A doubly stochastic model for pyroclastic density current hazard assessment: the example of Campi Flegrei caldera

A. Bevilacqua (1,2), A. Neri (1), T. Esposti Ongaro (1), R. Isaia (3),
W. Aspinall (4), P. J. Baxter (5), A. Bertagnini (1), M. Bisson (1), F. Flandoli (6),
E. Iannuzzi (3), M. Pistolesi (7), S. Orsucci (1,8), M. Rosi (9), S. Vitale (10)

(1) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa, Italy,
(2) Scuola Normale Superiore, Pisa, Italy,
(3) Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy,
(4) University of Bristol, Bristol and Aspinall and Ass. Trisbury, United Kingdom,
(5) University of Cambridge, Institute of Public Health, Cambridge, United Kingdom,
(6) Università di Pisa, Dip.to di Matematica, Pisa, Italy,
(7) Università di Firenze, Dip.to di Scienze della Terra, Firenze, Italy,
(8) Università di Pisa, Dip.to di Fisica, Pisa, Italy,
(9) Università di Pisa, Dip.to di Scienze della Terra, Pisa, Italy,
(10) Università di Napoli Federico II, Dip.to di Scienze della Terra, dell'Ambiente e delle Risorse, Napoli, Italy.

Mediterranean Supersite Volcanoes – Mid term Meeting – Napoli, 6 July - 9 July 2015

INGV

SCUOLA
NORMALE
SUPERIORE

MEDiterranean SUpersite Volcanoes
MED-SUV

The objective

The PDC hazard mapping in Campi Flegrei caldera is particularly challenging due to

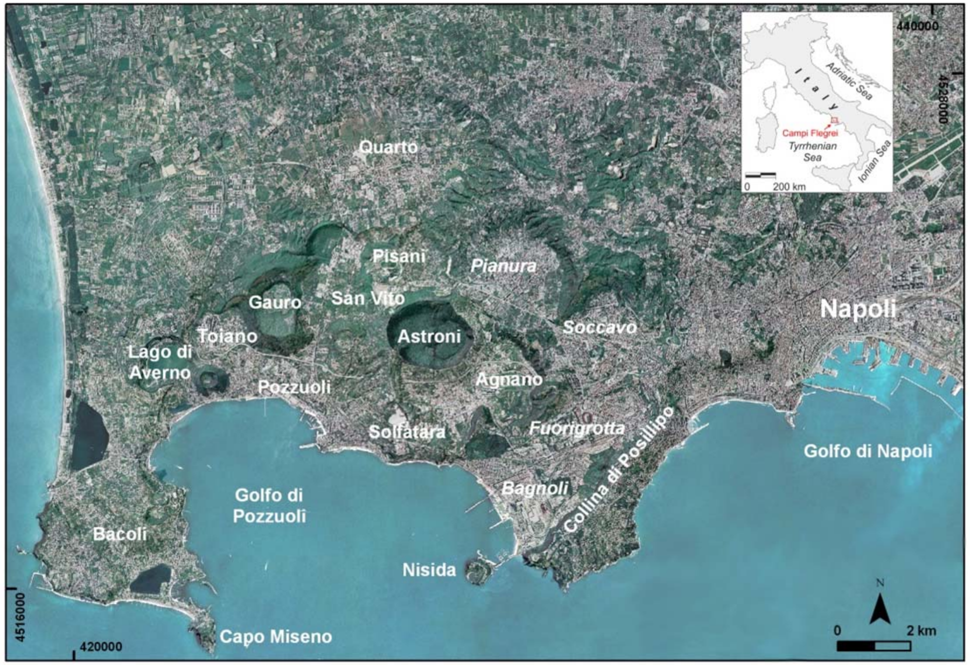
1) the large uncertainty on **future vent location**

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

3) the **complex dynamics of PDC**

A quantitative **probabilistic background** (long-term or base-rate) mapping of PDC invasion, including the intrinsic uncertainties of the system, is a requisite for a robust short-term hazard assessment.

We focused our work on the **quantification of the different sources of uncertainty** based on expert judgement techniques, for producing median and percentile spatial probability maps **conditional to an event**.



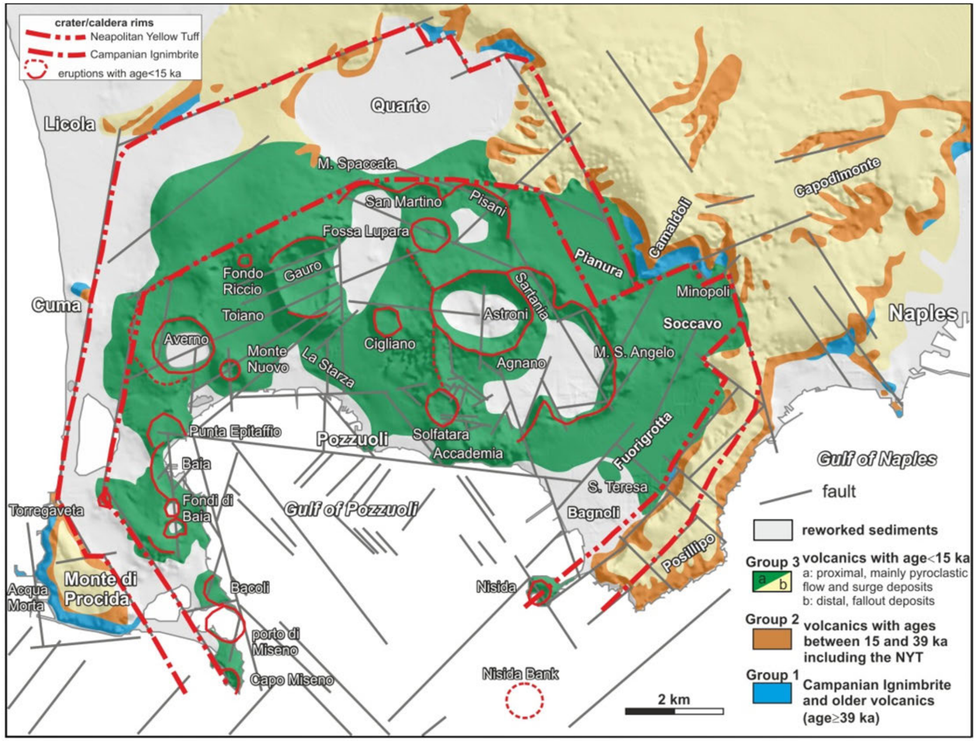


Figure 1. Campi Flegrei caldera; Bevilacqua et al. [2015].

Probability models of physical variability

We represented the physical variability of the next explosive eruption with:

- a **probability map of new vent opening** (i.e. susceptibility map) based on revised/new data (Fig.2).

- a **probability density function describing the distribution of past eruptive scales (i.e. PDC invasion areas)** , i.e. without selecting a reference scenario (Fig.3).

The two models are linked inside a Monte Carlo (MC) simulation, including the implementation of a **simplified PDC invasion model** for repeating a large number of PDC invasion samples of different scales and from various vent locations.

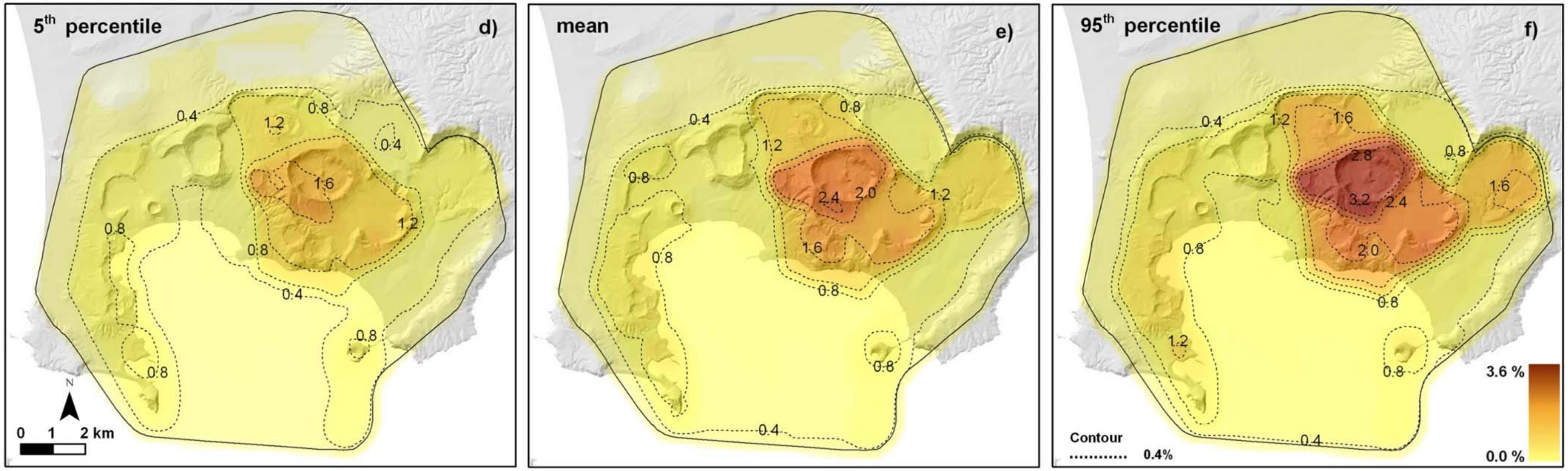


Figure 2. Probability maps of new vent opening; from Bevilacqua et al. [2015].

Included sources of epistemic uncertainty

Epistemic uncertainty is modelled by using a **doubly stochastic approach**, i.e. each sample in the MC simulation is accomplished in two steps:

A) the random choice of the epistemic assumptions,

B) the random determination of the observables of interest conditional on them.

We included several sources of epistemic uncertainty as:

- the uncertainty on the **spatial location of eruptive vents/fissures**

- the uncertainty due to the **incompleteness of the datasets** of the variables considered (e.g. lost vents, zones of unknown fracturation, lost PDC units, underestimation of past PDC)

- the **uncertainty on the relative weights** of the different variables considered for the vent opening map definition
(as a linear combination of different layers)

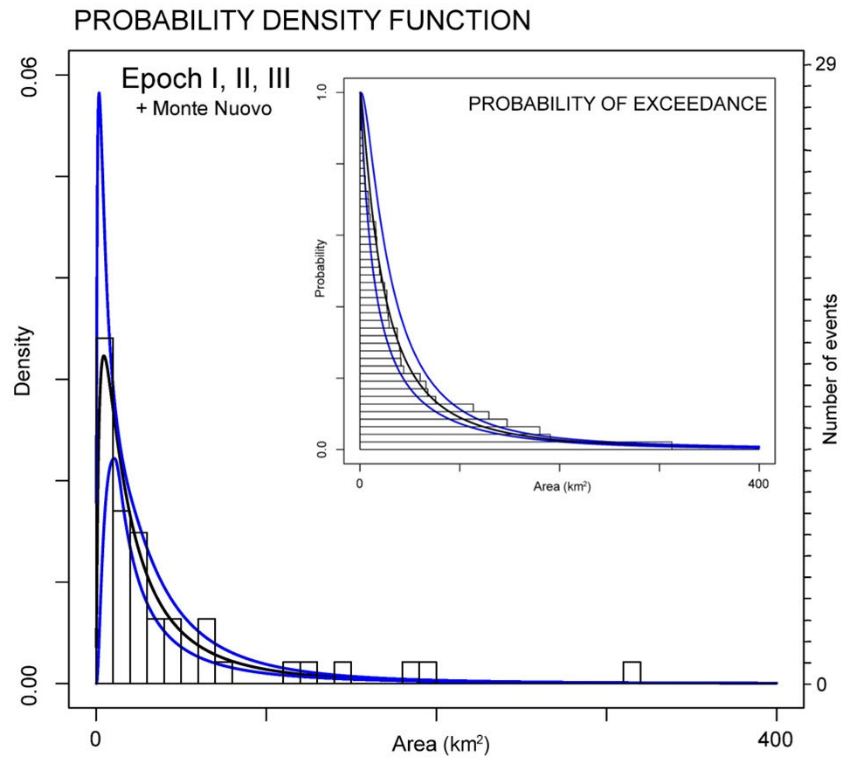
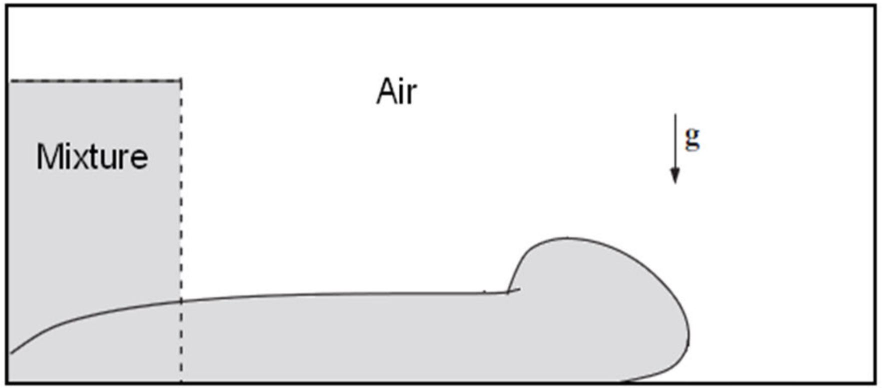


Figure 3. P.d.f. for PDC invaded areas; from Neri et al. [2015].

Integral model for sedimenting density currents

Figure 4. The instantaneous release configuration.



The dynamics of the PDC are described as the **collapse of a finite volume of dense fluid in a lighter atmosphere** and on a flat surface.

Von Karman [1940], Huppert and Simpson [1980]

The model allows computation of **flow kinematics** and the **flow run-out** reached over a sub-horizontal surface by a current generated by instantaneous release of a constant finite volume of gas and solid particles, homogeneously mixed.

$$\begin{cases} u = \dfrac{dl}{dt} = Fr(g_p \phi h)^{1/2}, \\ \dfrac{d\phi}{dt} = -w_s \dfrac{\phi}{h}, \\ l^2 h = V. \end{cases}$$

$$l(t) = \left[tanh(t/\tau)\right]^{1/2} l_{max}$$

$$l_{max} = \left(8\phi_0^{1/2} Fr \, g_p^{1/2} V^{3/2} w_s^{-1}\right)^{1/4}$$

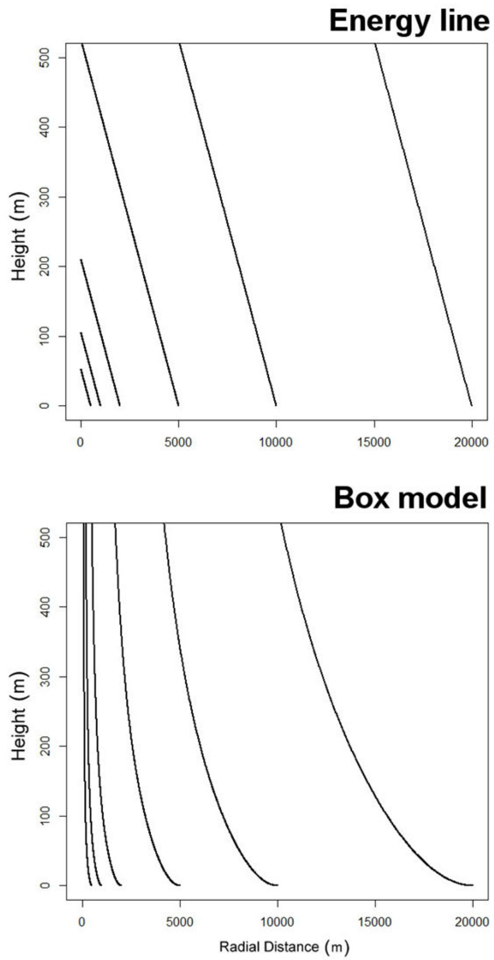


Figure 5. Comparison of energy curves as a function of distance from the vent.

The propagation model for PDC

For quantifying **first-order effects of topography** on the propagation of a PDC, the **flow kinetic energy** is compared to the **potential energy required** to overcome the topographical reliefs that the flow encounters.

$$H = \frac{1}{2g}\left[\frac{C\, l_{max}^{1/3}}{x\cosh^2 \operatorname{artanh}(x^2)}\right]^2, \quad C = (Fr^2 w_s \phi_0 g_p)^{1/3} / 2 \qquad x = l / l_{max}$$

This PDC invasion model is applied in an **inverse mode** repeated for each sample of the Monte Carlo simulation. From the estimate of the invaded areal size we compute the initial conditions required for generating such propagation, given a specific vent location.

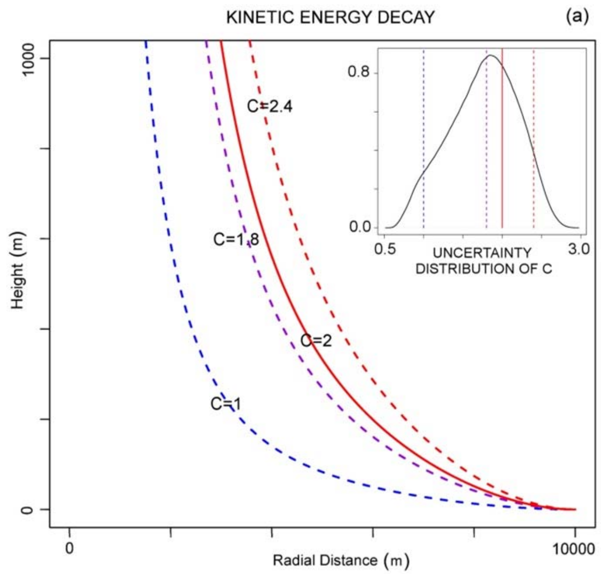


Figure 6. Example of decay of flow head kinetic energy; from Neri et al. [2015]

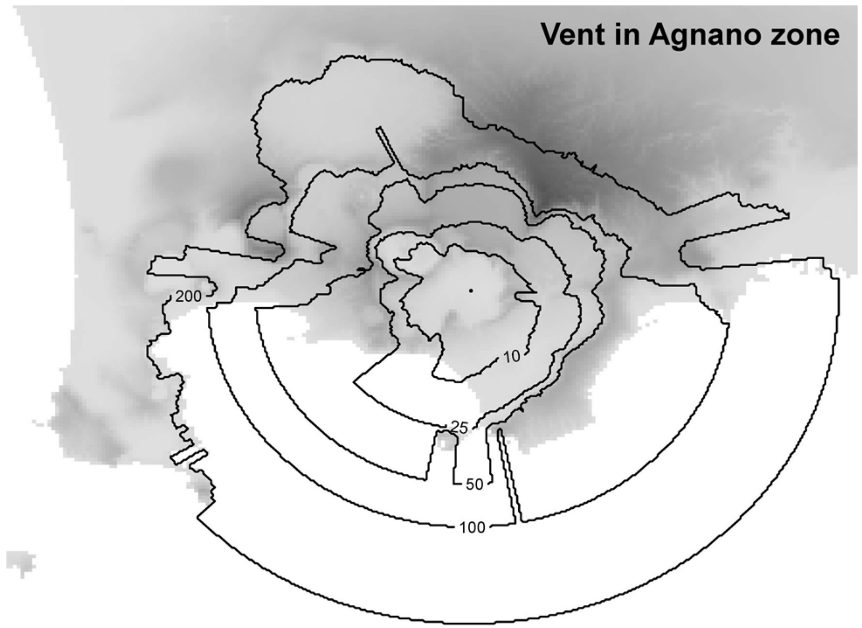
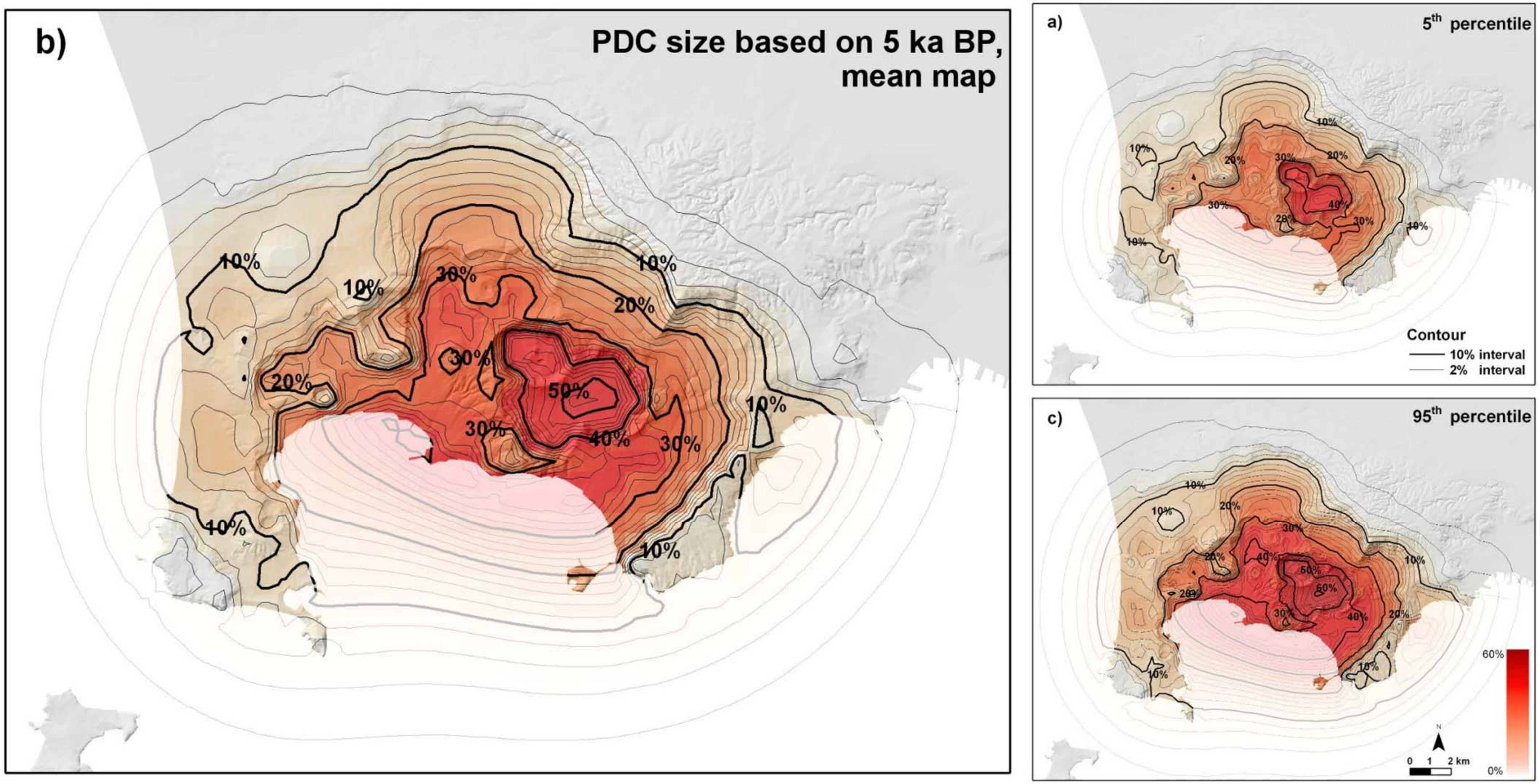


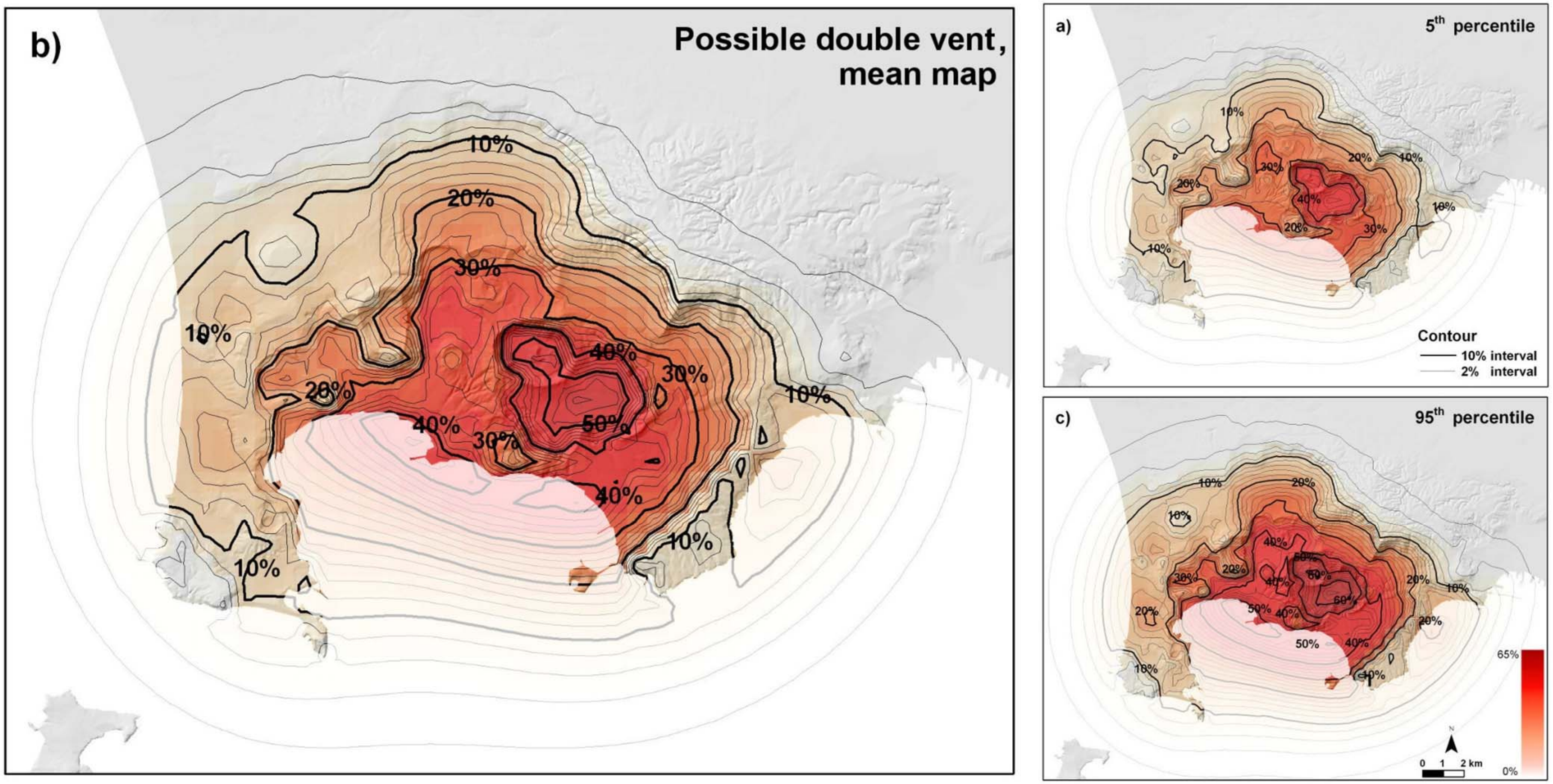
Figure 7. Examples of five different PDCs modelled with the integral emulator from the same vent location, but invading different areal sizes, reported on the contours.

PDC invasion probability maps - reference case



PDC invasion probability maps computed by assuming the density distribution of invasion areas of the **last 5 ka**. We assume that PDCs originate from a **single vent** per eruption, and that the vent is located in the **on-land part** of the caldera. Contours and colours indicate the percentage probability of PDC invasion conditional on the occurrence of an explosive eruption. (from Neri et al., 2015).

PDC invasion hazard probability maps – double vent

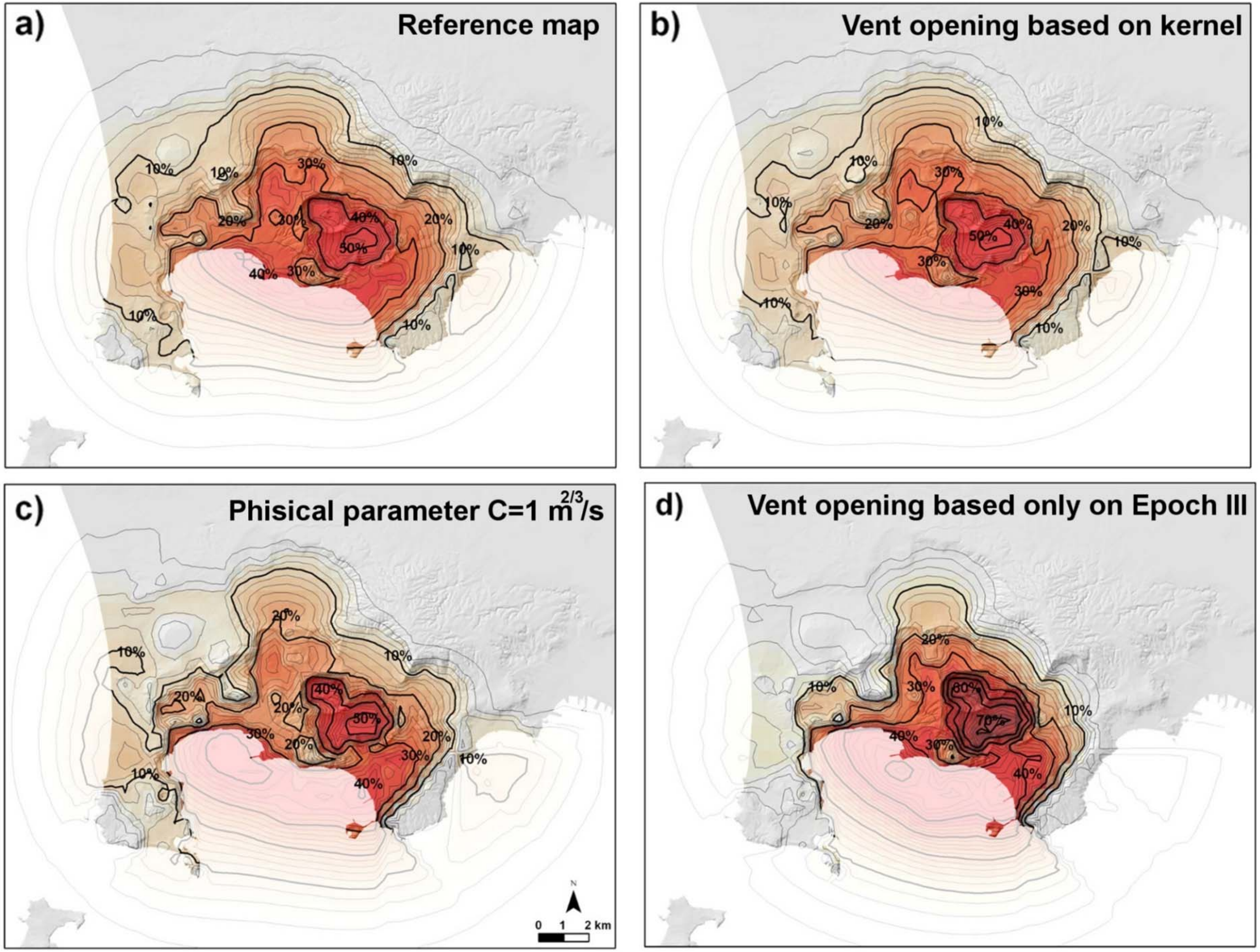


PDC invasion probability maps computed by assuming the possibility that two PDCs originate from different vents during a single eruption, both located in the onland part of the caldera; from Neri et al. [2015].

Probability of two vents: [5% - **10%** - 25%]

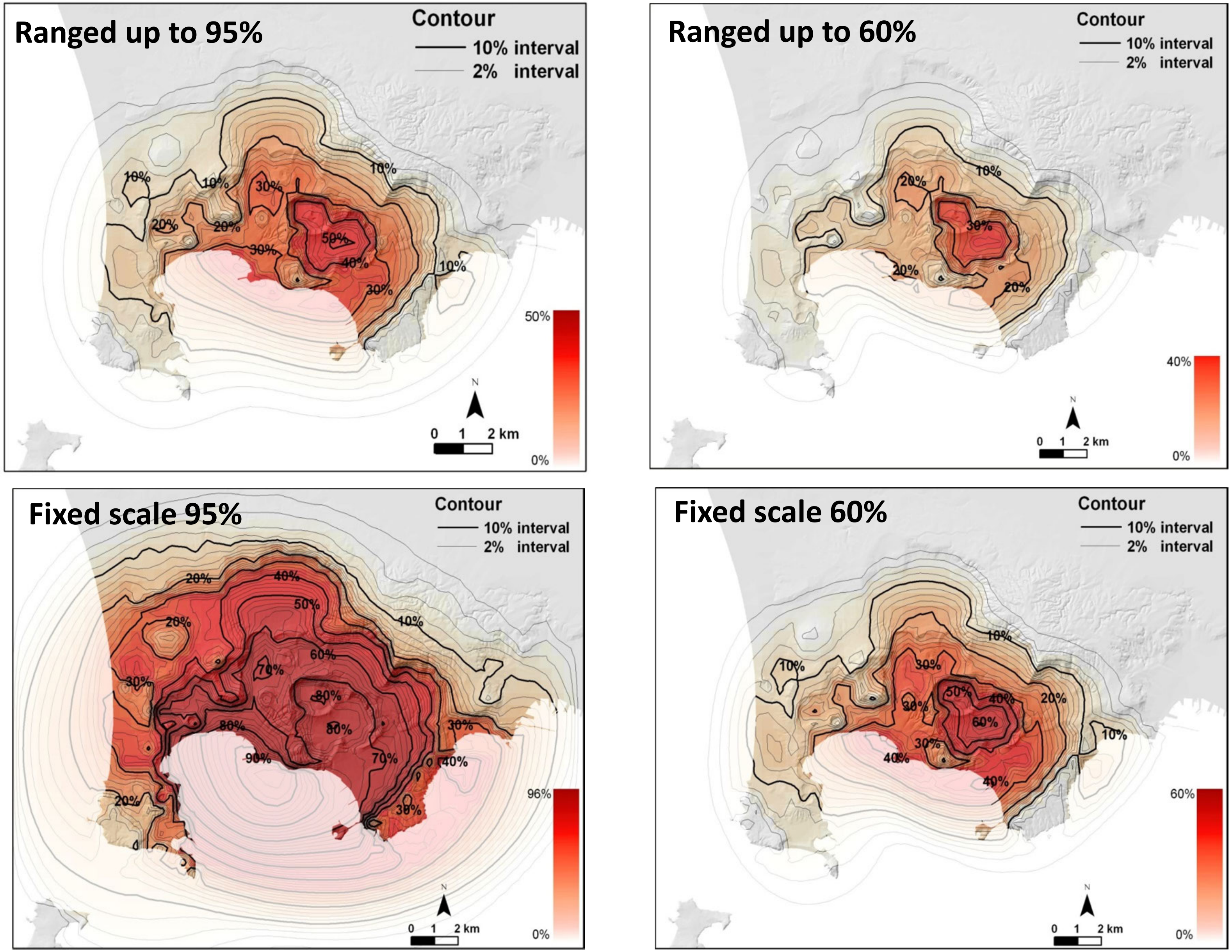
Distance between simultaneous vents: [1 – **4.7** – 10] km

PDC invasion hazard probability maps – VO maps/physical parameters



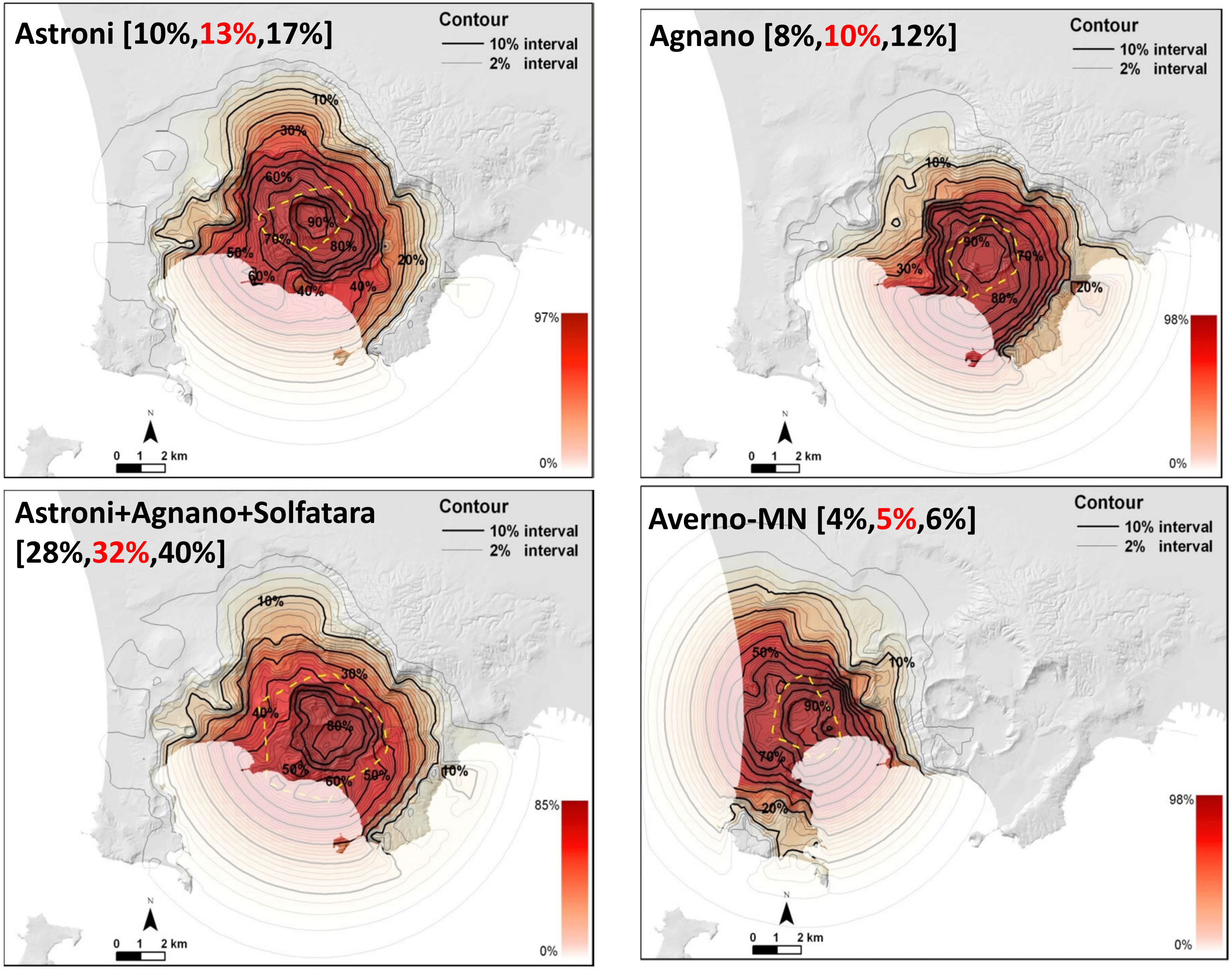
Mean PDC invasion probability maps computed under different assumptions.

PDC invasion probability maps – ranged vs fixed scales



Mean PDC invasion probability maps computed under different assumptions.

PDC invasion probability maps – specific vent zones [prob%]



Mean PDC invasion probability maps computed under different assumptions.

Summary and conclusions

- **Doubly stochastic spatial probability maps** of PDC hazard have been produced, conditional to the next explosive eruption at Campi Flegrei.

- A key objective was to **quantify the epistemic uncertainty** on the hazard maps; this was done by using structured expert judgment techniques and Monte Carlo simulations.

- Outcomes show that the **central-eastern areas** of the caldera are the most exposed to flow invasion but significant probability values exist **all over the caldera** and also in some areas **outside it**.

- The model have been **applied under different volcanological assumptions** for assessing the sensitivity of the outcomes on them and obtaining hazard maps conditional on particular scenarios.

- The analysis will be extended by including a **doubly stochastic temporal model** for the remaining time before the next explosive eruption at Campi Flegrei.

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., doi:10.1002/2014JB011775, 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., doi:10.1002/2014JB011776, 120 (4), 2330-2349.

Acknowlegments

• **Project MED-SUV** “*Mediterranean Super-Volcanoes*”, European Union, 2013-2016.
• **Project DPC-V1** “*Valutazione della pericolosità vulcanica in termini probabilistici*”, Dipartimento della Protezione Civile (Italy), 2012-2015.
• **Project SPEED** “*Scenari di pericolosità e danno per i vulcani della Campania*”, Dipartimento della Protezione Civile (Italy) and Regione Campania, 2007-2010.
• **Project EJN** “*Expert Judgment Network*”, COST Action, European Union, 2013-2017.