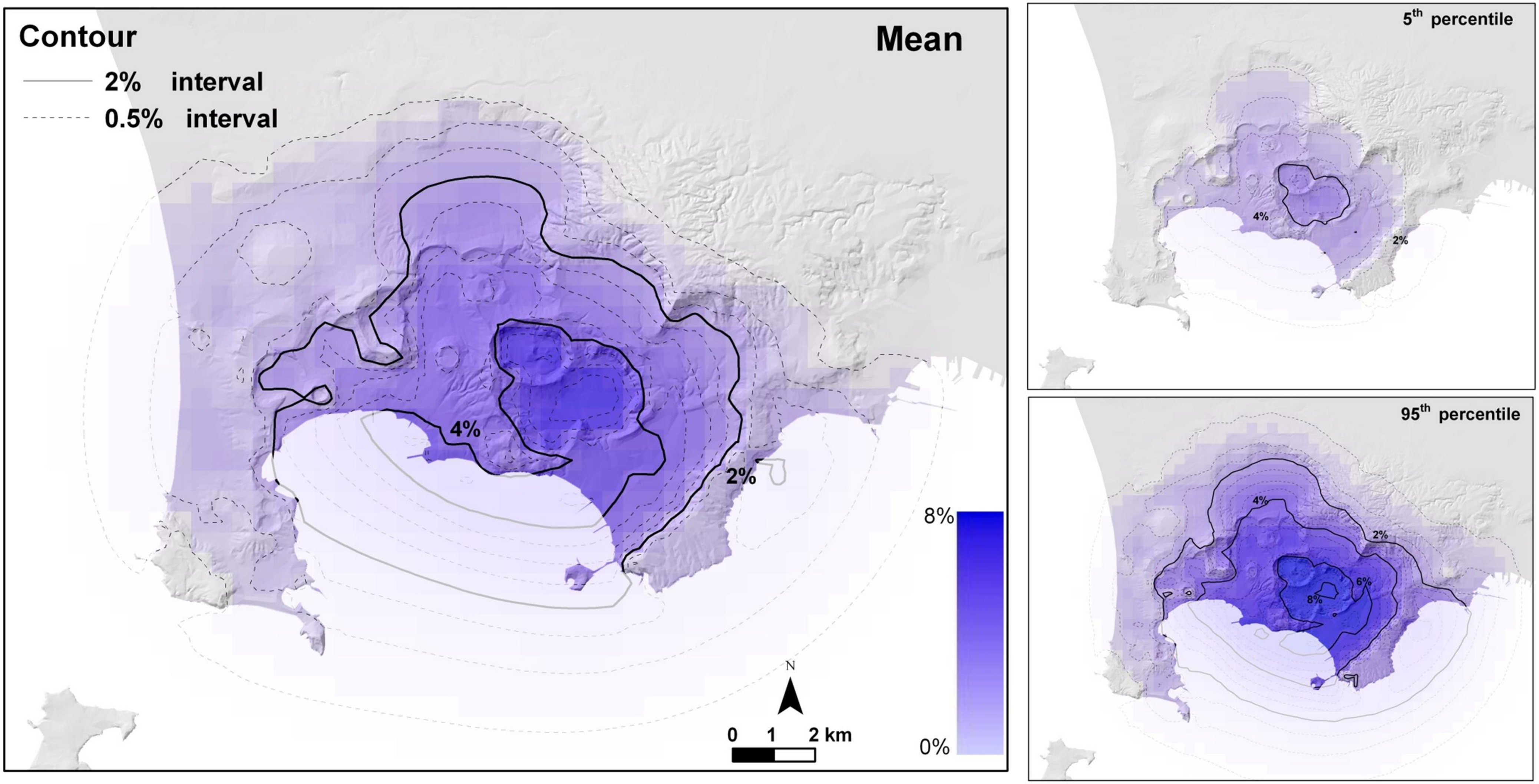
It represents the **PDC invasion hazard in the <u>next 50 years</u>**.

PDC invasion hazard maps – <u>50 years</u>
West/East times and scales estimated separately



The different PDC scales between the two sectors produced again a **shift towards East** of the PDC invasion hazard.

PDC invasion hazard maps – 10 years
West/East times and scales estimated separately



These maps represent the PDC invasion hazard from **the next event in 10 years.**
Different colours and contours from the other figures have been adopted.

Concluding remarks

- **Doubly stochastic models** are a general tool for assessing random systems that depend on uncertain information, as in the case of volcanic processes. **Cox and Hawkes processes** allow to consider data uncertainty and to reproduce spatial and temporal clustering of eruptive events.

- **Quantitative maps** of PDC invasion hazard at Campi Flegrei have been produced exploring a range of volcanological assumptions. The maps convolve the variability of the **three main future unknowns** of the system (vent location, eruption scale, time).

- By assuming that Monte Nuovo represents the start of a new epoch of activity, and by considering the caldera as a whole, the **average time to the next eruptive event** is of the order of ~100-120 years, with the 5th and 95th percentiles of physical variability corresponding to ~5 and ~350 years, respectively. Epistemic uncertainty was quantified as ±25-35%.

- PDC invasion hazard maps considering the **western and eastern sectors separately** result significantly different from those obtained considering the caldera as homogeneous. Maps significantly change also based on the temporal period assumed.

Publications

Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: I. Vent opening maps, *A. Bevilacqua , R. Isaia, A. Neri, S. Vitale , W. P. Aspinall, M. Bisson, F. Flandoli, P. J. Baxter, A. Bertagnini, T. Esposti Ongaro, E. Iannuzzi, S. Orsucci, M. Pistolesi, M. Rosi,* J Geophys Res, 120 (4), 2309-2329.

Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: II. Pyroclastic density current invasion maps, *A. Neri, A. Bevilacqua, T. Esposti Ongaro, R. Isaia, W. P. Aspinall, M. Bisson, F. Flandoli, P. J. Baxter, A. Bertagnini, E. Iannuzzi, S. Orsucci, M. Pistolesi, M. Rosi, S. Vitale*, J Geophys Res, 120 (4), 2330-2349.

Doubly Stochastic Models for Volcanic Hazard Assessment at Campi Flegrei Caldera, *A. Bevilacqua*, "PhD Thesis", Edizioni della Normale, Birkhäuser/Springer.

Acknowlegments

This study was developed through a PhD scholarship of Istituto Nazionale di Geofisica e Vulcanologia and Scuola Normale Superiore di Pisa (Convenzione INGV-SNS 2009-2011), and the following projects:

- **Project MED-SUV** "*Mediterranean Supersite Volcanoes*", European Union, 2013-2016.
- **Project DPC-V1** "*Valutazione della pericolosità vulcanica in termini probabilistici*", Dipartimento della Protezione Civile (Italy), 2012-2015.
- **Project EJN** "*Expert Judgment Network*", COST Action, European Union, 2013-2017.

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