A DDDAS Framework for Volcanic Ash Propagation and Hazard Analysis

UB - UAF Working Group on Volcanic Ash and Aviation
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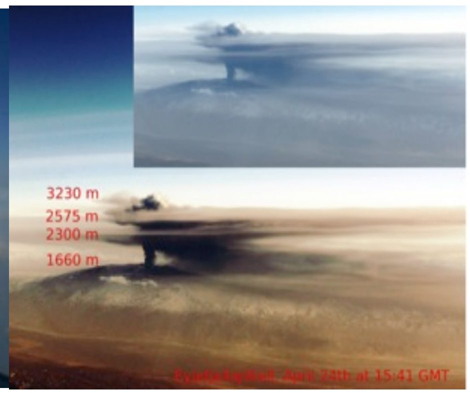
Volcanic Hazard

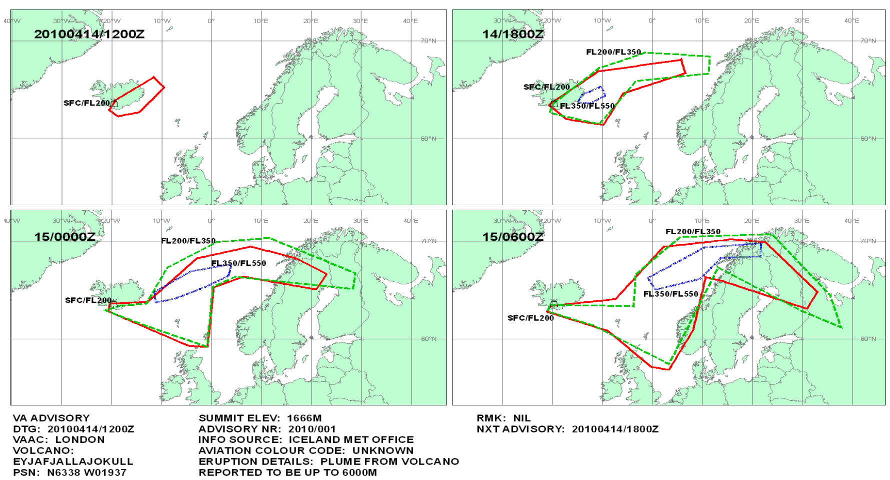
- Ash transport into atmosphere – wind borne fine particulates travel O(1000) km in atmosphere

Photo: M. Roberts,Icelandic Meteorological Office (IMO).

- Dense fast moving (*O(10) m/s*) ground-hugging flows comprised of heterogeneous particulates and water – travel O(10) km

The Ash Problem





Problem: Currently used forecasts of ash transport in eruption of Eyjafjallajokull, Iceland caused total shutdown of large swathes of airspace, the cancellation of more than 100,000 flights and total disruption!

Significant discrepancy between no-fly zones, ash observation, and multiple model forecasts!

Solution: *Provide* ***probabilistic map*** *that can be updated dynamically with observations using a data driven (DDDAS) approach*

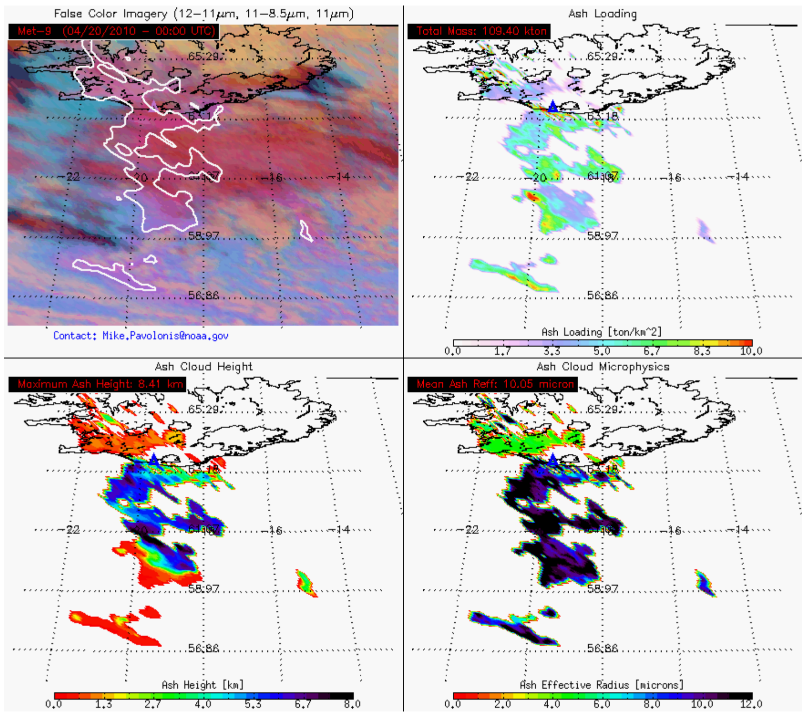
Challenges: Uncertainty Analysis (Source/Wind); High fidelity models of complex physics capable of needed near real time execution; Data and Workflow Management; Sensor error; measurement mismatch; imagery analysis

Problems

- Physics models are hard (non-linear hyperbolic systems) and simulators are expensive.
  - Model/Numerical Error in Solutions can be large
- Model parameters and forcing terms are **uncertain**
- Quantity of interest (QOI) –is high dimension

  and **time dependent**
- Simulations take O(1hr) – ensembles for UQ are small! Need smart ensembles.

New Methods to Mitigate the Risk to Aviation



Ash retrieval 20 April 2010

- Loading, height, grain size

What if it was possible to:

- run stochastic models in real-time to generate a *practical assessment of ash risk over large jurisdictions*?
- Give *estimates* of cloud position, height, mass loading and grain size?

Challenges

- Computability
- Adaptability – DDDAS methods
- **Uncertainty!**

Basic Approach

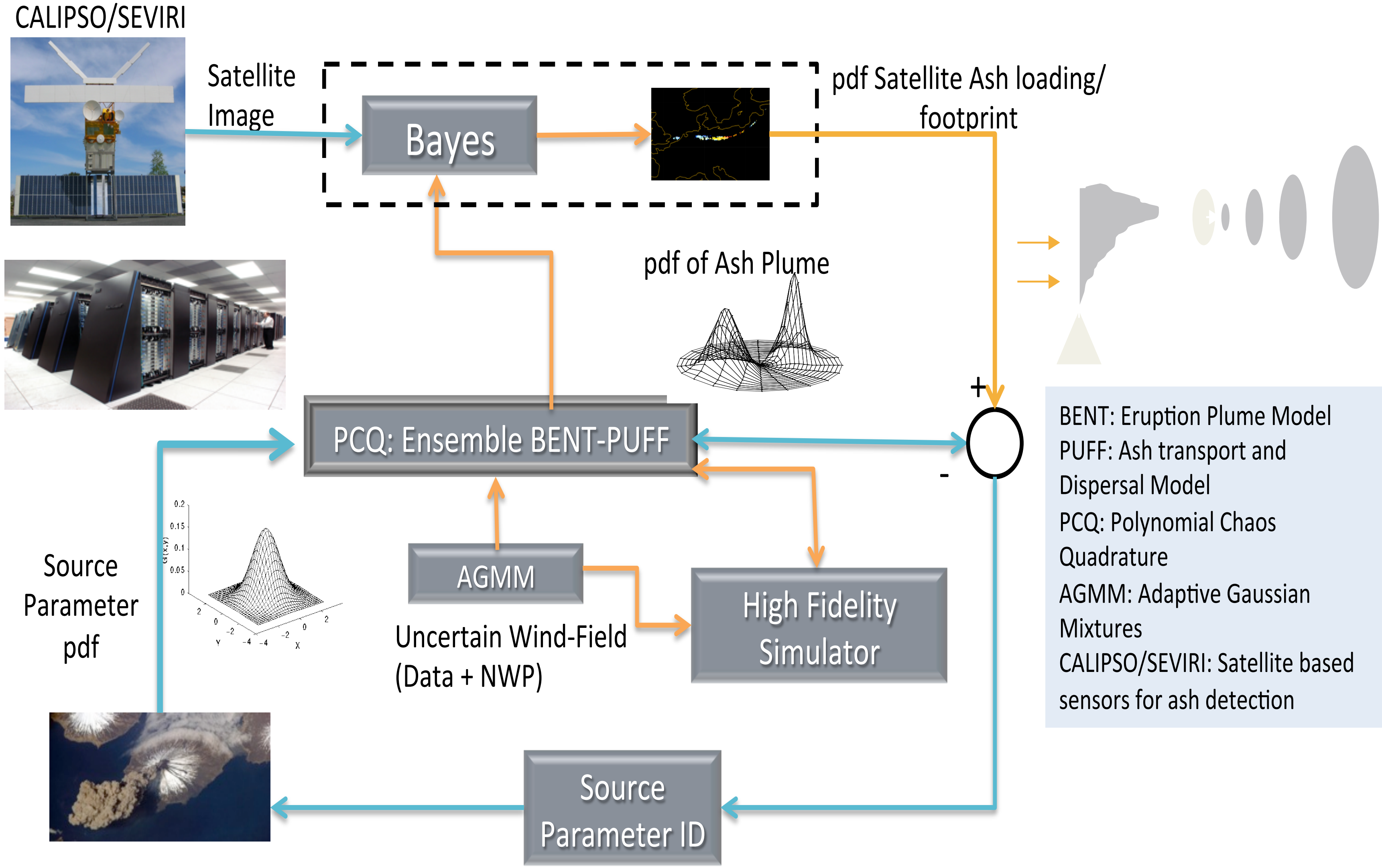
- *Physics based Coupled Models + Data e.g. BENT+ PUFF + Observations*

→ *reduced (surrogate) model (polynomial chaos)*

→ *updated reduced models*

→ *Probabilistic hazard analysis*

DDDAS Approach To Volcanic Ash Transport And Dispersal Forecast



Approaches

- Simulators using "best-in-practice" numerical methods and modeling
  - Many models – PUFF, NAME, HYSPLIT, Ash …
  - Traditional VATD models use difficult to characterize mass eruption rate, ash distribution in column …
    →*much larger uncertainty!*
  - *bent-puff*[2] -- novel coupled eruption column model + Lagrangian advection/diffusion model of ash transport, inputs of vent parameters, grain size distribution and wind field

[2]Bursik et. al in review, Tanaka, Searcy et. al'xx

PUFF

- PUFF is a *Lagrangian* Trajectory Volcanic Ash Tracking Model which initializes and transports a collection of discrete ash particles, representing a sample of the eruption cloud.

- Different types of transport include:
  - Advection: due to the wind field (W)
  - Diffusion: due to turbulent dispersion (Z)
  - Fallout: due to the gravity and Stoke's law (S)

- **Lagrangian Model:**

$$R_i(t+\Delta t) = R_i(t) + W(t)\Delta t + Z(t)\Delta t + S_i(t)\Delta t$$

i =1, . . . Number of particles

where, $R_i(t)$ is position vector of i^{th} ash particle at time t.

PUFF

- **W(t)** is the local wind velocity which is calculated for each particle by interpolating four dimensional (longitude/latitude/height/time) wind data (obtained from forecast meteorological data) to the particle's position and time.

- Turbulent dispersion for each particle is modeled with a *random walk* process Z(t).
  - A random walk is a process where a particle takes a step at discrete time intervals in such a manner that each step is independent of the others.

- Turbulent dispersion is a vector containing three dimensional Gaussian random numbers with zero mean and specific standard deviation .

  - Diffusion coefficient **K** is independent of particle size and local wind dynamics.

- Ash fallout $S_i(t)=[0\ \ 0\ \ s_i]^T$ is three dimensional vector where the terminal speed s_i is approximated by using Stoke's law and is a function of radius of the particle r_i, dynamic viscosity coefficient η, gravitational acceleration g, density of the particle ρ_{pi}, and density of the atmosphere ρ_f:

$$s_i = \frac{2}{9}\frac{\left(\rho_{p_i} - \rho_f\right)}{\eta} g R_i^2$$

BENT[1]

- In this simulation, Bent model has been used instead of mentioned methods for describing the initial distribution of particles along the height.

- BENT solves a cross-sectionally averaged system of equations for continuity, momentum and energy balance as a function of the eruption vent radius and speed of the ejecta.

- BENT assumes a distribution of pyroclasts of different sizes, and the model equations then predict the height distribution of the various sized clasts.

- For this research, the vent size, vent velocity, mean and deviation of particle size form the source parameters which drive the BENT/PUFF model.

[1]Bursik'01

Approaches

- Input data modeled by suitable distributions can be sampled and outcomes of simulations combined **systematically** to get **probabilistic** estimate hazard

- For expensive simulators surrogate based methods (polynomial chaos, Bayes linear models, GaSP) can reduce the overall cost of computation

- Additional Simplification by looking at integral/maximum e.g. *"maximum or total over a time period"*

Approach

$$\frac{dx}{dt} = f(t_k, x_k, \Theta_k) \qquad\qquad x(t_0) = x_0$$

- Study the evolution of pdf $p(x_k,t_k)$ through time
  where
  f= *bent-puff,*
  x_k state variables (e.g. ash concentrations),
  time t_k,
  Θ_k parameters

- *Use Monte Carlo ☹*

- Replace by Polynomial Chaos Quadrature (PCQ) or Conjugate Unscented Transforms (CUT)

Approach

$$\theta_i(\xi) = \sum_{k=1}^{N} \theta_{ik}\phi_k$$

$$x_i(t,\Theta) = \sum_{k=0}^{N} x_{ik}(t)\phi_k(\xi)$$

- Galerkin collocation can be used to obtain the weights
- Interchanging order of time and probability integration

$$\left\langle x(t)^N \right\rangle = \sum_q w_q \left(\int_0^t f(t,x,\Theta_q)\,dt \right)^N$$

- “Smart Ensemble” of *bent-puff*

PARALLELIZED WORKFLOW FOR ENSEMBLE PCQ BENT-PUFF

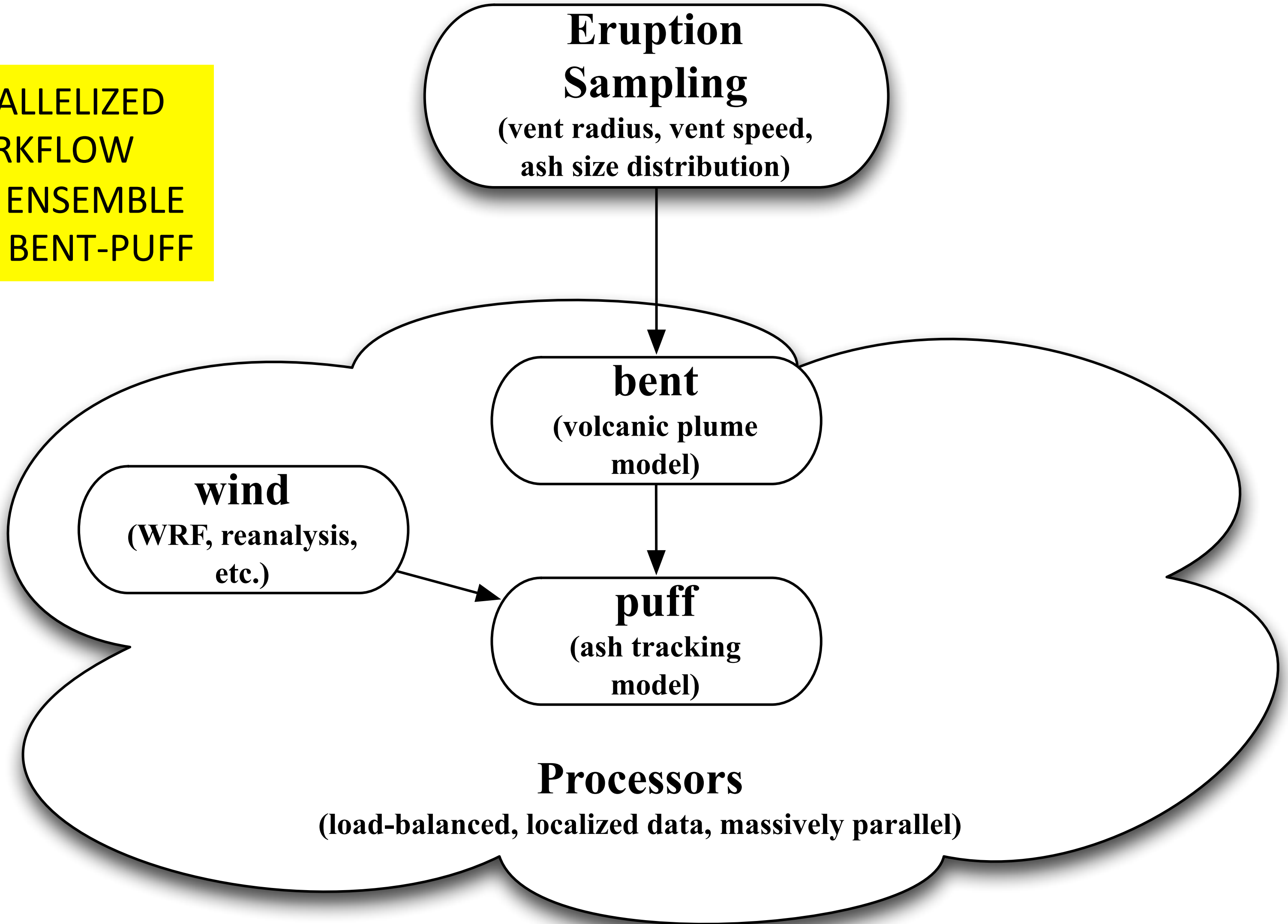


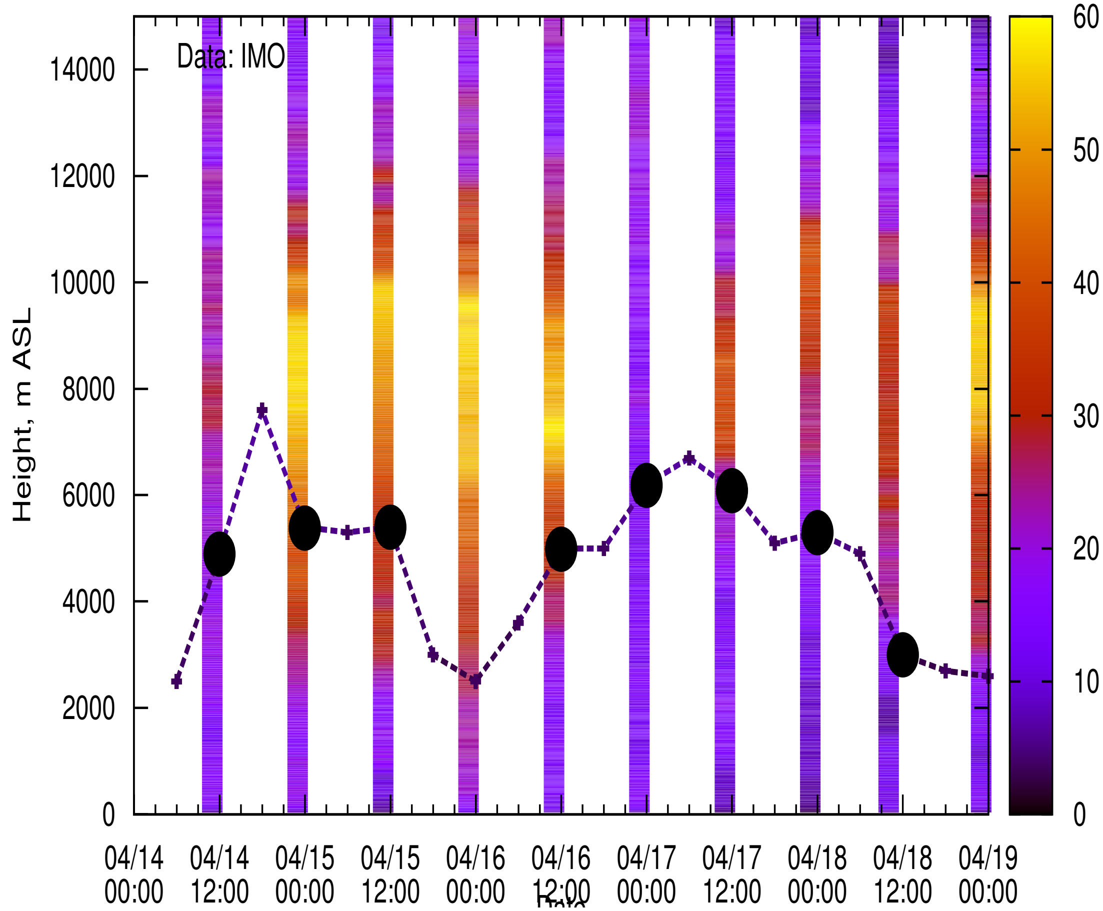
Table 1: Eruption source parameters based on observations of Eyjafjallajökull volcano and information from other similar eruptions of the past.

Parameter	Value range	PDF	Comment
Vent radius, b_0, m	65-150	Uniform, $+$ definite	Measured from IMO radar image of summit vents on 14 April 2010
Vent velocity, w_0, m/s	Range: 45-124	Uniform, $+$ definite	Measured by infrasound (*Ripepe et al.*, 2010) 6-21 May, when MER similar to 14-18 April
Mean grain size, Md_φ, φ units	2 boxcars*: 1.5-2 and 3-5	Sum of two uniform, $\in \mathbb{R}$	(*Woods and Bursik*, 1991), Table 1, vulcanian and phreatoplinian. A. Hoskuldsson, Eyjafjallajökull Eruption Workshop, 09/2010, presentation, quote: 'vulcanian with unusual production of fine ash'.
σ_φ, φ units	2.0 ± 0.6	Uniform, $\in \mathbb{R}$	(*Woods and Bursik*, 1991), Table 1, vulcanian and phreatoplinian

*

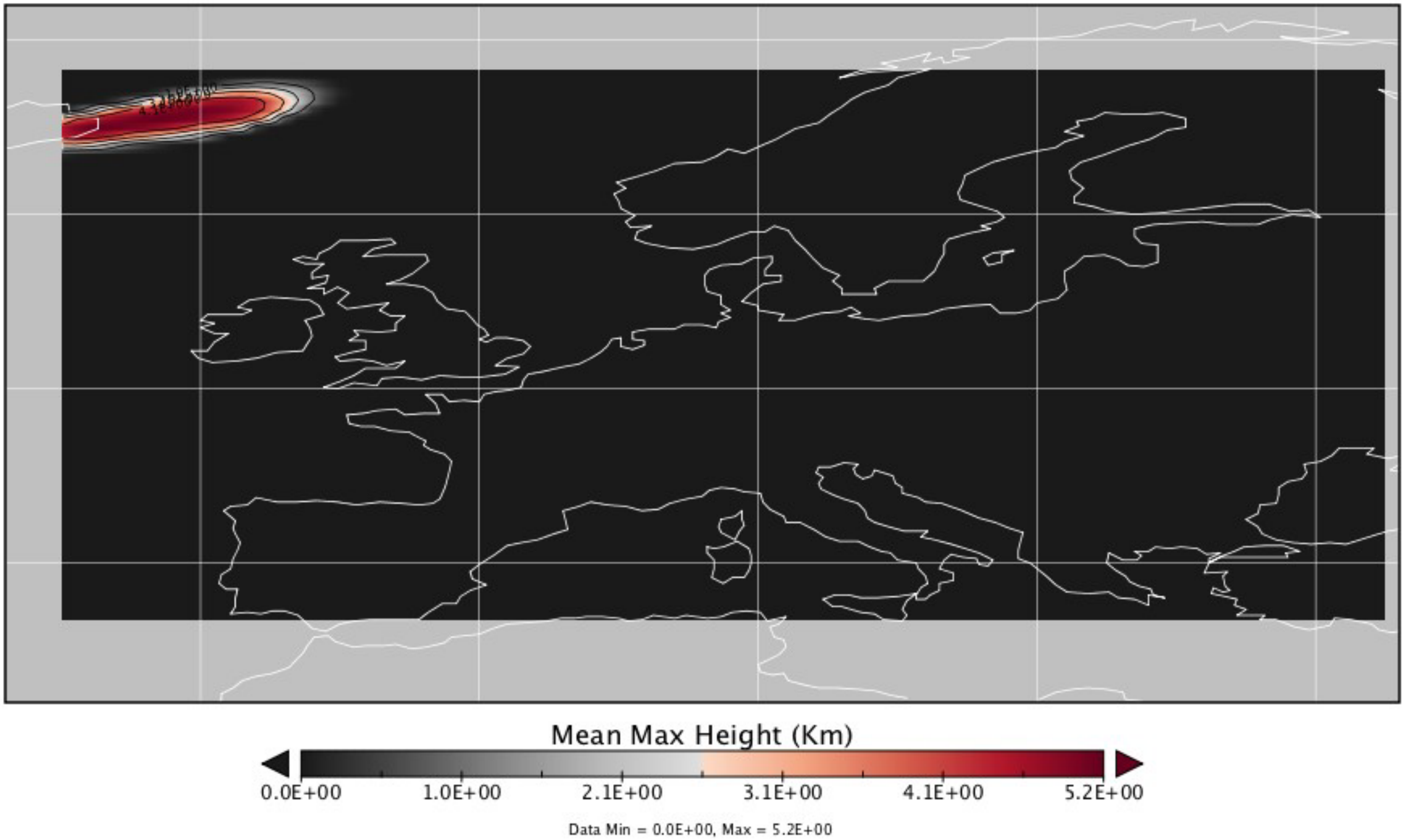
boxcar: function that is zero everywhere except over a short interval where it is constant

Preliminary Results

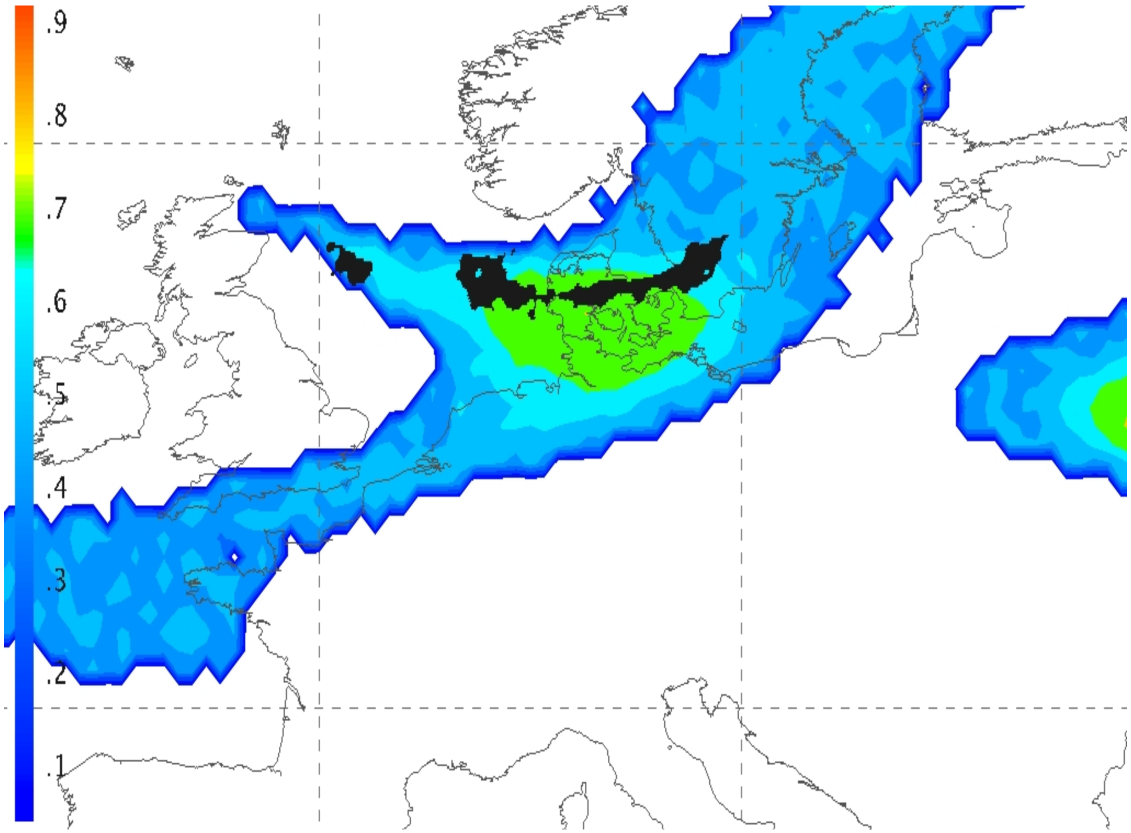


Blue line is observed plume height (minimum observable about 2500 m using IMO Doppler radar at Keflavik airport); black circles are calculated plume height with (bent) using IMO Keflavik radiosonde windspeed data (vertical colored bars) centered on nominal time of measurement (every 12 h). Windspeed color bar in m/s.

Time: 1271224800



Preliminary Results



Meteosat-9 SEVIRI cloud outline (filled black region) at 16 April 2010 00Z, compared with model generated probabilities of ash presence based on source parameter uncertainty propagation. Color scale bar in fractional probability. Outer edge of blue area is at 20% probability.

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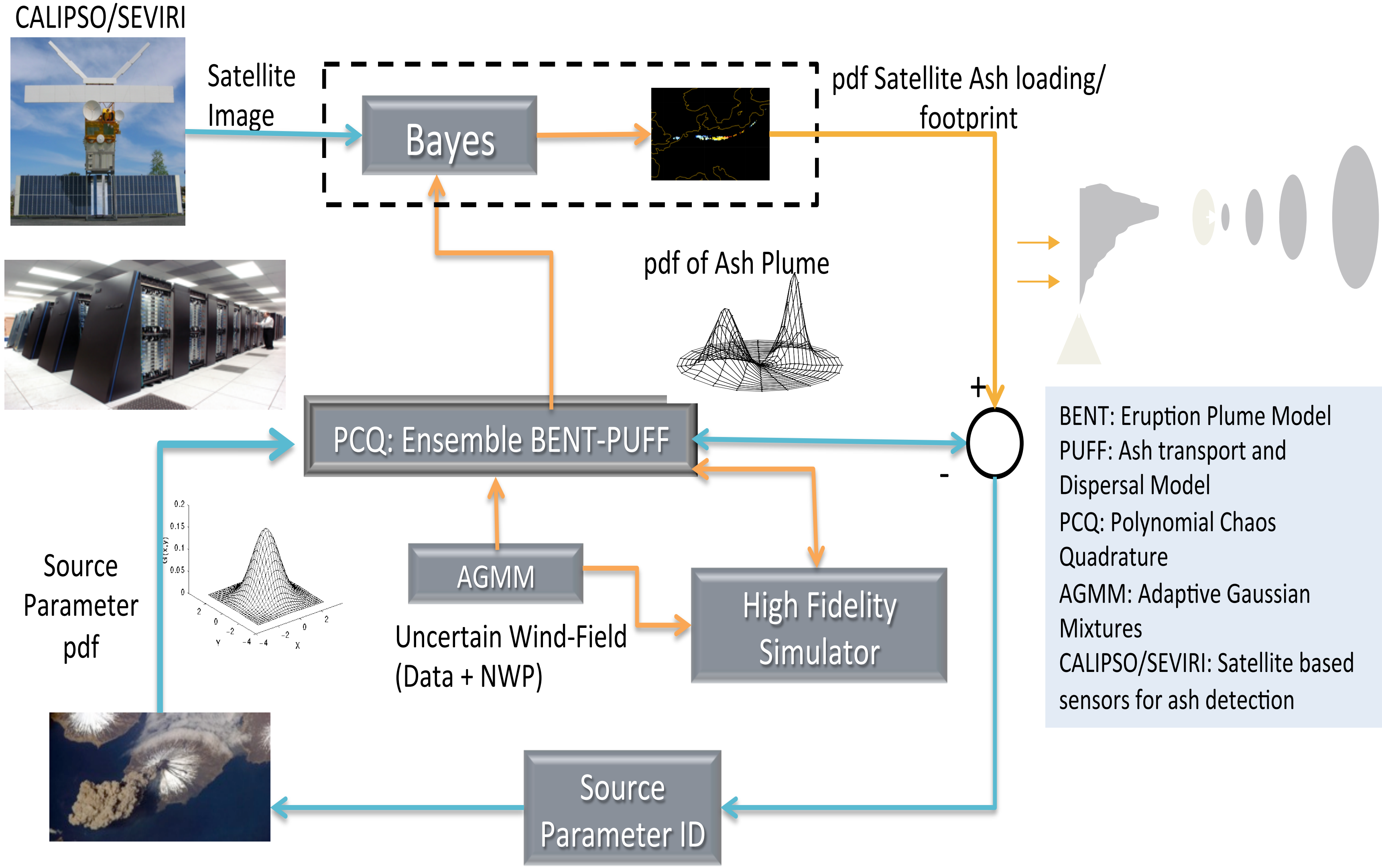

Summary and Current work

Developed parallelized PCQ/Bent-Puff HPC based tool for probabilistic ash forecasting

Physics based methodology for VATD "transport and dispersion" model inputs – poorly characterized column height, mass eruption rate replaced by pdf of observable vent parameters and speed.

PCQ based inverse problems for source parameter estimation.

New CUT methods reduce ensemble size dramatically!

Talk by P. Singla
In next session

PCQ based probabilistic hazard analysis replaces predictions of existing tools.

Results for Eyjafjallojokull are very promising – all ash observed was inside a Probability>0.2 contour with most in Probability >0.7

Risk based (probabilistic) forecast for ash cloud with full transport modeling !!

Current Work

- Incorporate wind uncertainty in more effective ways
- Ash imagery interpretation using model outcomes
- Near Real Time Probabilistic Forecast informed by observation and best-in-class models/numerics
- Large dimensional (physical fields) UQ/prediction using localization ideas