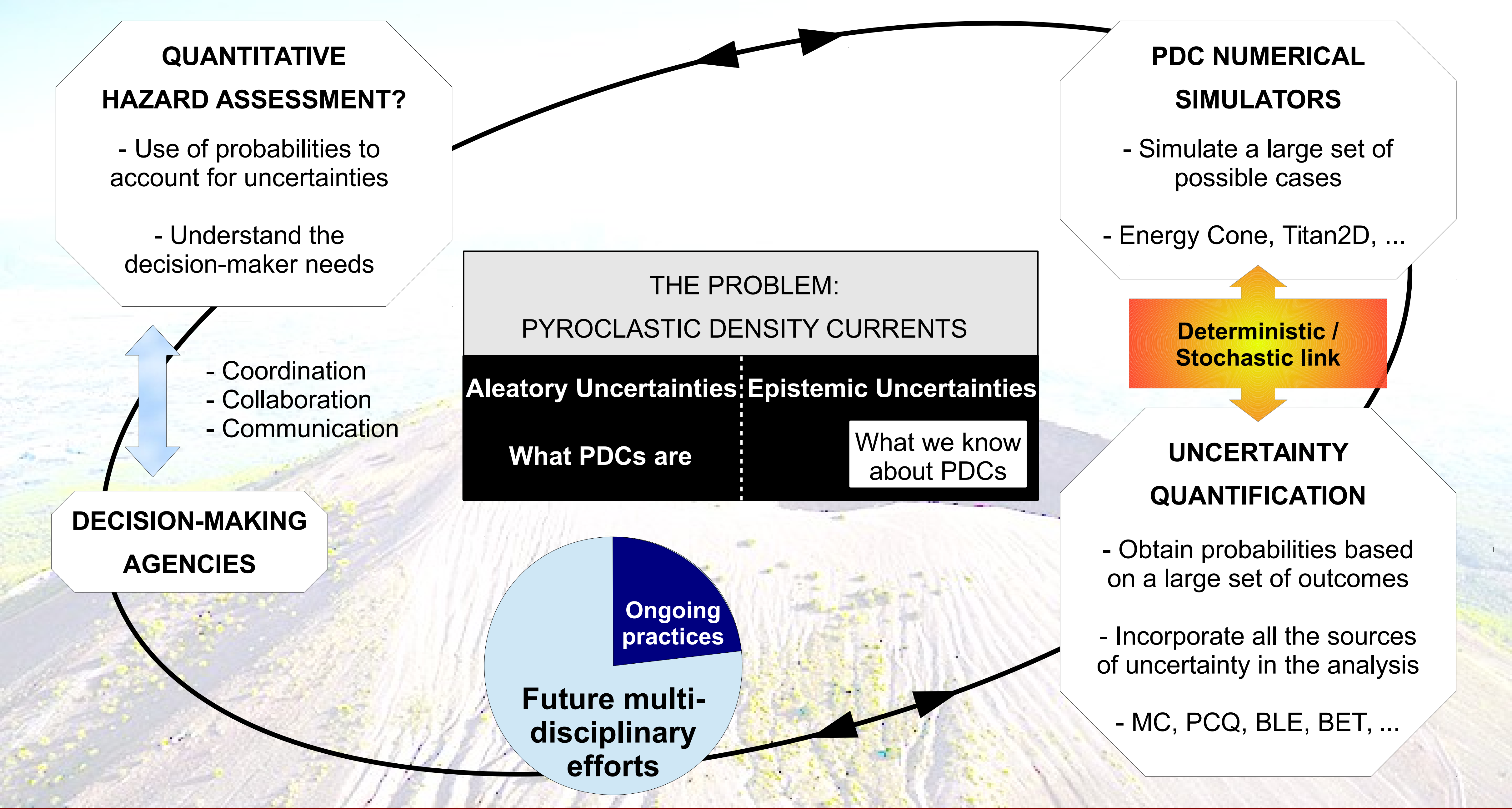
GMP32/NH2.6. PICO2.8. EGU2014-15580
Probabilistic volcanic hazard assessments of Pyroclastic Density Currents: ongoing practices and future perspectives

Pablo Tierz[1], Laura Sandri[1], Elena Ramona Stefanescu[2], Abani Patra[2], Warner Marzocchi[3], Antonio Costa[1], Roberto Sulpizio[4]
1: INGV, *Sezione di Bologna* (Italy) // 2: University at Buffalo (USA) // 3: INGV *Roma* (Italy) // 4. *Università di Bari* (Italy)


QUANTITATIVE HAZARD ASSESSMENT?
- Use of probabilities to account for uncertainties
- Understand the decision-maker needs
PDC NUMERICAL SIMULATORS
- Simulate a large set of possible cases
- Energy Cone, Titan2D, ...
THE PROBLEM:
PYROCLASTIC DENSITY CURRENTS
Aleatory Uncertainties
Epistemic Uncertainties
What PDCs are
What we know about PDCs
Deterministic / Stochastic link
- Coordination
- Collaboration
- Communication
DECISION-MAKING AGENCIES
UNCERTAINTY QUANTIFICATION
- Obtain probabilities based on a large set of outcomes
- Incorporate all the sources of uncertainty in the analysis
- MC, PCQ, BLE, BET, ...
Ongoing practices
Future multi-disciplinary efforts

WHAT'S NEMOH?

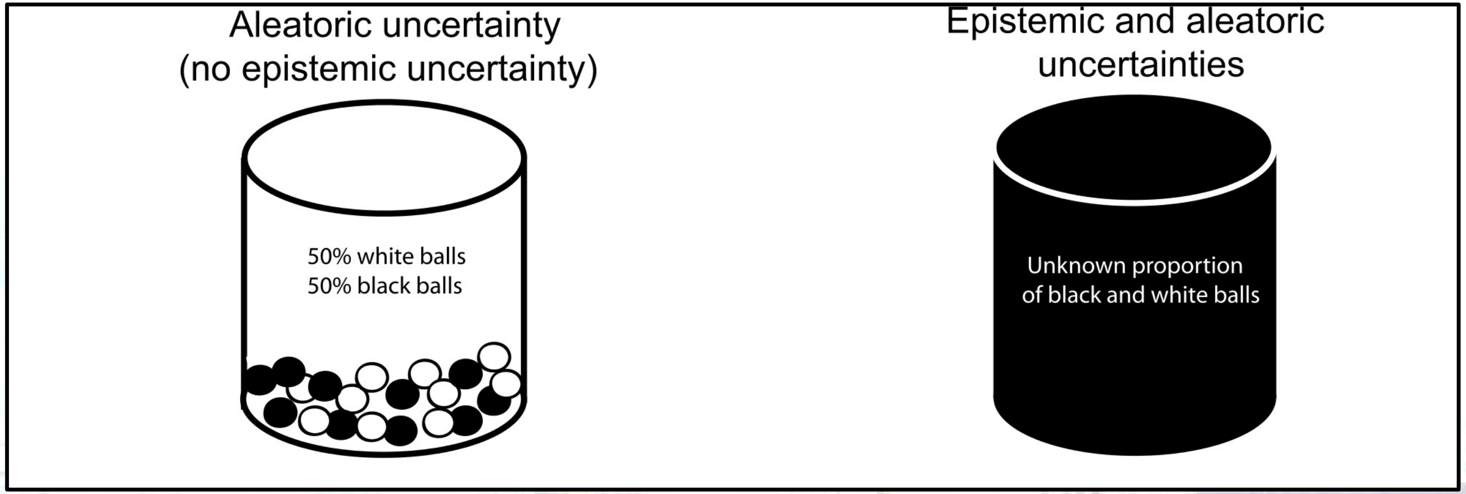
- **N**umerical, **E**xperimental and stochastic **M**odelling of v**O**lcanic processes and **H**azard:
  - Initial Training Network under the European Community FP7.
  - **Training through research**.
  - The next generation of European volcanologists.
- 9 full Network Partners + 4 Associated Partners (8 countries).
- 18 Early-Stage Researchers (8 nationalities, 3 continents).

NEMOH

PEOPLE

MARIE CURIE ACTIONS

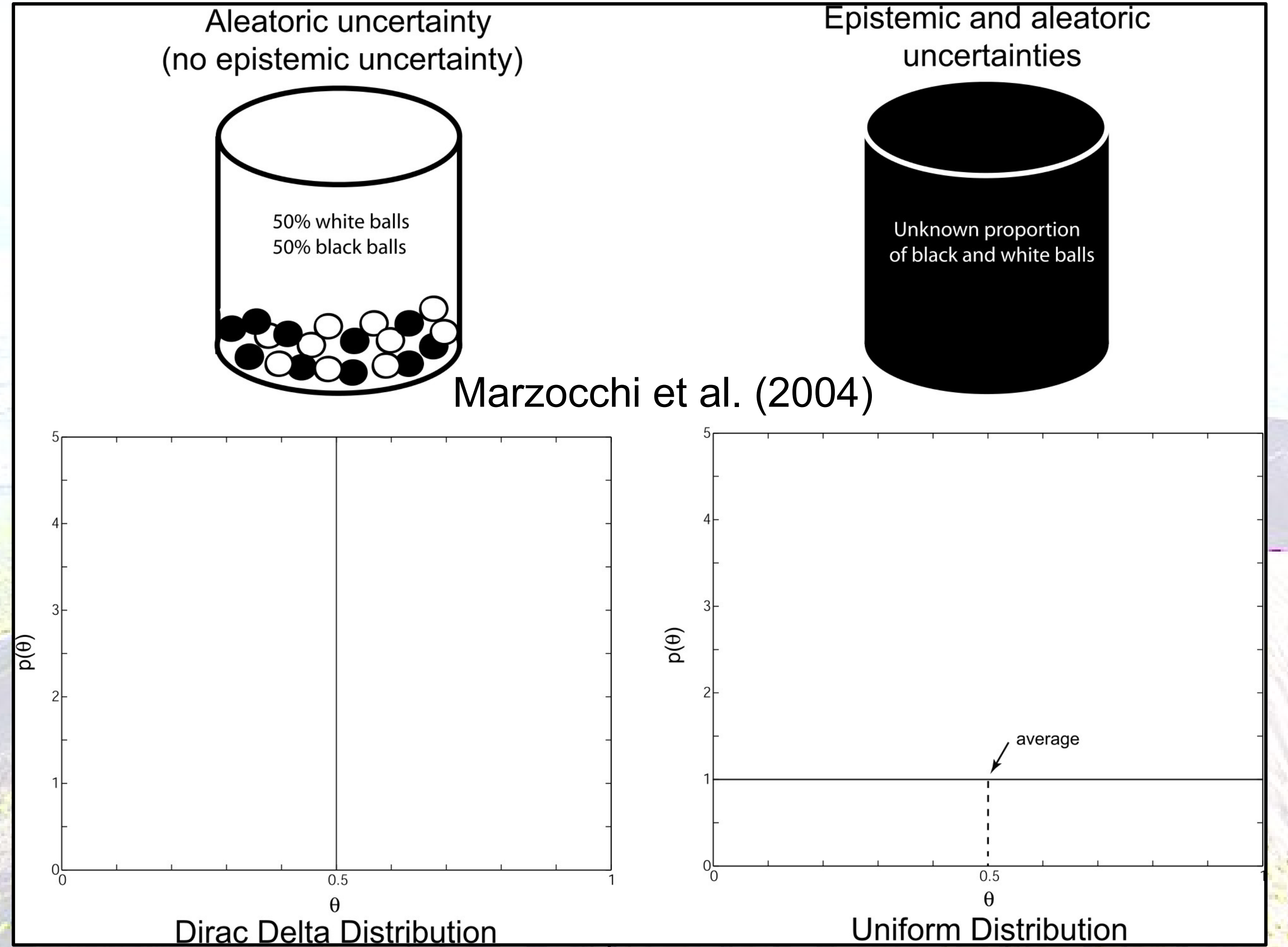
Types of uncertainties: probability of getting a black ball?



You win 50 euros for each black ball you get...

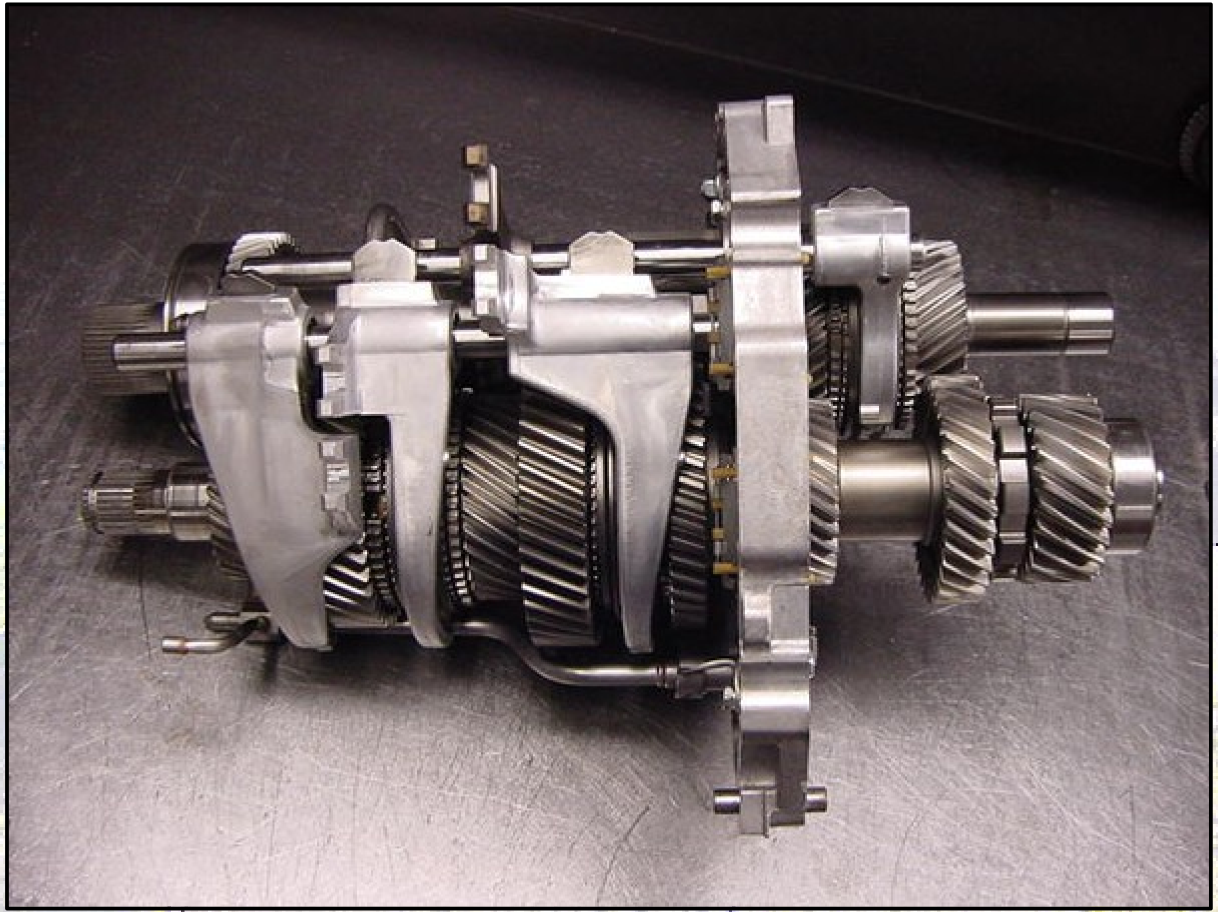
Which box would you choose?

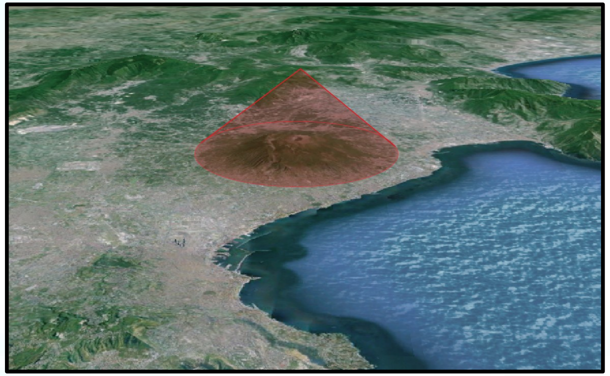
Types of uncertainties: probability of getting a black ball?



ALEATORY		EPISTEMIC
Inherent	VS	Knowledge-related
Irreducible		Reducible
Expressed as a single (expected) value		Expressed as a dispersion (variance) around the value

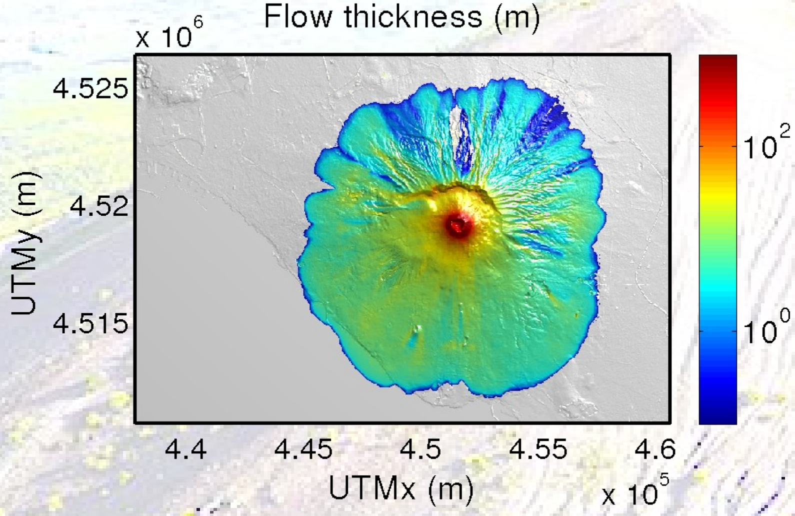
The “basic” picture





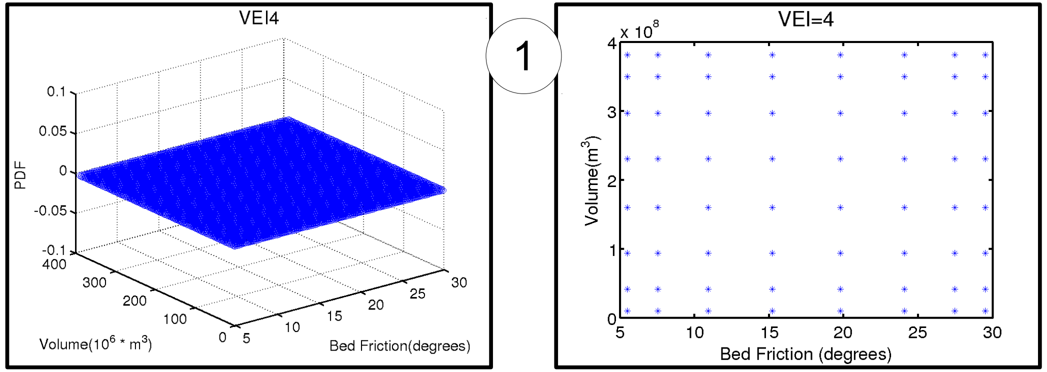
Energy Cone

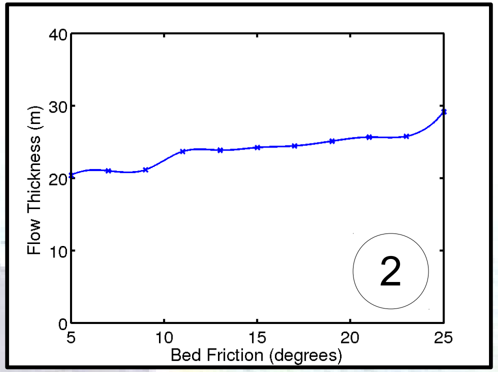
PDC NUMERICAL SIMULATORS

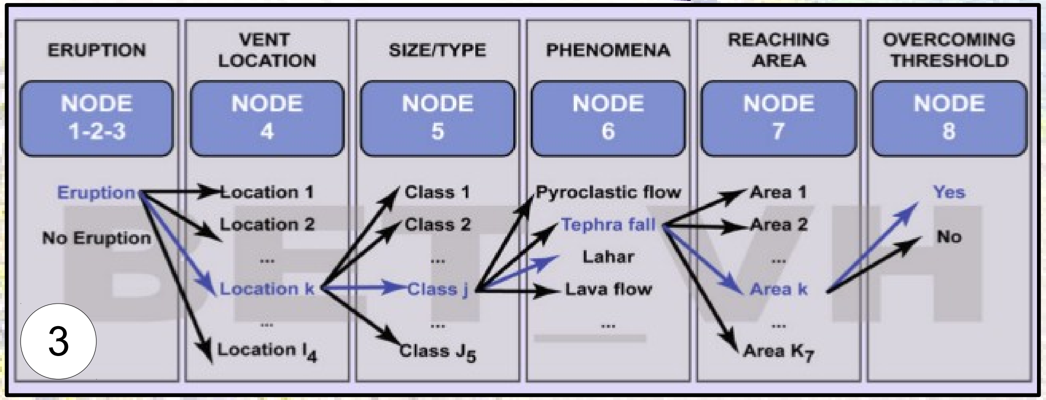


Titan2D

UNCERTAINTY QUANTIFICATION TECHNIQUES (1: PCQ, 2: BLE, 3: BET)







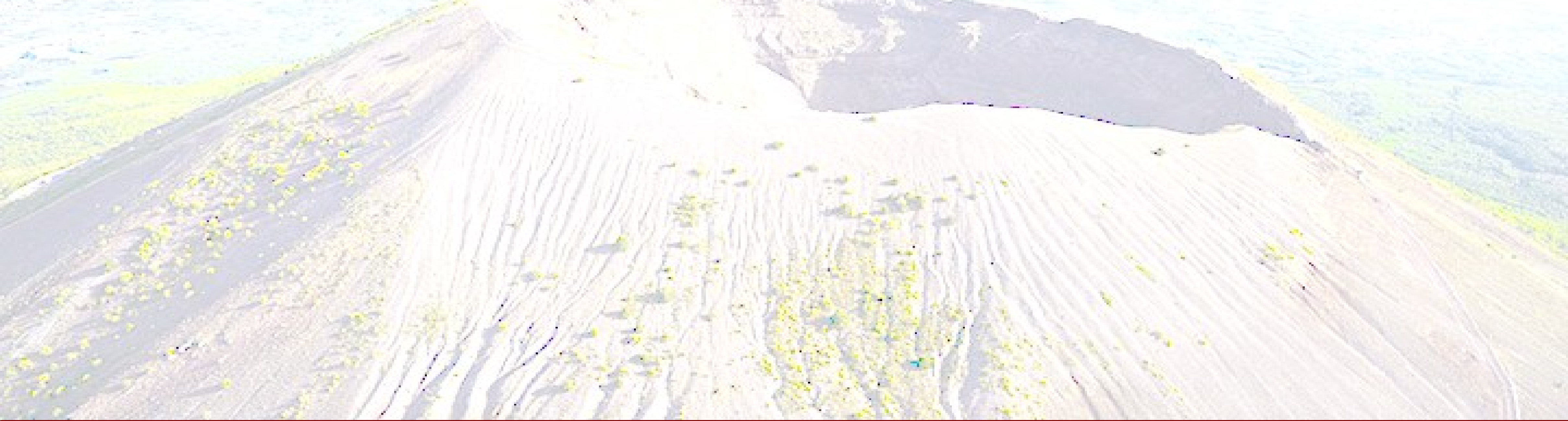
Outline

A) Simulator or technique description

B) Pros and Cons

C) What's been recently done

D) What can be done



The simulators (I): Energy Cone (EC)

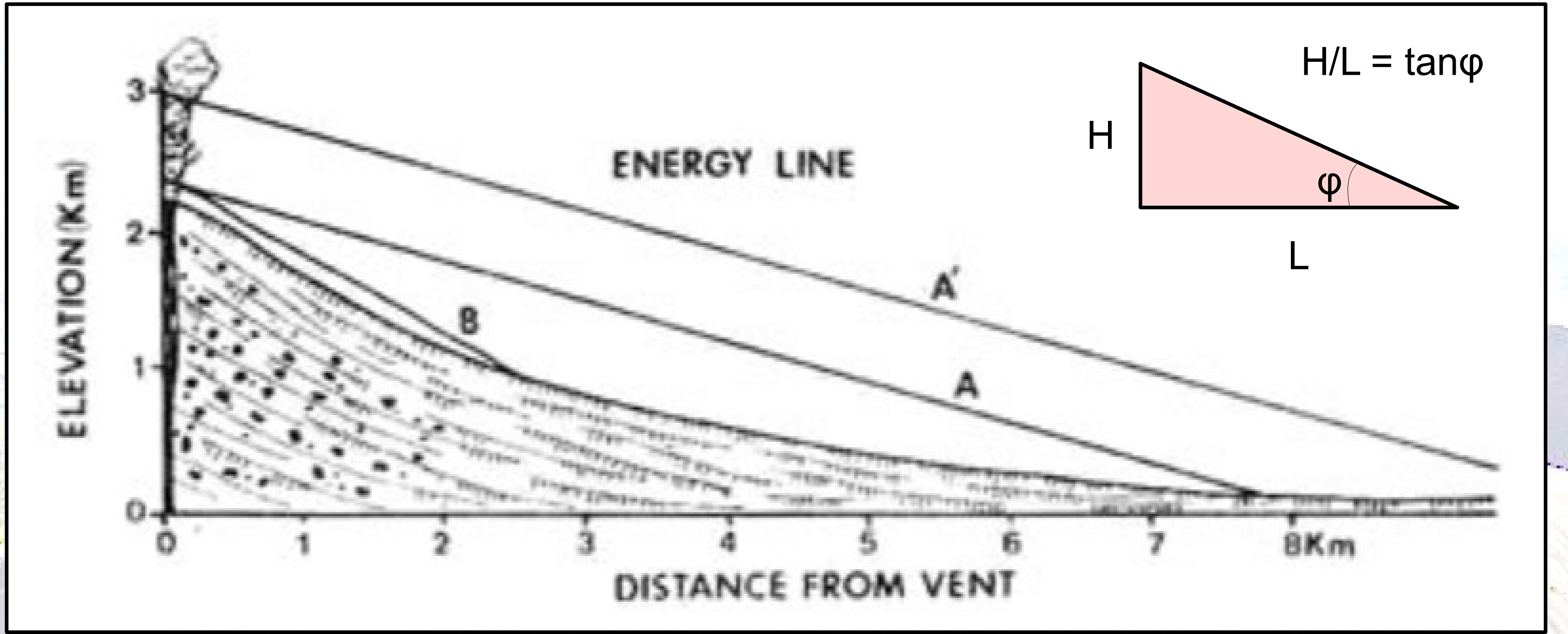
Computer-Assisted Mapping of Pyroclastic Surges

Abstract. *Volcanic hazard maps of surge boundaries and deposit thickness can be created by using a simplified eruption model based on an "energy line" concept of pyroclastic surge and flow emplacement. Computer image-processing techniques may be used to combine three-dimensional representations of the energy relations of pyroclasts moving under the influence of gravity (defined by an "energy cone") with digital topographic models of volcanoes to generate theoretical hazard maps. The deposit boundary and thickness calculated for the 18 May 1980 eruption of Mount St. Helens are qualitatively similar to those actually observed.*

Maps of volcanic hazards provide a basis for making policy decisions regarding public safety during times of impending volcanic crises. A useful map is one that is produced by methods that are (i) reliable (the data base should accurately reflect the distribution of products from all hazardous phenomena recorded by outcrop patterns of prehistoric events, and observed phenomena of historic eruptions), (ii) applicable (an understanding of the phenomena should be sufficient to predict the distribution of products of renewed activity given adequate assumptions regarding the magnitude of the event, location of the vent,

Malin, M.C., Sheridan, M.F. (1982). *Science*, 217, 637-640.

The simulators (I): Energy Cone (EC)



Modified from Sheridan, M.F (1980). *Bull. Volcanol.*, 43-2, 397-402.

Potential energy transformed into kinetic energy as the PDC moves away from the source

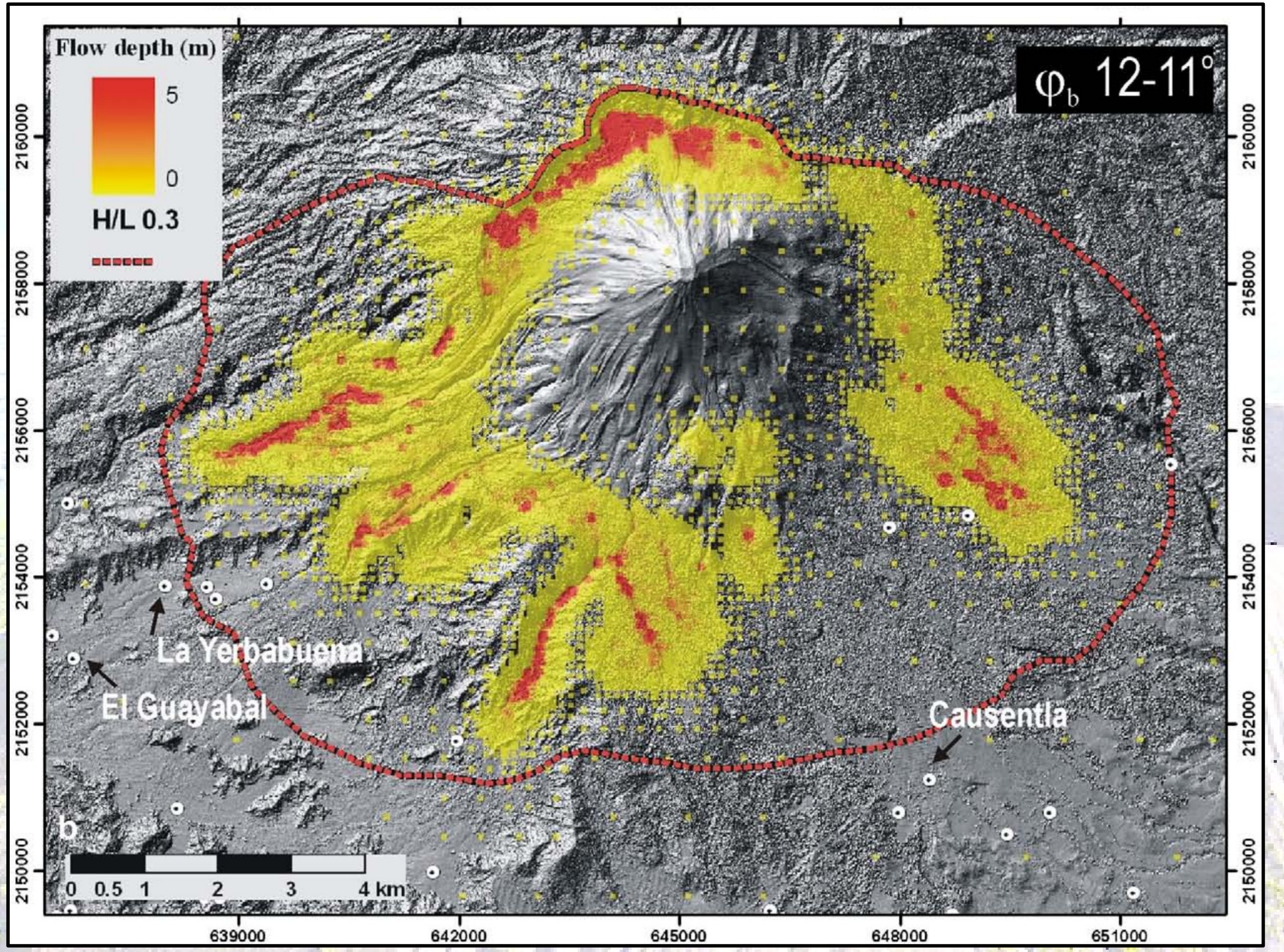
φ accounts for PDC mobility (the greater φ, the more reduced the mobility)

PDCs are estimated to stop when the energy line cuts the topographic surface

The simulators (I): Energy Cone (EC)

MAJOR STRENGTHS	MAJOR WEAKNESSES
Extremely short runtimes (seconds to few minutes).	Very strong simplification of the physical processes involved.
In principle, able to simulate both dense and dilute PDCs.	Just able to output PDC invasion area and an approximation to PDC speed.
Can be run using a Digital Elevation Model (DEM).	1D simulator extrapolated to 2D (does not account for 2D-3D effects).

The simulators (I): EC. What has been (recently) done.



Sulpizio et al. (2010). *J. Volcanol. Geotherm. Res.*, 193, 49-66.

Coupling Titan2D (colorbar) and Energy Cone (outer red line) to evaluate PDC (block-and-ash flows) single scenarios at Colima (Mexico)

The simulators (I): EC. What has been (recently) done.

IAVCEI 2013 Scientific Assembly - July 20 - 24, Kagoshima, Japan
Forecasting Volcanic Activity - Reading and translating the messages of nature for society
IAVCEI 2013 Kagoshima
3P1_4C-O13 Room A6 Date/Time: July 23 16:15-16:30

Probabilistic invasion maps of long-term pyroclastic density current hazard at Campi Flegrei caldera (Italy)

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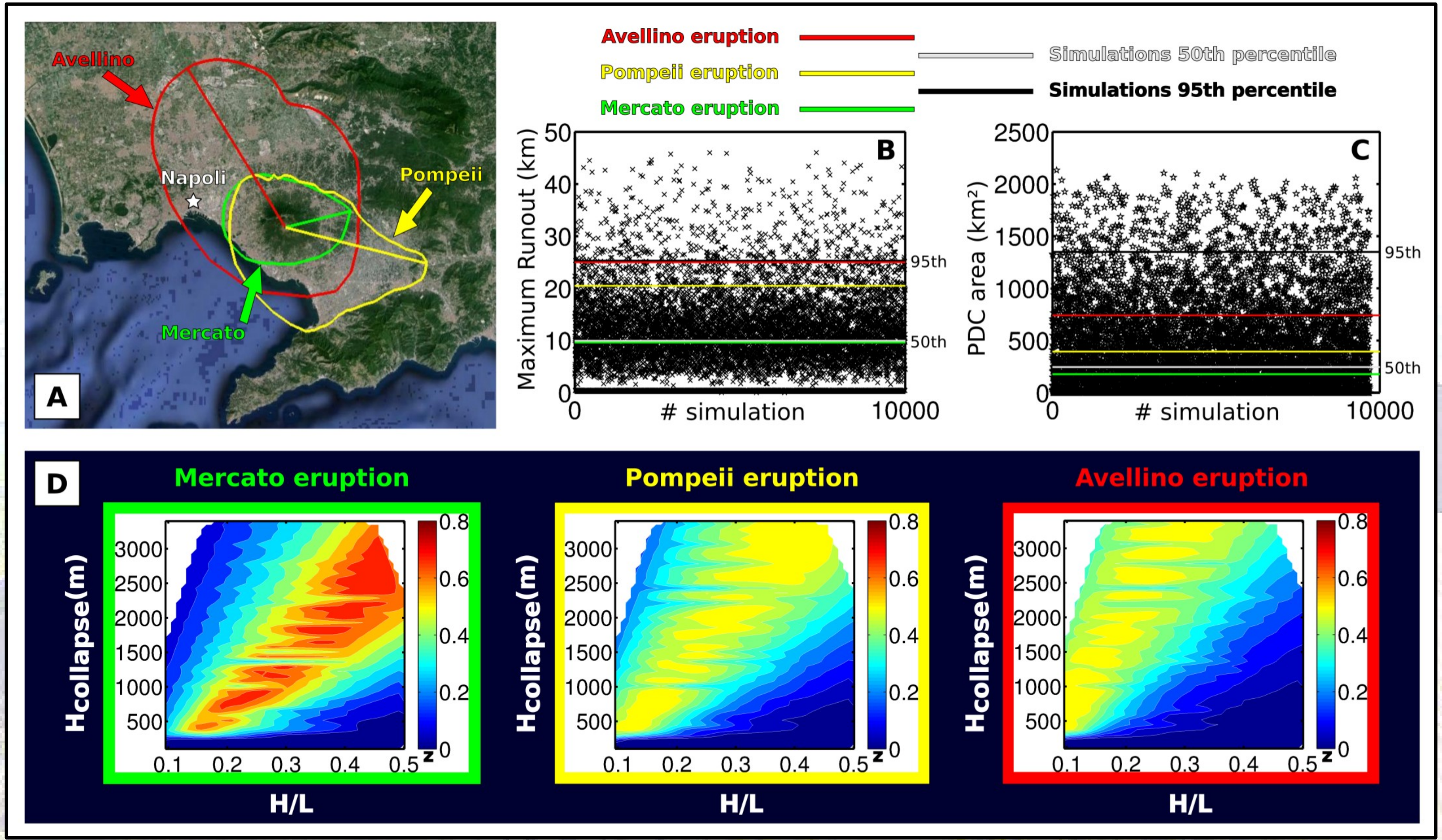
Campi Flegrei is an example of active and densely urbanized caldera with a very high risk associated with the occurrence of pyroclastic density currents (PDCs) produced by explosive events of variable scale and vent location. The mapping of PDC hazard in such a caldera setting is particularly challenging not only due to the complex dynamics of the flow but also due to the large uncertainty on future vent location and the complex topography affecting the flow propagation. Nevertheless, probabilistic mapping of PDC invasion, able to account for the intrinsic uncertainties affecting the system, is needed for hazard assessment. In this study we present a variety of probabilistic PDC hazard maps of the Campi Flegrei area based on different invasion models and accounting for the uncertainty in vent opening and event size. Invasion models were based on simple empirical correlations derived by field reconstruction of past events, simplified one-dimensional models based on a linear decay of the flow energy (e.g. energy line), and correlations derived from 2D and transient numerical simulations of the flow dynamics. Field

Bevilacqua et al. (2013). *IAVCEI Scientific Assembly.* Kagoshima, Japan.

Probabilistic assessment based on single scenarios of past eruptions and exploring different possible vent opening areas at Campi Flegrei (Italy)

The simulators (I): EC. What has been (recently) done.



Tierz et al. (2013).
AGU Fall Meeting.
San Francisco, USA.

Energy Cone validation through parametric uncertainty characterization and comparison to PDC deposits of VEI5 eruptions at Vesuvius (Italy)

The simulators (I): EC. What can be done.

1. Further apply validation procedures in order to define the simulator structural uncertainties (as defined in Rougier et al., 2013).

2. Check the contribution of input uncertainties (mainly related to DEM resolution, in this case) to the overall simulator epistemic uncertainties.

3. Couple Energy Cone with BET_VH (Marzocchi et al., 2010) to obtain a complete, time-window framed, long-term hazard assessment which will inform, explicitly, of all the uncertainties involved.

The simulators (II): Titan2D

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Journal of Volcanology and Geothermal Research 139 (2005) 1–21

Journal of volcanology and geothermal research

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Parallel adaptive numerical simulation of dry avalanches over natural terrain

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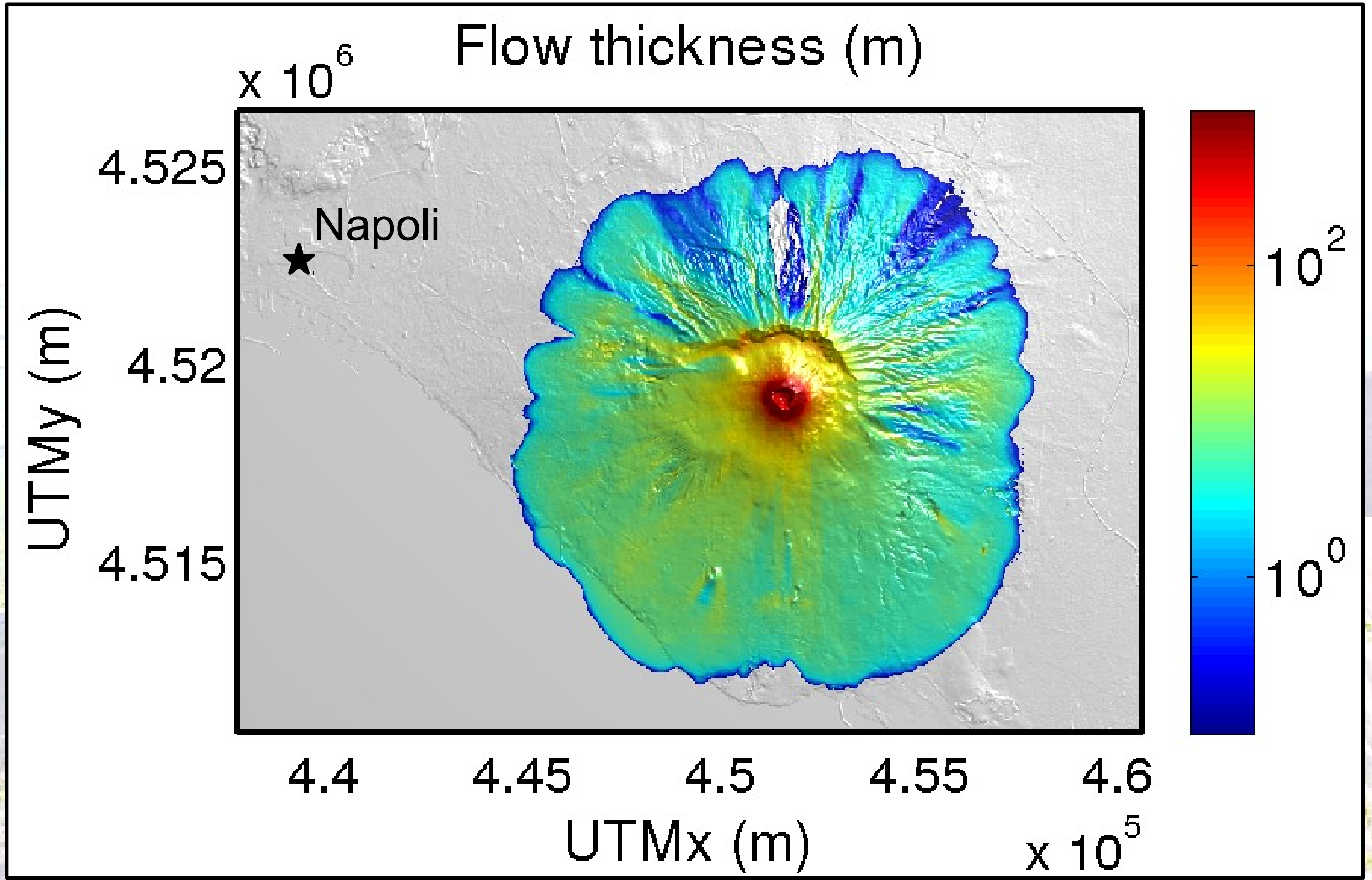
Accepted 29 June 2004

Patra et al. (2005). *J. Volcanol. Geotherm. Res.*, 139, 1-2, 1-21.

The simulators (II): Titan2D



Initial pile(s) of material that collapses under its own weight.

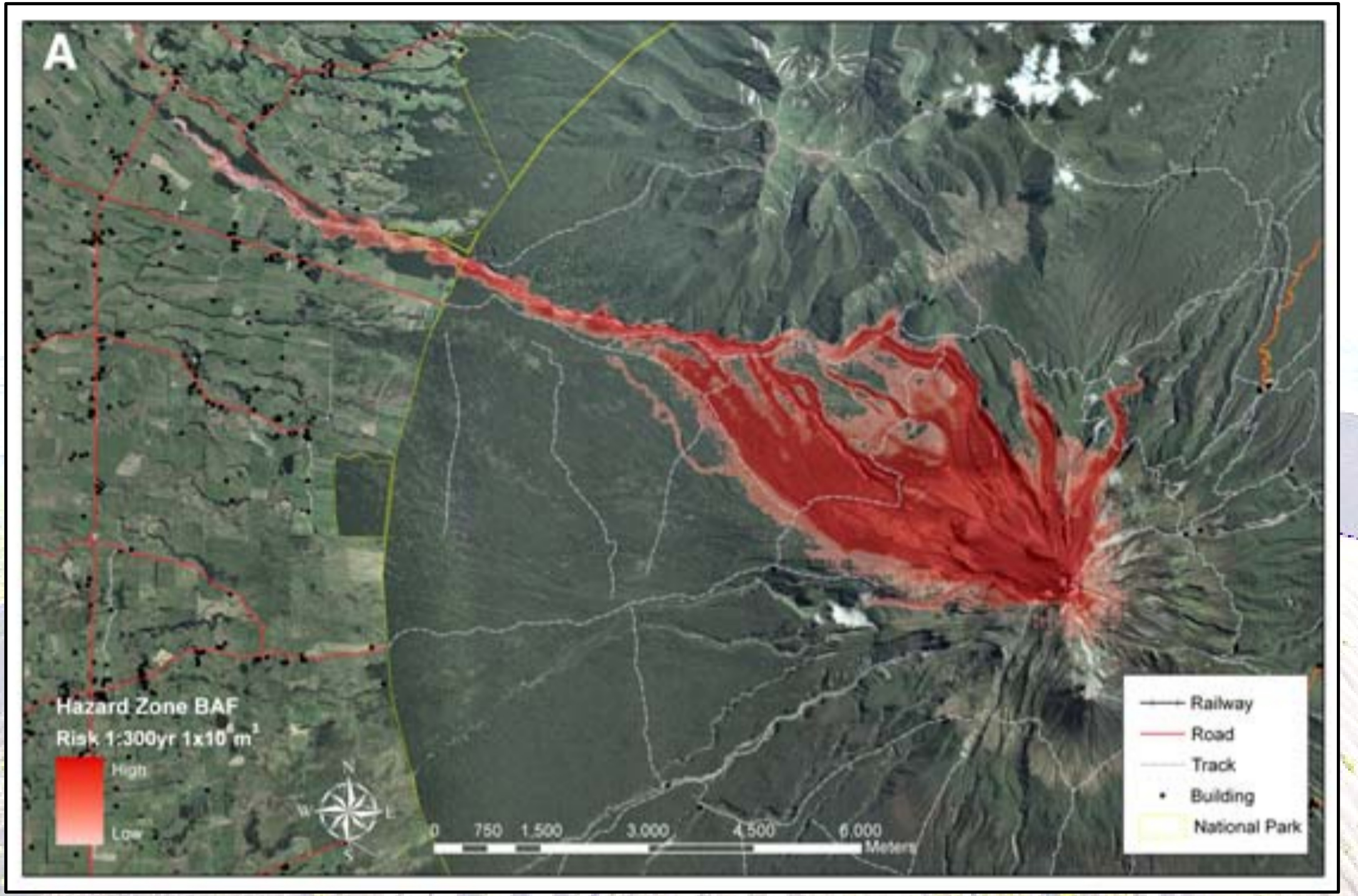
As it gets away from the source, the generated mass flow loses its momentum due to frictional forces, namely: internal and bed friction.

Governing equations are similar to the shallow water equations.

The simulators (II): Titan2D

MAJOR STRENGTHS	MAJOR WEAKNESSES
Detailed physical approach to flows dominated by particle-particle interactions.	Only applicable to dense PDCs (i.e. in the absence of turbulence).
Very versatile simulator, even in volcanic settings: PDCs, lahars, hot avalanches,...	Flow runout depends on the simulation stopping time chosen by the user.
Despite its 2D nature, runtimes are short enough to allow uncertainty estimation.	Neither sedimentation nor erosion processes can be simulated.

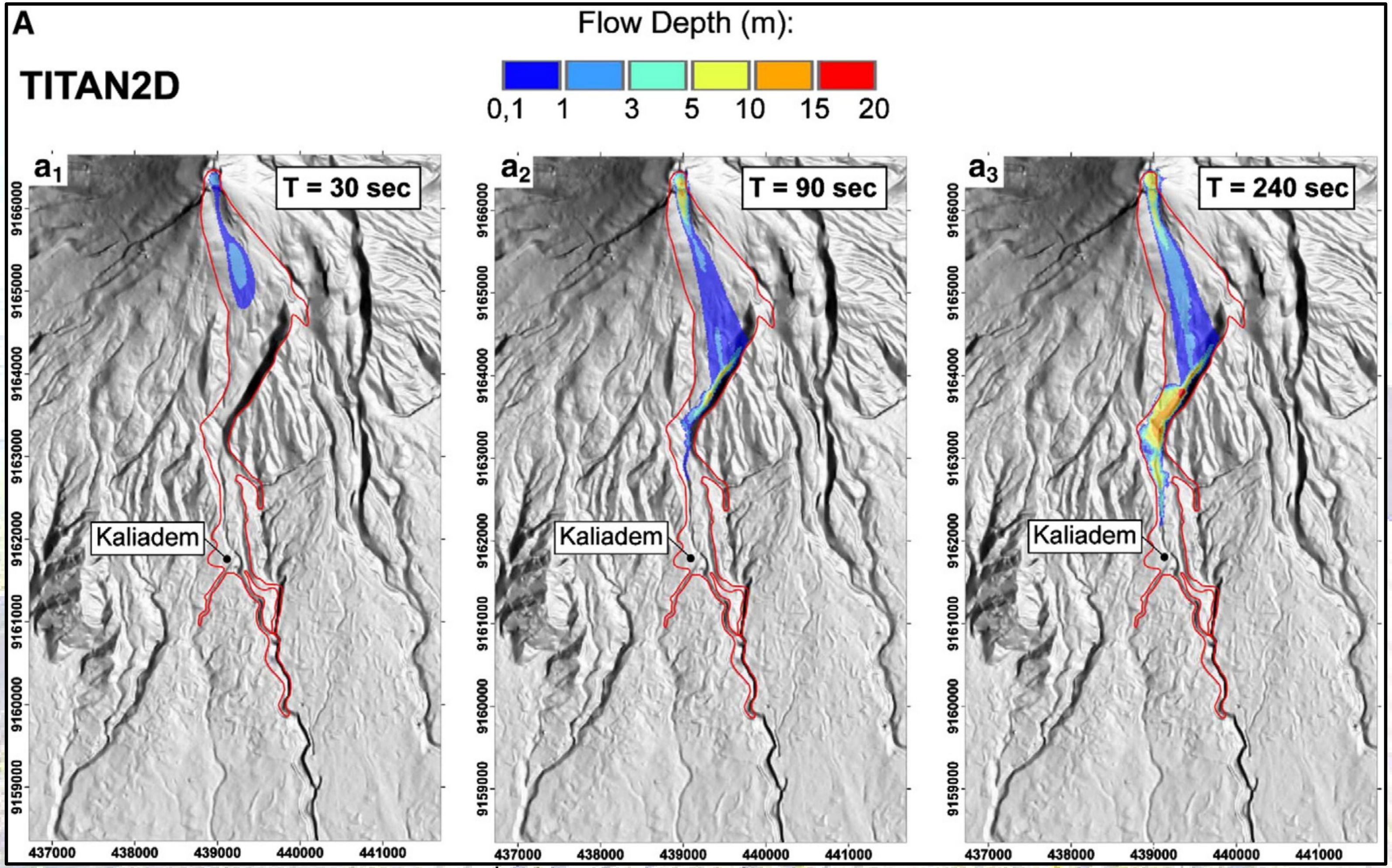
The simulators (II): Titan2D. What has been (recently) done.



Procter et al. (2010). *Natural Hazards*, 53, 483-501.

Risk assessment based on a small set of Titan2D simulations at Mt. Taranaki (New Zealand)

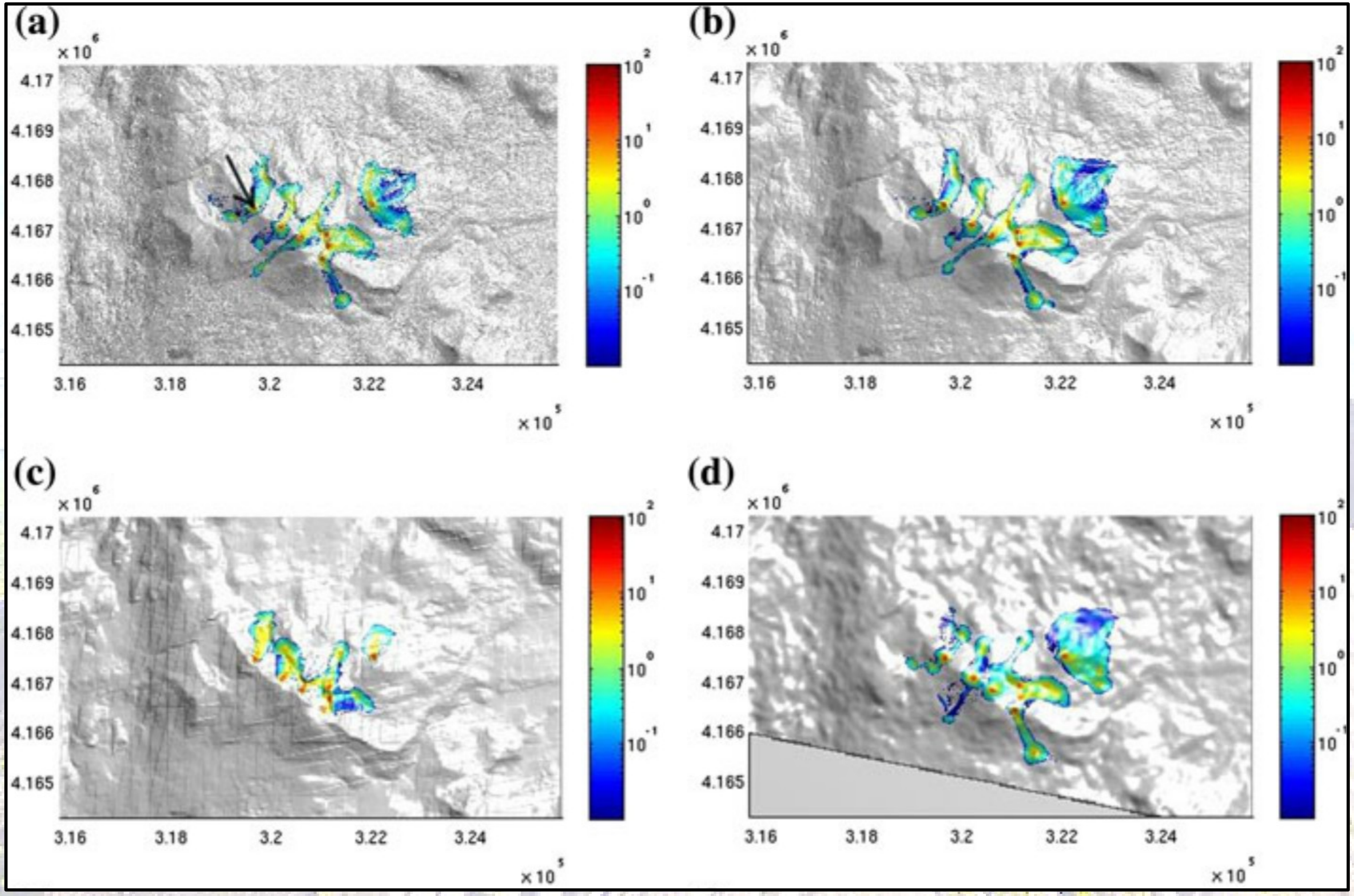
The simulators (II): Titan2D. What has been (recently) done.



Charbonnier, S.J., Gertisser, R. (2012). *J. Volcanol. Geotherm. Res.*, 231-232, 87-108.

Titan2D evaluation using the 2006 block-and-ash flow deposits at Merapi (Indonesia)

The simulators (II): Titan2D. What has been (recently) done.



Stefanescu et al. (2012). *Natural Hazards*, 62, 635-656.

Titan2D input uncertainty estimation through simulator output analysis using different DEM products at Mammoth Mountain (USA)

The simulators (II): Titan2D. What can be done.

1. Further apply validation procedures in order to define the simulator structural uncertainties (as defined in Rougier et al., 2013).

2. Link Titan2D output with a simple, but still physically more reliable than EC (e.g. Box model), PDC simulator to account for the propagation of dilute PDCs.

3. Again, join Titan2D procedures and BET_VH to obtain a complete, time-window framed, long-term hazard assessment which will inform, explicitly, of all the uncertainties involved.

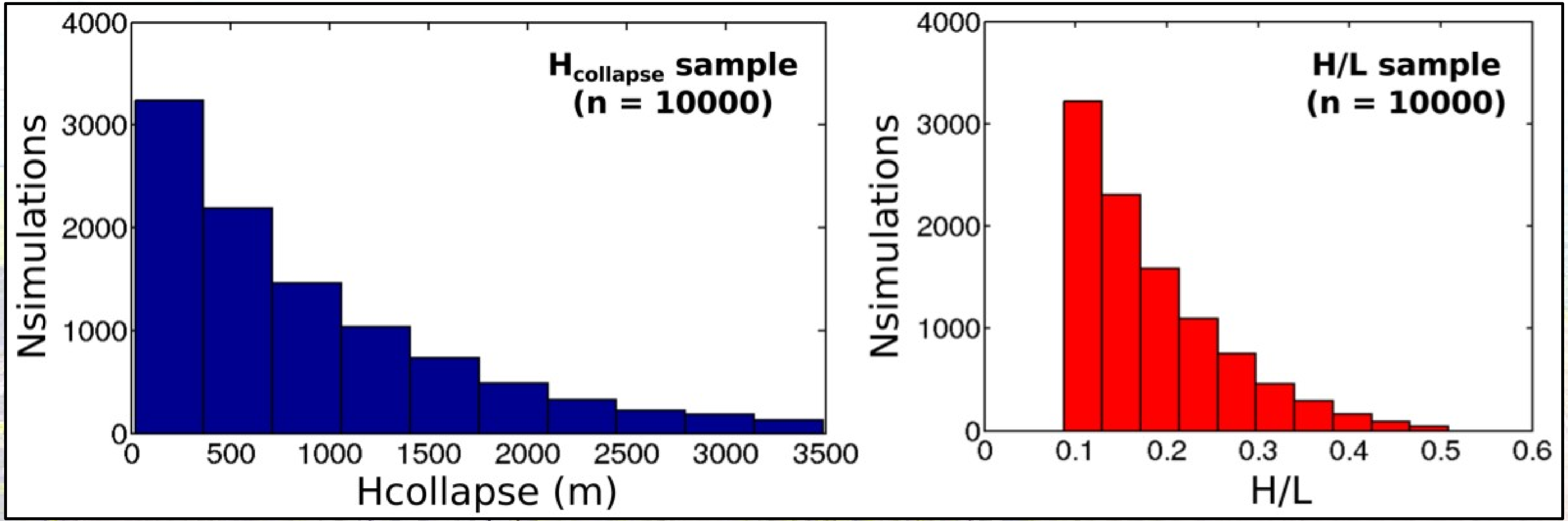
Uncertainty Quantification (I): Monte Carlo sampling (MC)

MAJOR STRENGTHS	MAJOR WEAKNESSES
Very robust method: independent on the course of dimensionality.	Slow convergence: 3-digits precision is obtained with samples n ≈ 10^6.
Widely used technique: every software has a routine to perform it.	Non-adaptative sampling: the results strongly depend on sample size.
Able to capture even high percentile statistics with moderately big samples.	Although feasible to apply to EC, completely intractable for Titan2D.

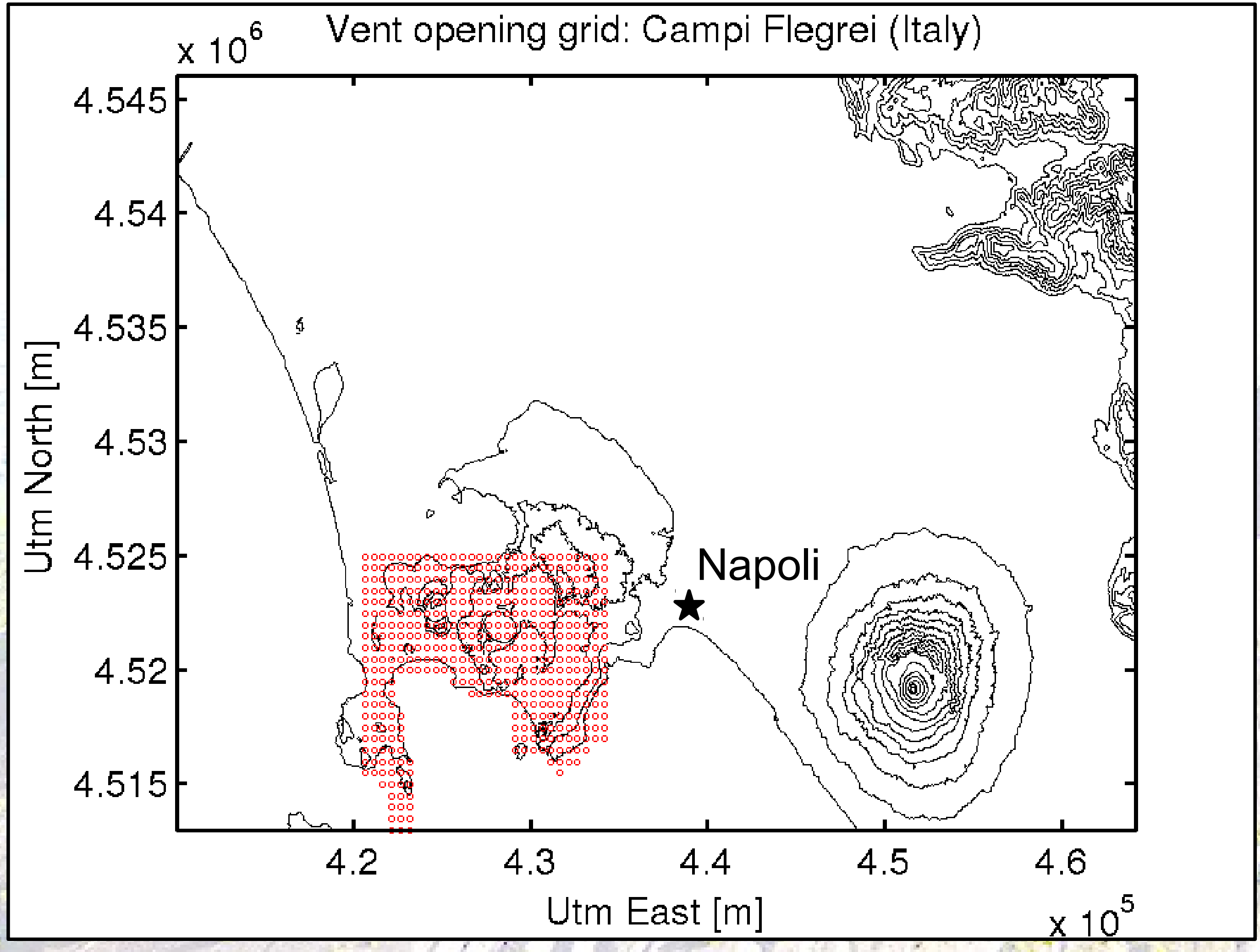
Uncertainty Quantification (I): MC. What has been (recently) done

Tierz et al. (2013).
AGU Fall Meeting.
San Francisco, USA.

MC sampling (n = 10^4) to quantify EC parametric uncertainty (H and H/L parameters) for VEI5 eruptions at Vesuvius (Italy).



Uncertainty Quantification (I): MC. What has been (recently) done



Tierz et al. (in prep.)

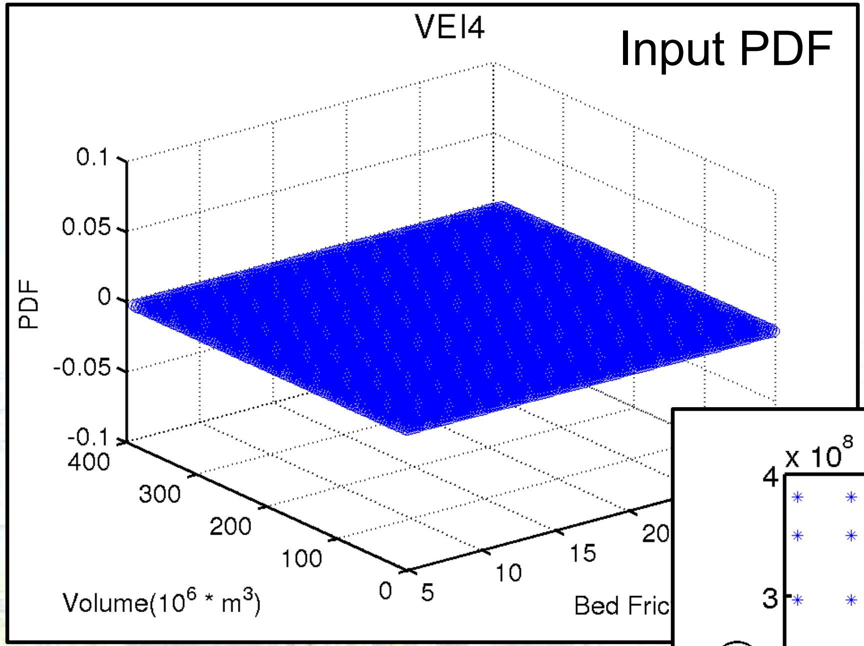
Nearly **1.4 million** of EC runs at Campi Flegrei (Italy) to account for:

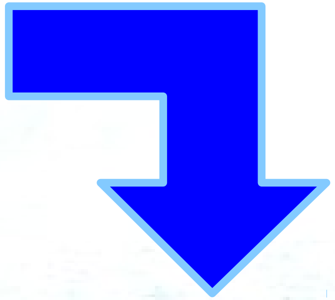
a) parametric uncertainty (Monte Carlo sampling, **N = 10^3**).

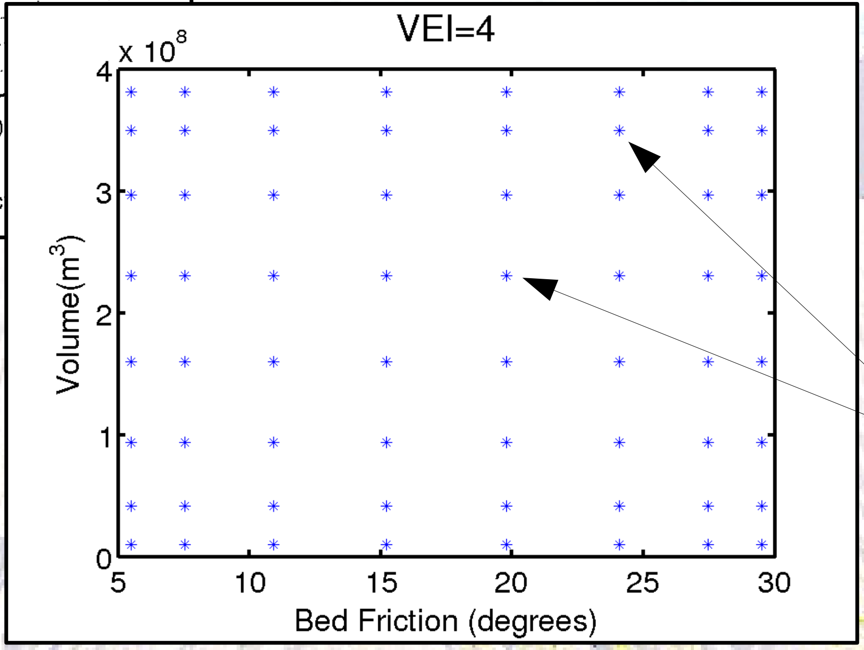
b) possible vent opening areas (after Selva et al., 2012, **N = 460)**.

c) 3 different eruption sizes (after Orsi et al., 2009).

Uncertainty Quantification (II): Polynomial Chaos Quadrature (PCQ)



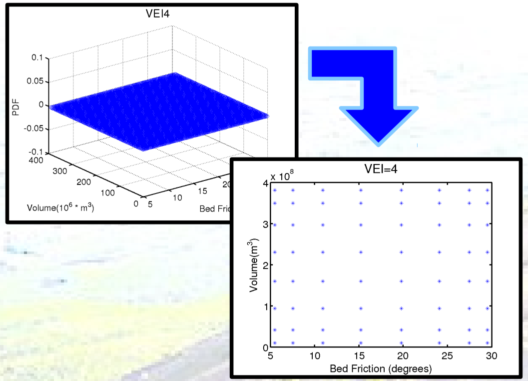




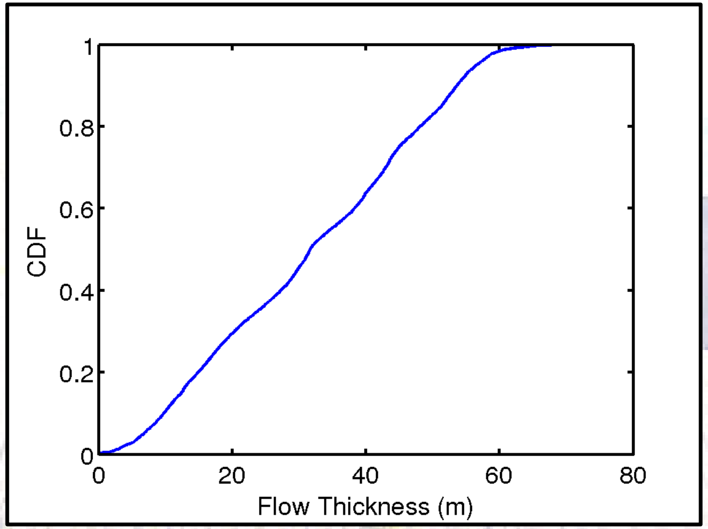
Input Probability Density Functions (PDFs) are approximated as a sum of polynomials.

The numerical integration that serves to compute the output PDFs is solved through a weighted sum of the considered functions evaluated at quadrature points.

Uncertainty Quantification (II): Polynomial Chaos Quadrature (PCQ)



Output PDF



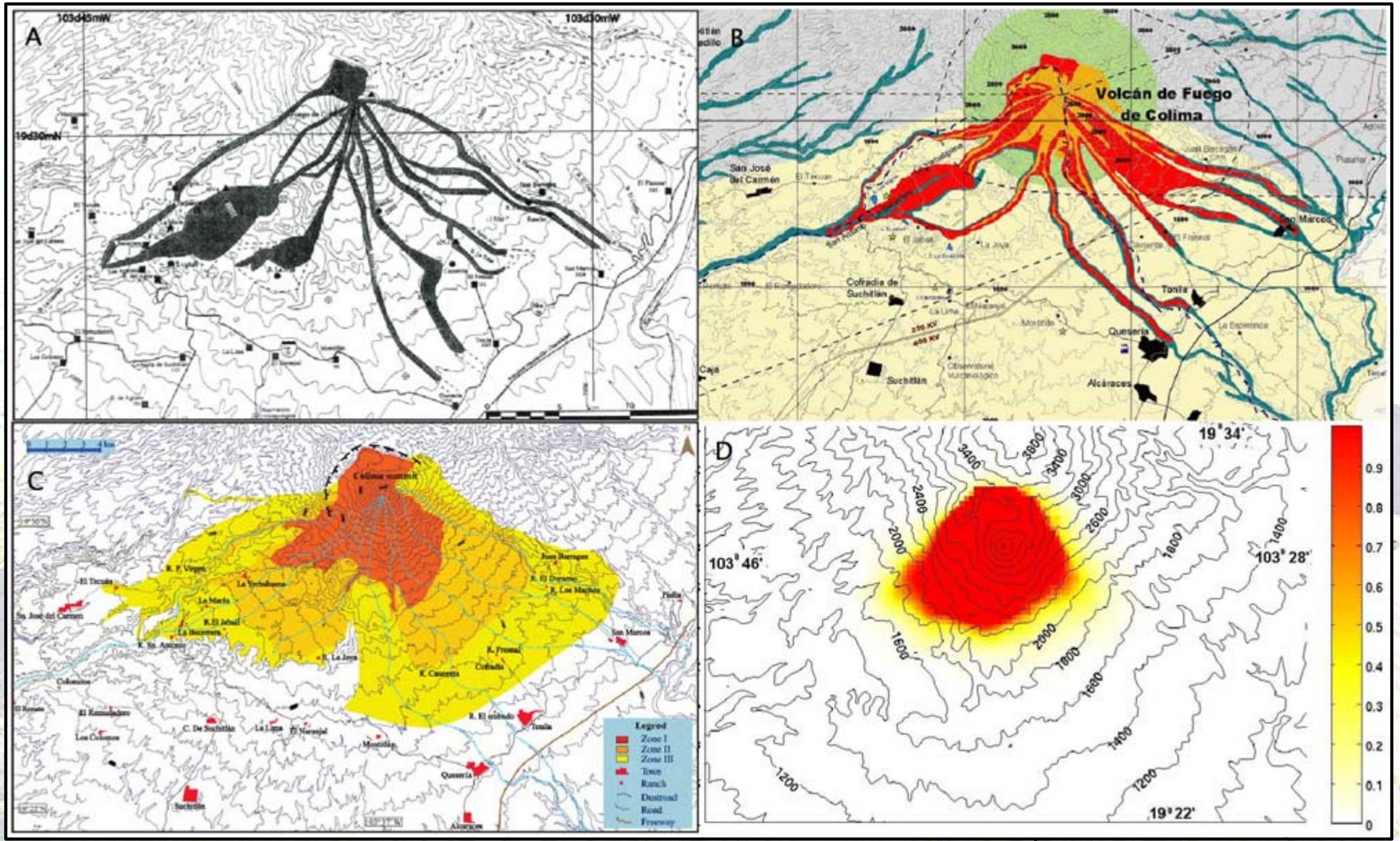
Once having run the simulator at those quadrature points, output distributions are obtained.

MC re-sampling of the output distributions (**N = 10^4-10^5**) is now a workable procedure.

Uncertainty Quantification (II): Polynomial Chaos Quadrature (PCQ)

MAJOR STRENGTHS	MAJOR WEAKNESSES
Allows to track and propagate epistemic uncertainties from input to output faster than MC.	Not free of the course of dimensionality: working with 4 uncertain variables may lead to MC-magnitude computing costs.
Indeed, it is faster enough to permit the computation of Exceedance Probability curves (i.e. Hazard Curves).	As far as a non-infinite number of polymials is computed, right-tailed input PDFs might be hard to reproduce.
Ideally, can be built to perform with any kind PDC simulator.	Previous simulations cannot be used later if input PDFs become better known.

Uncertainty Quantification (II): PCQ. What has been (recently) done

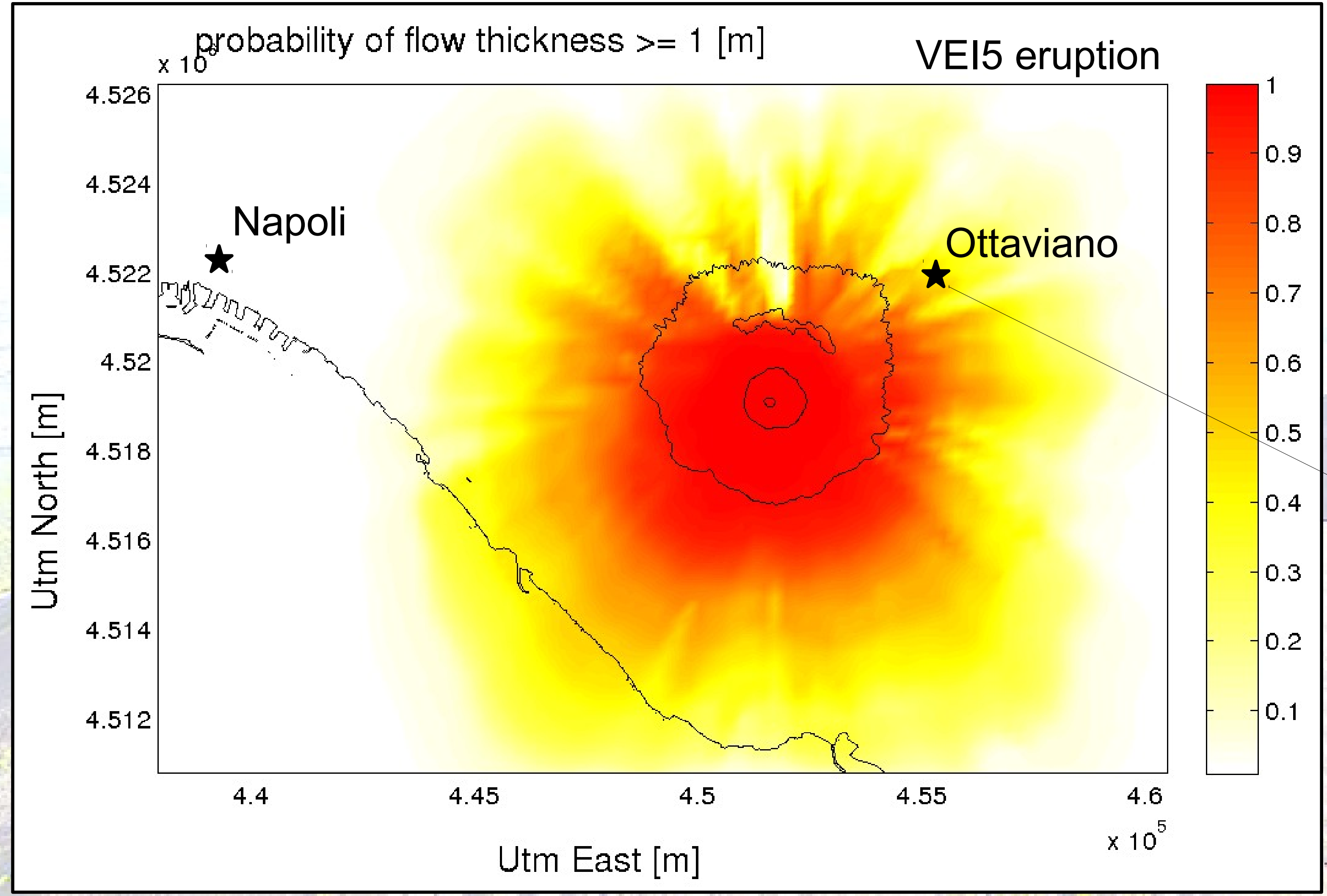


Dalbey et al. (2008). *J. Geophys. Res.*, 113, 1-16.

PCQ definition, discussion on diverse epistemic uncertainty quantification techniques and application of PCQ to Colima (Mexico)

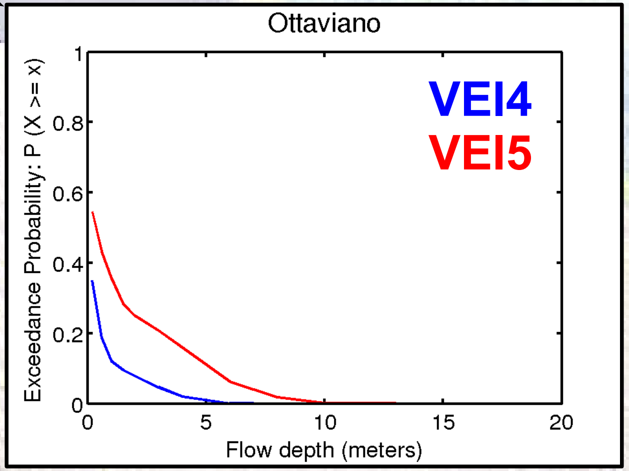
PCQ-based map: Exceendance Probability (flow thickness ≥ 1 m)

Uncertainty Quantification (II): PCQ. What has been (recently) done

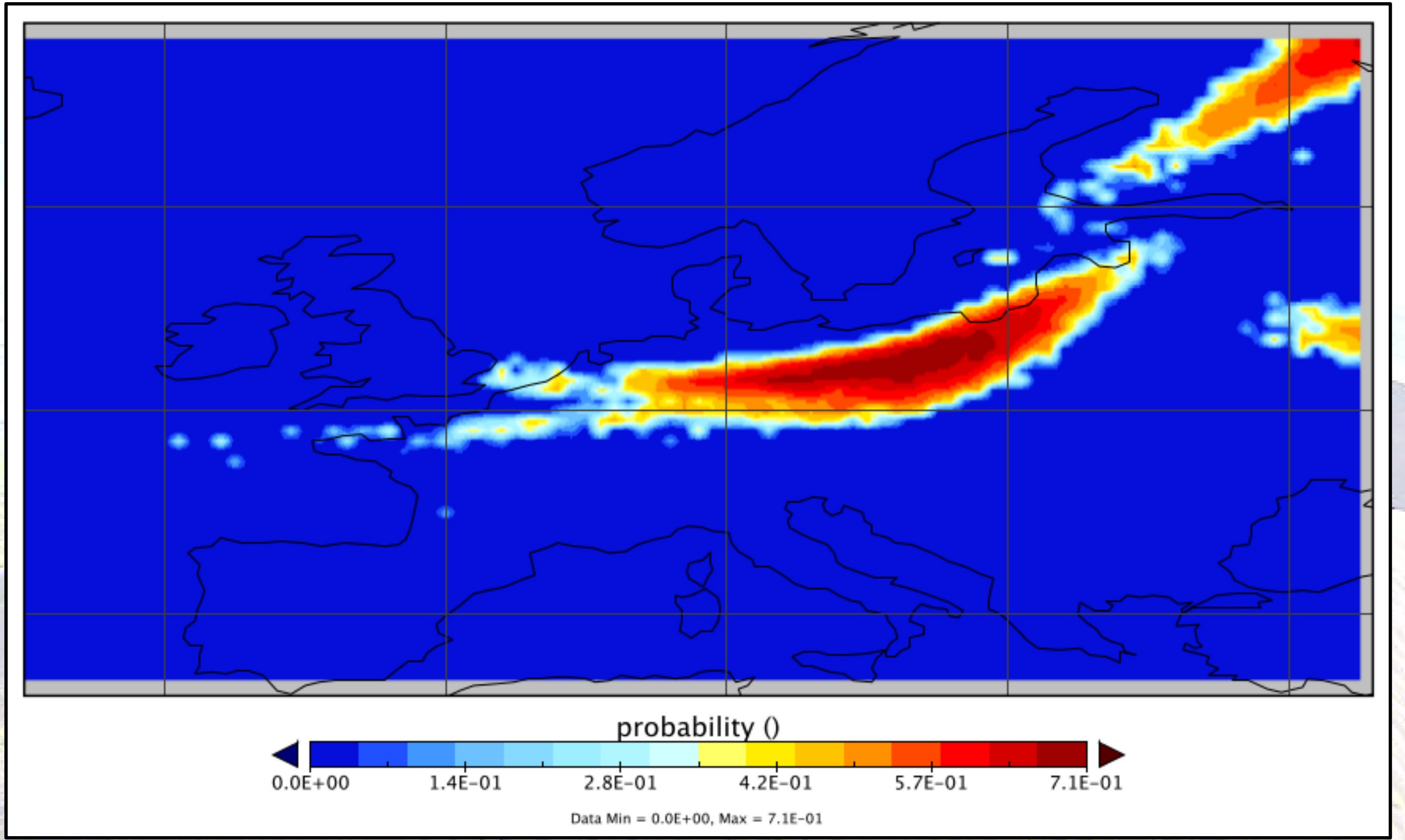


Tierz et al. (2014). NH2.1. B183. EGU2014-12229. Monday 28th April 2014. Blue Posters

PCQ and Hazard Curves conditional to the occurrence of VEI3, VEI4 and VEI5 eruptions at Vesuvius (Italy)



Uncertainty Quantification (II): PCQ. What has been (recently) done



Stefanescu et al. (2013)
Patra et al. (2013)

Probability of having volcanic ash at 2000 m height, computed using PCQ and applied to the April 2010 eruption of Eyjafjallajökull (Iceland)

Uncertainty Quantification (II): PCQ. What can be done

1. Figure out which simulator for dilute PDCs could be linked to PCQ analysis.

2. Test the performance of PCQ through Sensitivity Analysis, checking the influence of the sample size, type of input PDF chosen and so forth.

3. Include the Hazard Curves conditional to the occurrence of an eruption of a specific size into BET_VH to obtain a complete, time-window framed, long-term hazard assessment which will inform, explicitly, of all the uncertainties involved.

Uncertainty Quantification (III): Bayesian Linear Emulation (BLE)

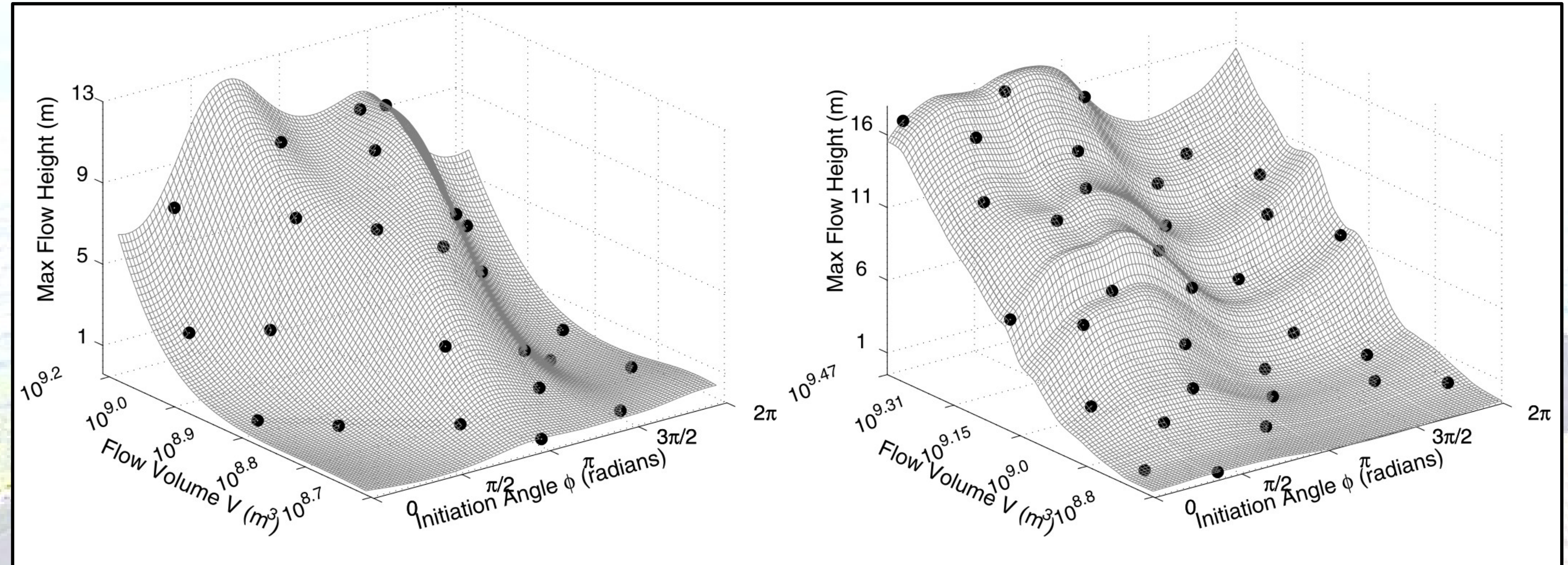


Figure 3. Left: Plymouth; right: Bramble Airport. Max-height surfaces are the mean of the GaSP emulators. Dark points represent the max-height simulation output at design points.

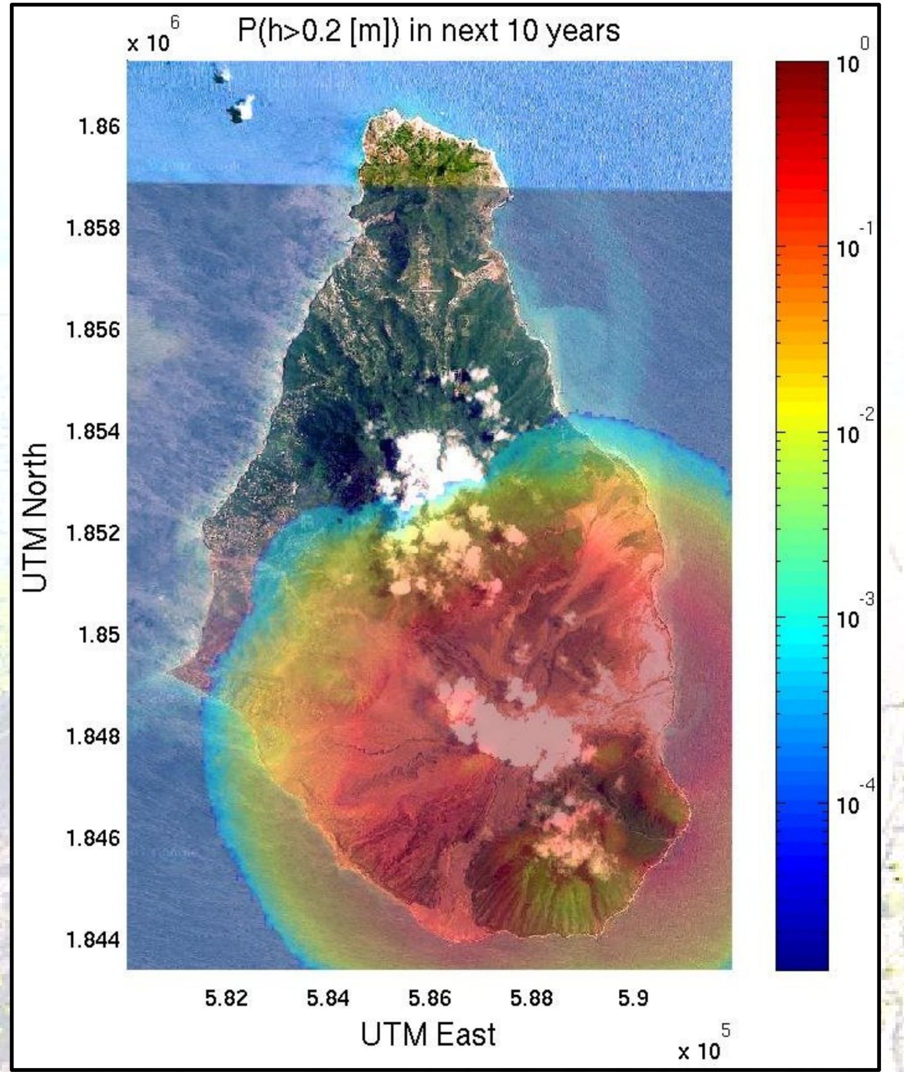
Bayarri et al. (2009). *Technometrics*, 51, 4, 402-413.

Simulator (Titan2D) behavior (dots) emulated as mean response (surface) plus a Gaussian error model.

Uncertainty Quantification (III): Bayesian Linear Emulation (BLE)

MAJOR STRENGTHS	MAJOR WEAKNESSES
Can supply both a mean response and an uncertainty estimation of this response.	Not perfectly implemented: the code still needs a definitive, complete version.
As a Bayesian tool, it is able to combine (with different weights) data coming from diverse sources (simulators, field data,...)	Does not produce, by itself, a time-window framed hazard assessment: that has to be considered in the input PDFs.
Conceptually, it may be able to bridge the gap between complex simulators and probabilistic assessments.	Being an emulator, its final evaluations strongly depend on the set of simulations run (↔ sampling size and strategy).

Uncertainty Quantification (III): BLE. What has been (recently) done



Dalbey, K. (2009). *PhD Thesis,*
Dept. of Mechanical and Aerospace Engineering,
University at Buffalo.

BLE compared to many other uncertainty quantification techniques and applied to obtain a probabilistic hazard map at the Soufrière Hills (Monserrat)

Uncertainty Quantification (III): BLE. What has been (recently) done

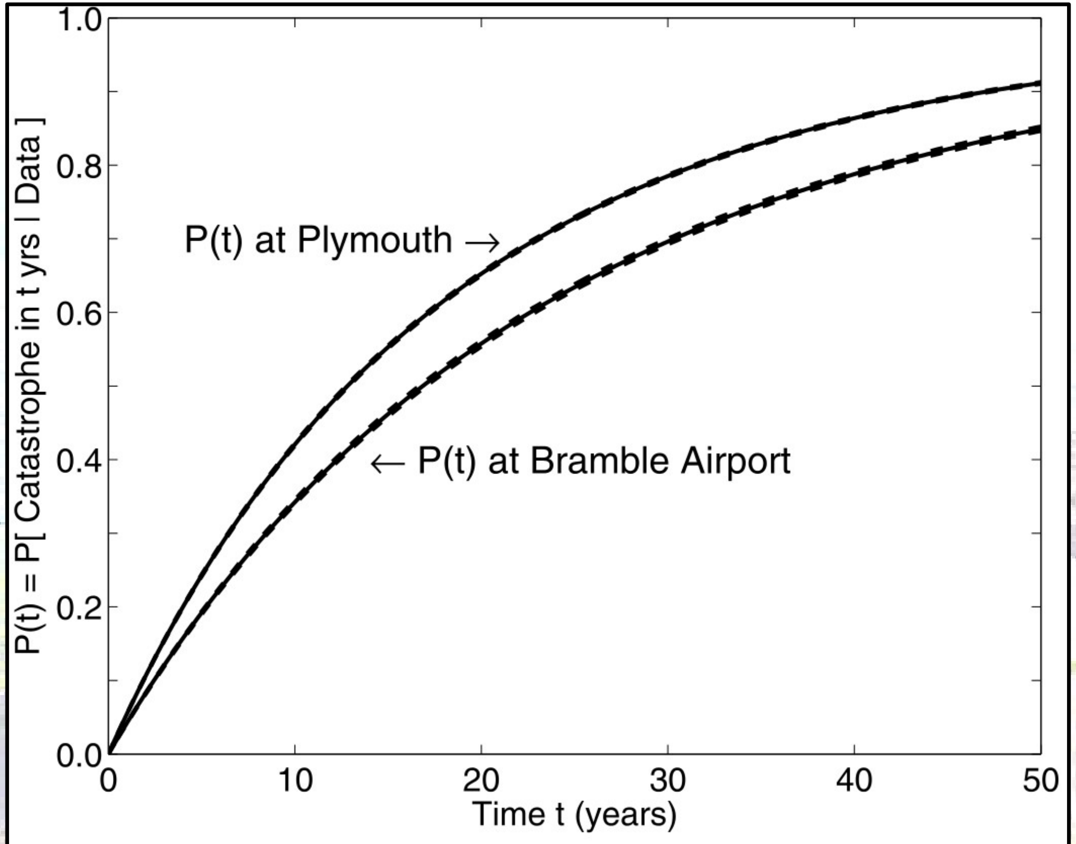
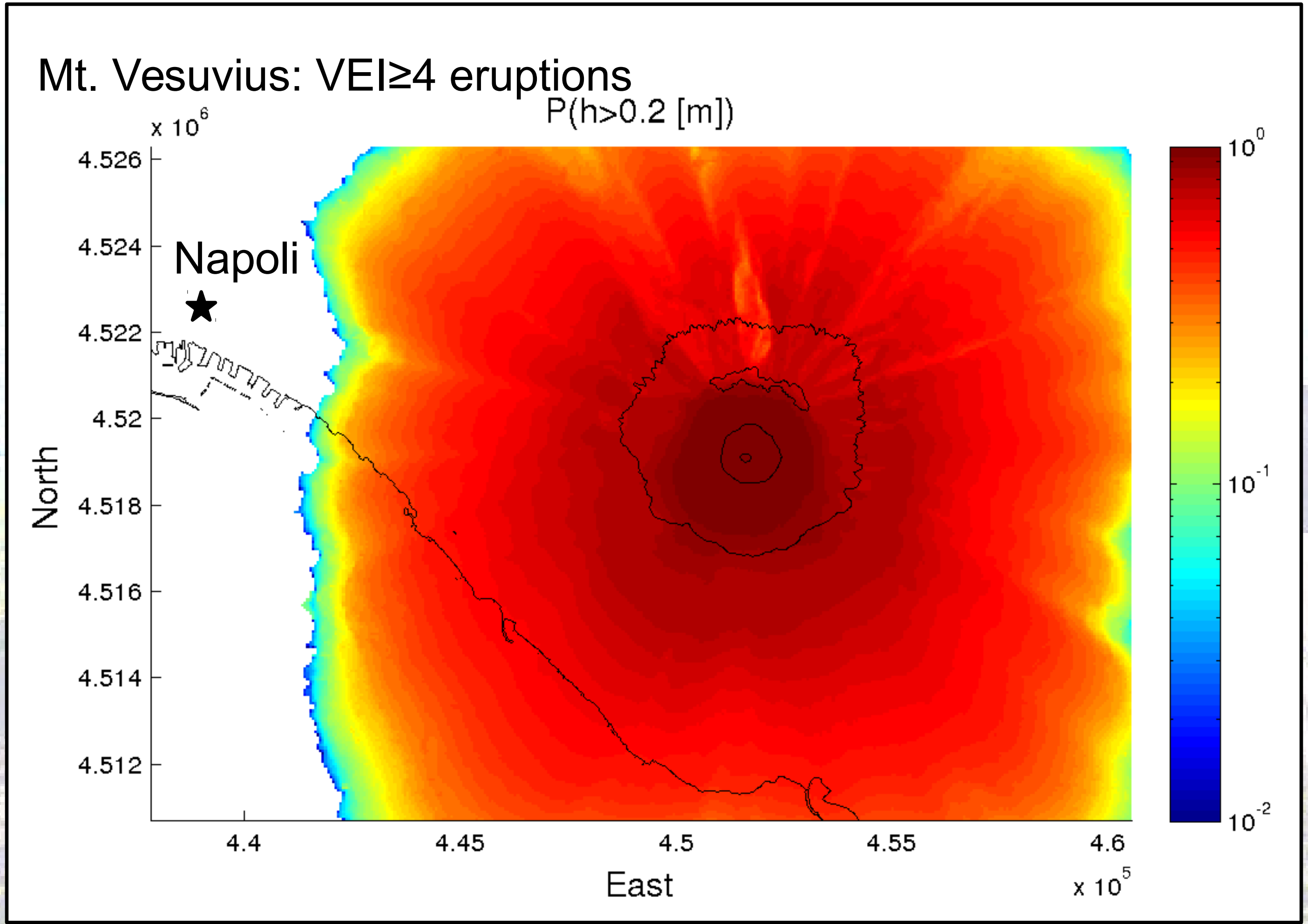


Figure 8. Posterior probability of catastrophe $P(t)$ at Plymouth (upper curves) and Bramble Airport (lower curves) within t years, for $0 \leq t \leq 50$. Solid lines indicate posterior medians, dashed curves indicate pointwise 90% credible bands.

Bayarri et al. (2009). *Technometrics,* 51, 4, 402-413.

BLE utilized to obtain the probability of catastrophe (over a selected time-window) at strategical points inside the Monserrat Island.

Uncertainty Quantification (III): BLE. What has been (recently) done



Tierz et al. (in prep.)

Preliminar results on the application of BLE to compute probabilistic maps for dense, column-collapse formed PDCs at Vesuvius (Italy)

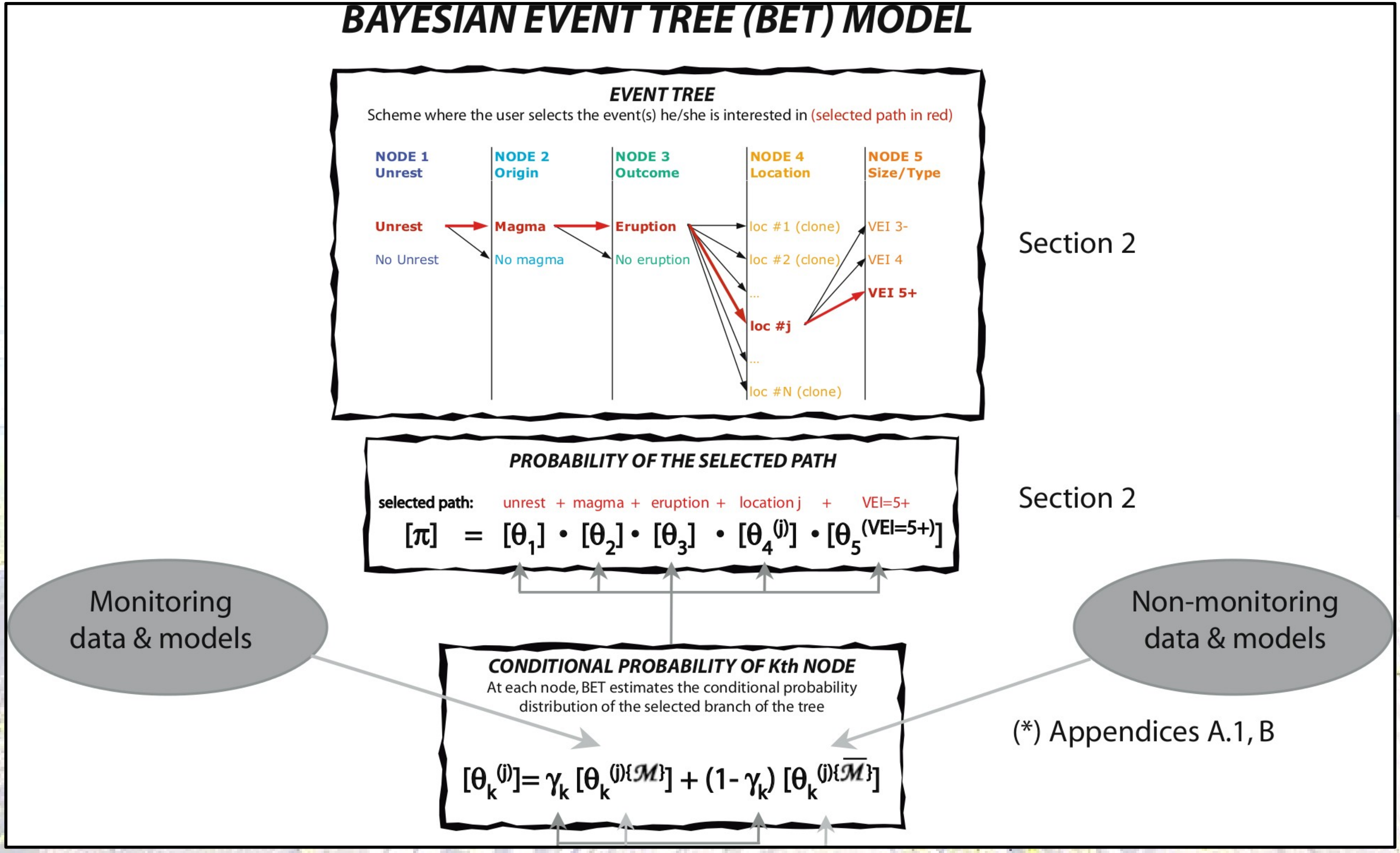
Uncertainty Quantification (III): BLE. What can be done

1. Build up a robust, free-software code of BLE that can be joined to different PDC simulators.

2. Test the performance of BLE through Sensitivity Analysis or comparing it with other uncertainty quantification techniques for Titan2D, such as PCQ, at specific volcanic systems (e.g. Vesuvius).

3. Couple BLE with BET_VH to obtain the complete picture of long-term probabilistic PDC hazard assessment for a specific volcanic system.

Uncertainty Quantification (IV): Bayesian Event Tree (BET)



Marzocchi et al. (2008). *Bull. Volcanol.*,70, 623-632.

First presented as an eruption forecasting tool.

Probabilities are attached to each Event inside a Node according to Bayesian inference (prior beliefs combined with data)

Uncertainty Quantification (IV): Bayesian Event Tree (BET)

MAJOR STRENGTHS	MAJOR WEAKNESSES
Probabilities are given in form of PDFs: all the uncertainties involved (aleatory and epistemic) are explicitly shown.	Some parameters which describe the epistemic uncertainties might be defined in a more structured manner.
As a Bayesian tool, it is able to combine (with different weights) data coming from diverse sources (simulators, field data,...)	Currently, it is not able to deal with outcomes different from magmatic eruption (e.g. phreatic eruptions).
Works directly with diverse time-windows, thresholds, exceedance probabilities: wide range of map plotting options.	Its output might include a brief description of which physical parameters influence (and how) on the results.

Uncertainty Quantification (IV): BET. What has been (recently) done

Sandri et al. (2012). *Bull. Volcanol.*, 74, 705-723.

Long-term (left; fig.5), short-term (right; fig.6) probabilistic surge hazard assessments, and link between them and cost-benefit analysis to aid in decision-making purposes (right; purple lines) at the Auckland Volcanic Field (New Zealand)

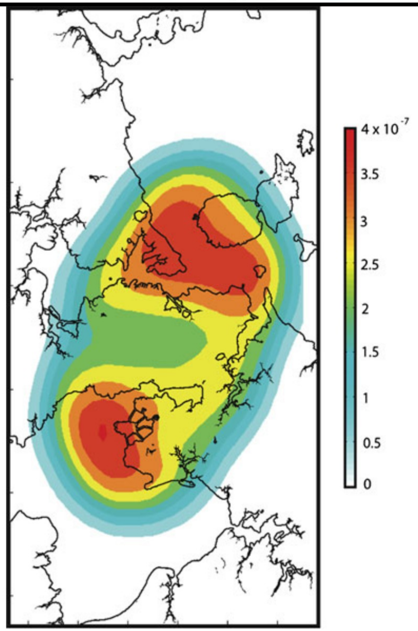
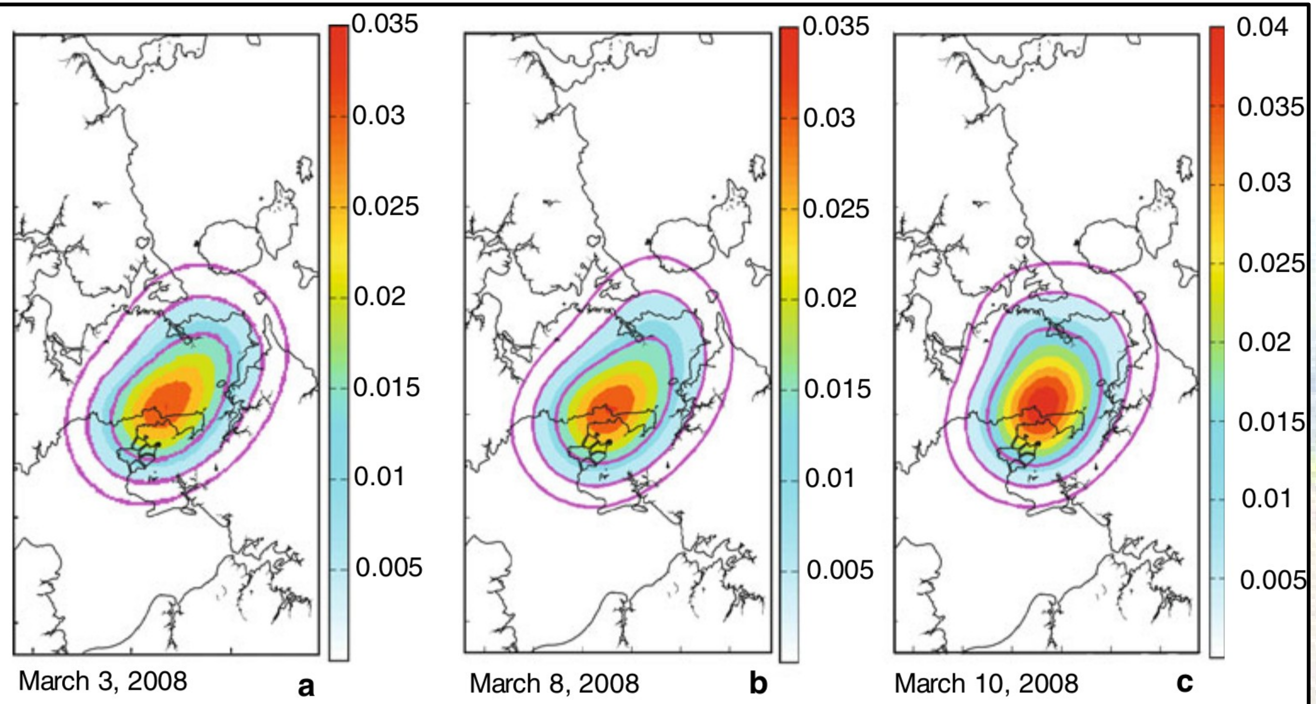


Fig. 5 Long-term yearly probability of base surge impact as estimated from BET_VH application. The domain corresponds to that of Fig. 1

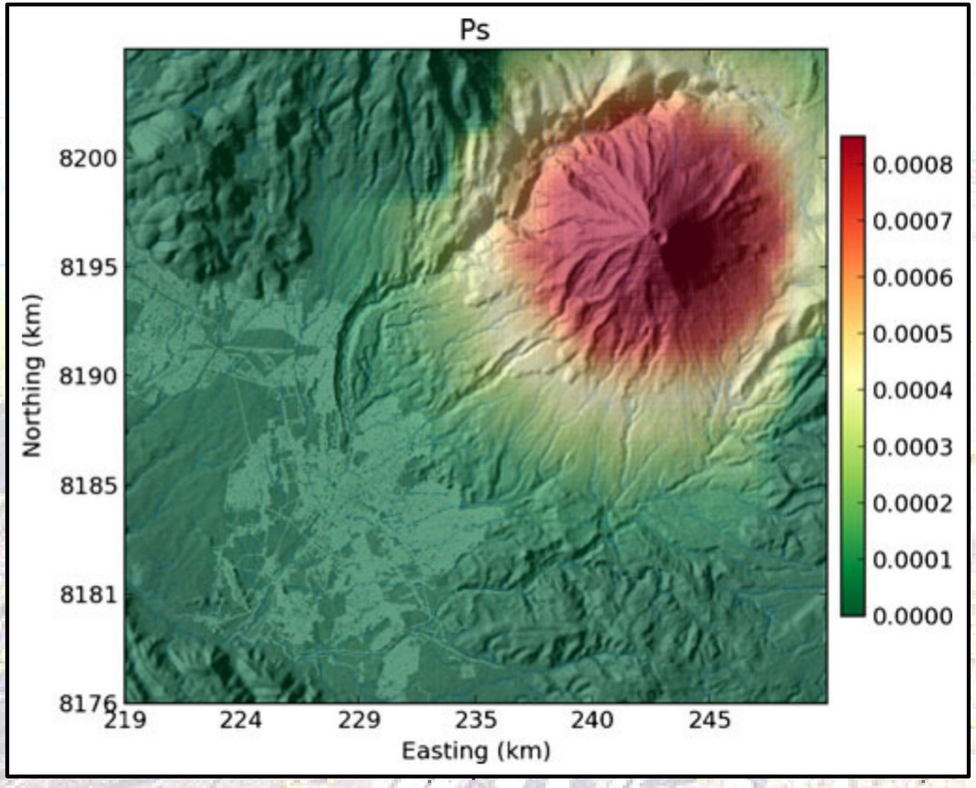
Fig. 6 Short-term average probability of base surge impact in the month after the date indicated in each panel, according to the information provided by simulated monitoring during Exercise Ruaumoko. Again, the domain corresponds to that of Fig. 1. The *magenta* contours encompass the areas that match the criterion for calling an evacuation based on cost-benefit analysis for different evacuation times, i.e. the areas where the probability of base surge invasion overcomes the threshold of 0.014 (innermost contour, for a 6-month

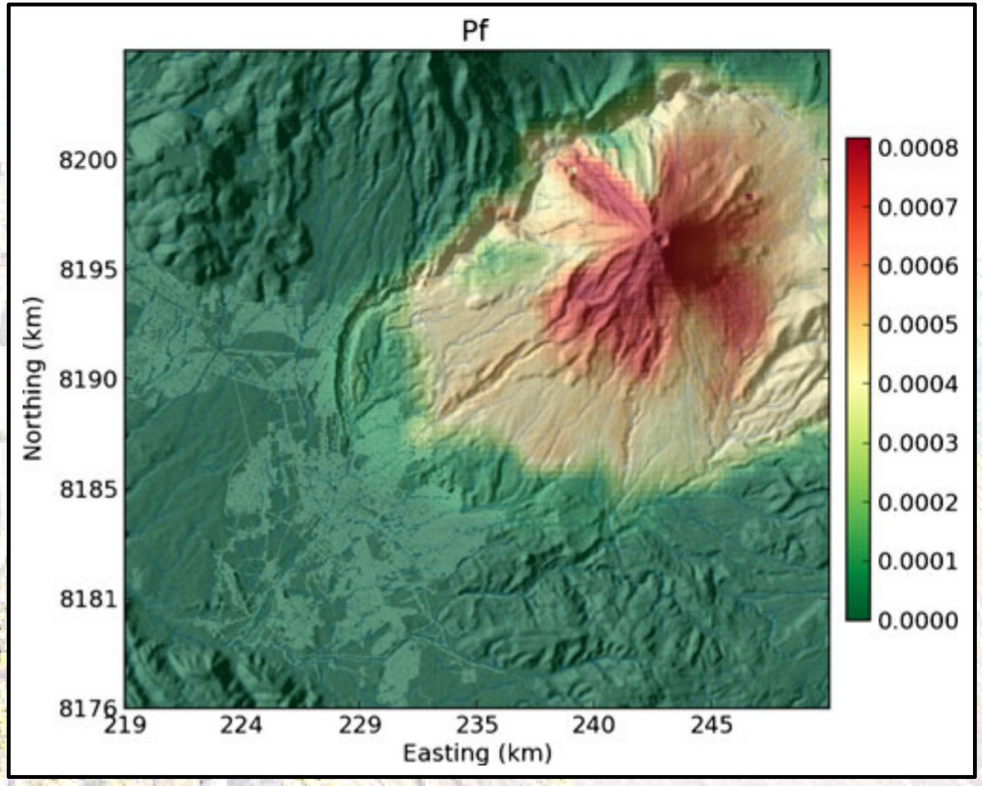


Uncertainty Quantification (IV): BET. What has been (recently) done

Sandri et al. (2014). *Bull. Volcanol.*, 76, 771-797.

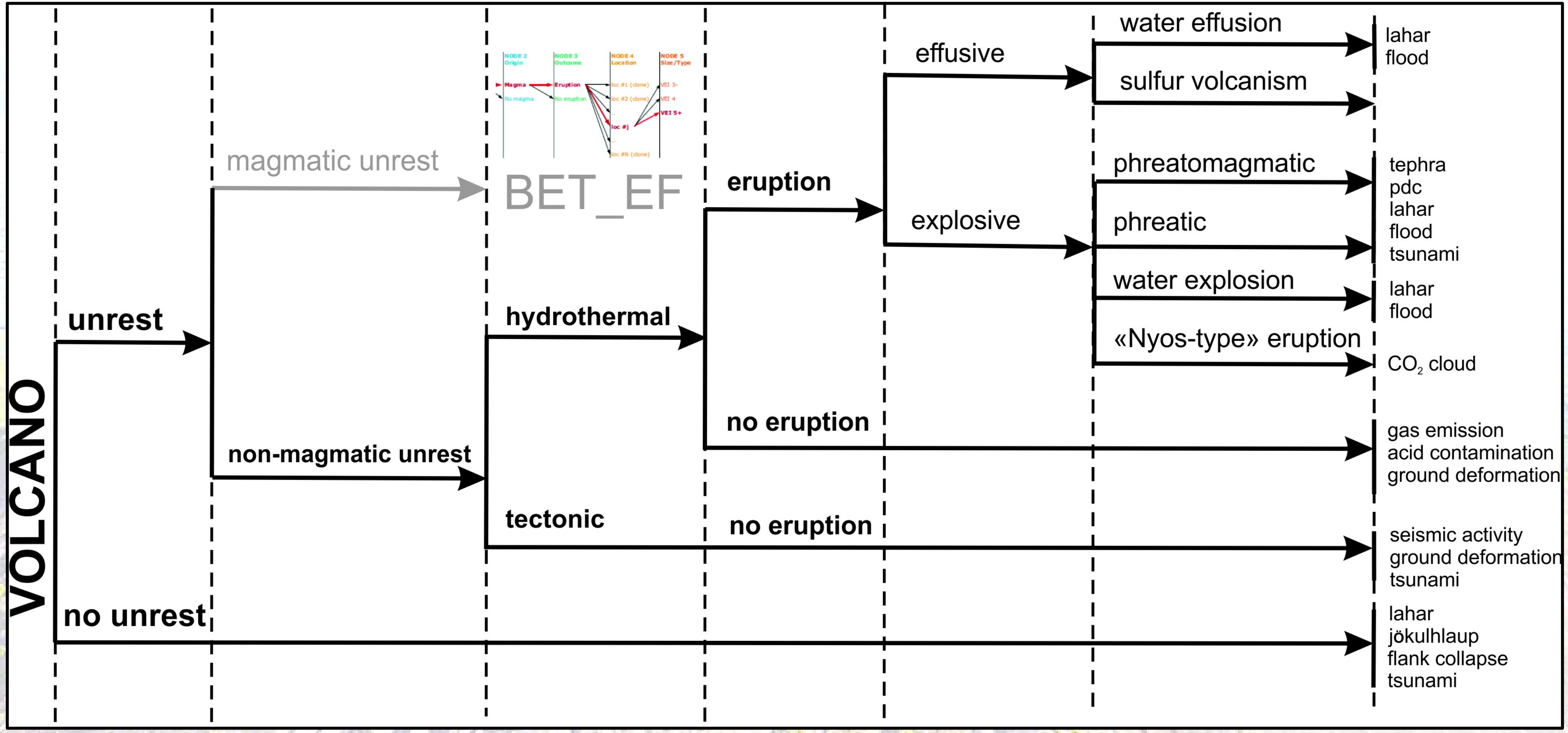
Long-term probabilistic hazard assessment at El Misti volcano (Peru): yearly mean probability of a given area to be impacted by pyroclastic surges (Ps; left) or pyroclastic flows (Pf; right)





Uncertainty Quantification (IV): BET. What has been (recently) done

Rouwet et al. (in prep.) BET expanded into non-magmatic branches of volcanic unrest.



Uncertainty Quantification (IV): BET. What can be done

1. Widen BET structure to take into account non-magmatic outcomes of diverse nature: phreatic explosions, flank collapses, gas hazard, etc.

2. Try to include more systematic descriptions of the epistemic uncertainties in the overall BET probabilistic hazard assessments.

3. Supply a more detailed written explanation of how the output probabilities were computed by the model, in order to help the users interpret the obtained results.

CONCLUSIONS

A. Even though probabilistic hazard assessment of PDCs is challenging, several kinds of approaches (applied to volcanic systems throughout the world) have been done so far to try describing, as best as possible, the role of uncertainties in this field of study.

B. Nevertheless, diverse multi-disciplinary efforts can be carried out to improve the qualitity of these assessments, following varied directions and mainly pursuing:
1) Reduce the uncertainties; 2) Define them in a more explicit way.

C. It is important to keep in mind the decision-maker needs and to reinforce the communication between hazard scientists and decision-making agencies.

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THANKS FOR COMING!!!

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