# Ensemble modelling of Eyjafjalla plumes

# Eruption column input

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**UB — UAF — MTU — NOAA-NESDIS — IMO**

**NSF – RAPID**

# 1. Use Case 0: Current Usage

- Current usage is to run separate deterministic runs
- Mass eruption rate, $Q$, is calculated from an empirical relationship derived for strong plumes ($w >> v$), e.g.,

$$H_T = 1.67Q^{0.259} \tag{1}$$

- This yields ash loading as a function of cloud height, $H_T$ alone
- It specifically excludes environmental factors important in small eruptions
- But we know that plume rise is sensitive to environmental factors like wind, $v$, as well as relative humidity, $R$ and temperature, $T$ through latent heat release, $\Lambda$

$$H_T = f(Q, v, \Lambda(R, T)) \tag{2}$$

(▷ Play movie)

# 2. Use Case 1: $\sim$ No Information

- Only know from seismology that the eruption is “small”
- We have a radiosonde from near the time of the eruption
- Use fast, stochastic plume model coupled to slower, deterministic VATD model $\leftarrow$ stochastic model cheap, so use Monte Carlo
- Monte Carlo runs, one variable input parameter, plume height, $H_T$ ($10^3 - 10^6$(?) runs); two variable input parameters, height and grain size ($10^3 - 10^6$(?) runs)
- Plume — `bent`: 1-10 CPU-secs, VATD — `puff`: minutes – 1 CPU-hr each
- *Combine outputs and compare probabilistic output to satellite data*

(▷ Play movie)

# 3. Use Case 2: Limited Information

- We have some measurements of several parameters: vent speeds and vent radii, or plume height, and some ground measurements of ash
- A radiosonde exists near the time of eruption
- Use polynomial chaos quadrature (PCQ), as dimensionality becoming important (S. 10.1→ More on PCQ . . . )
- Computations: serial; 2.5 CPU-hours/run, 1 GB RAM, 1 GB HD each; 800 CPU-hr ($10^6$ particles)
- *Again, combine outputs and compare probabilistic output with satellite data – improvement?*

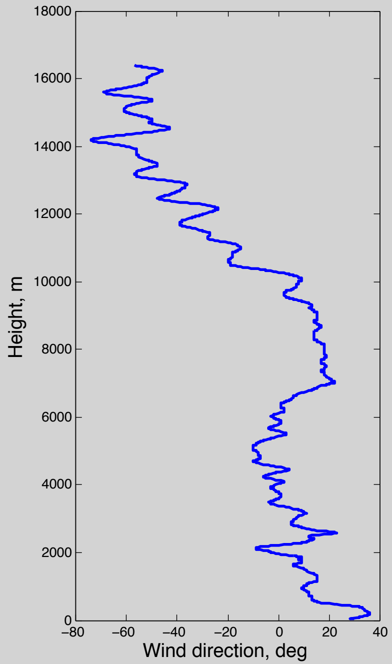
(▷ Play movie)

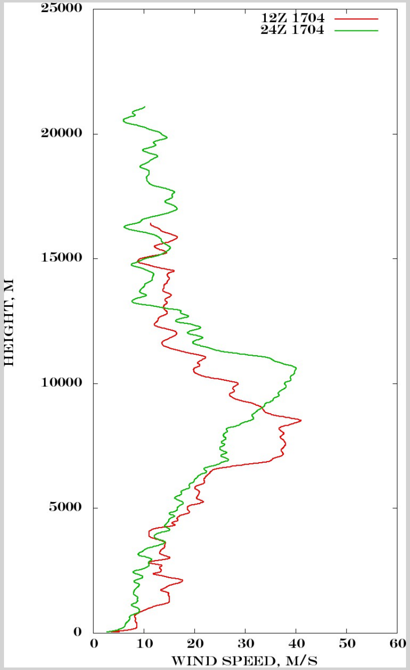
| Parameter | Value range | PDF | Comment |
|---|---|---|---|
| Vent radius, $b_0$, m) | 25-150 | Uniform | Measured using scale in radar image of several summit vents on 14 April 2010, from 'Eruption in Eyjafjallajokull' - `http://www2.norvol.hi.is/page/ies_Eyjafjallajokull_eruption` |
| Vent velocity, $w_0$, m/s) | Mean: 40-60; max: 80 (assume this is $2\sigma$(?)) | Standard distribution with compact support | M. Ripepe, Iceland meeting 2010, presentation |
| Mean grain size, $Md_\varphi$ | 2 boxcars: 1.5-2 and 3-5 | Uniform | Woods and Bursik (1991), Table 1, vulcanian and phreatoplinian. A. Hoskuldsson, Iceland meeting 2010, presentation, 'vulcanian with unusual production of fine ash'. |
| $\sigma_\varphi$ | $1.9 \pm 0.6$ | Gaussian | Woods and Bursik (1991), Table 1, vulcanian and phreatoplinian |

# 4. Use Case 3: Large Amount of Information

- Numerous measurements of plume height at source from weather radar and visual observation
- Radiosonde every 12 h
- Numerous visual observations of plume characteristics
- Deterministic run?
- *How does one deterministic run compare with satellite data?*

# 5. High discharge: 14–17 April




Wind at all levels ∼ northerly

Jet 5-10 km, ∼40-60 m/s


M. Roberts, IMO

↑ Enlarge ↑ Annotate (▷ Play movie)

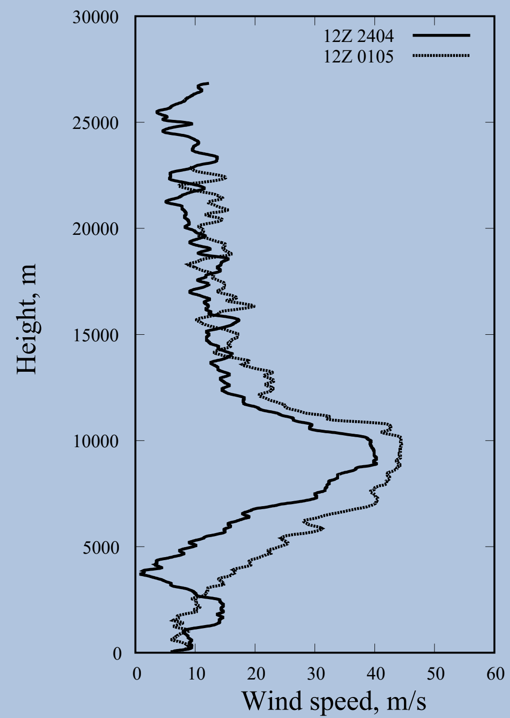
- Discharge (MER, $Q$) $\approx 7.5 \times 10^5$ kg/s
- Ejection of initial gas rich cap, followed by more densely laden steady flow
- Upper-level bent over plume
- No flow separation over mountain
- Initially slow, dense eddies drafted downwind – partial wind-driven column collapse
- Low-level gravity current (phoenix cloud) with source S of vent; sharp upwind edge
- Downwind diverging of lower-level and upper-level flow



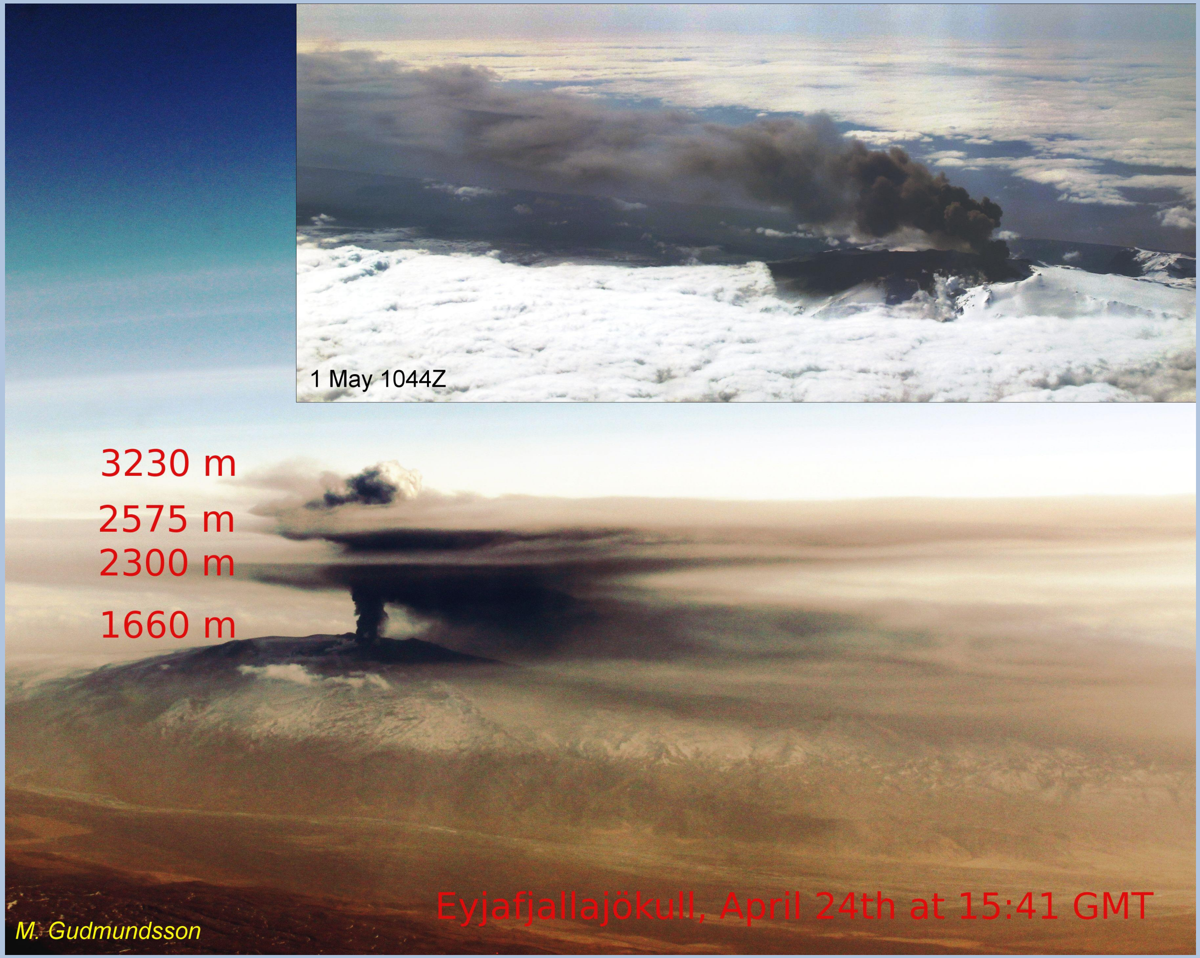
S. Jonsson, ISAVIA

↑ Wider view 1 ↑ Enlarge 2

# 6. Low Discharge: 18 April – 4 May




- Discharge, $Q < 5 \times 10^4$ kg/s
- Discharge generally low, wind dying, resulting in interplay to produce varying phenomenology
- 24 April: Discharge $\uparrow$, winds weak
  - Umbrella clouds (gravity current intrusions) at multiple levels, which merge downwind
- 1 May: Discharge low, winds stronger
  - Bent over plume

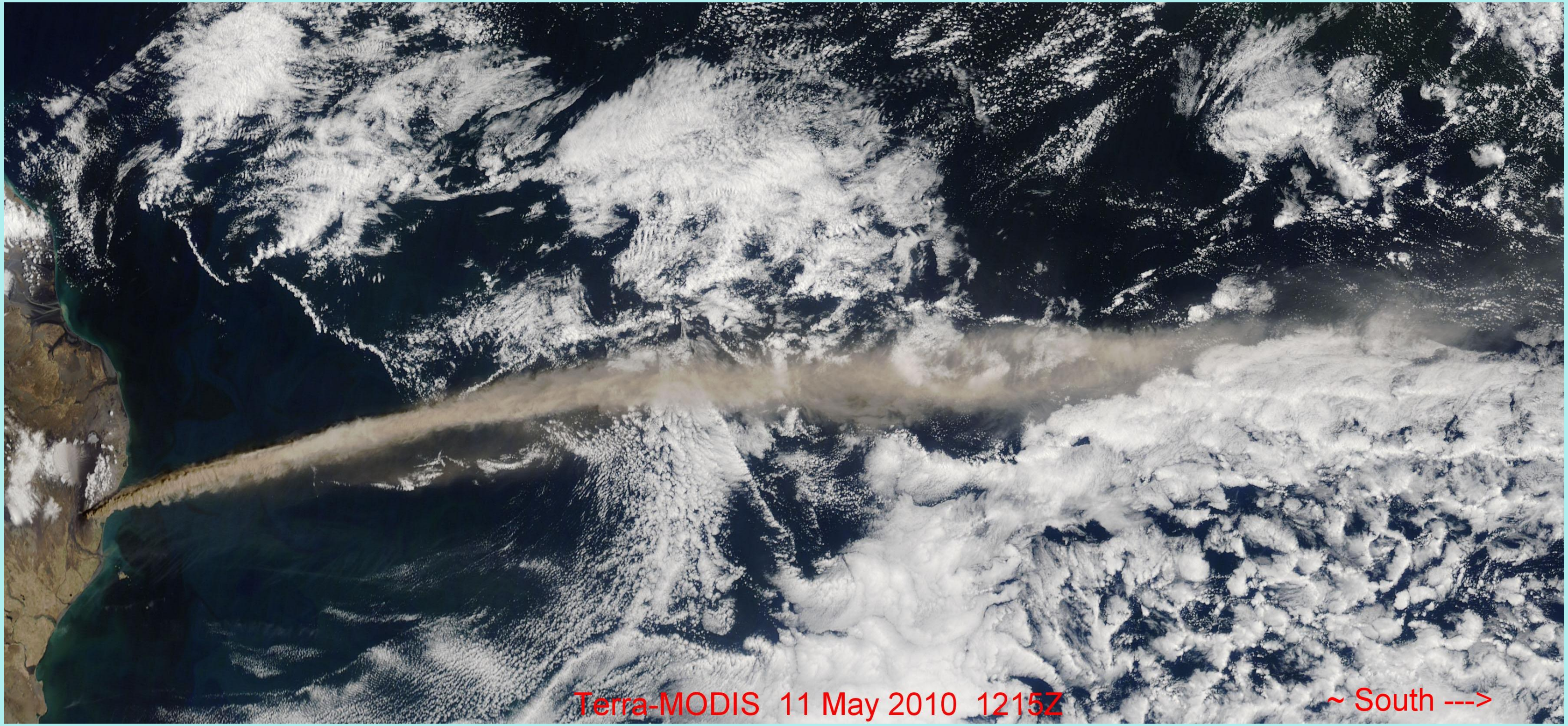



↑ Satellite view

# 7. Resumed explosivity: 5 – 23 May

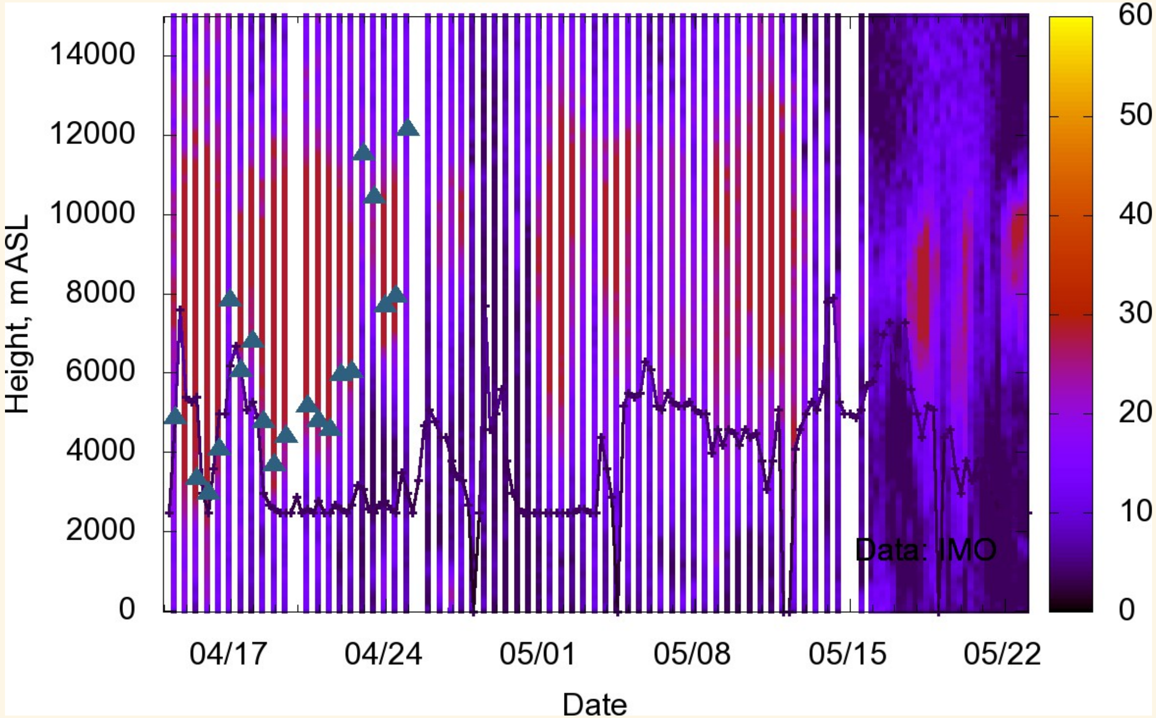
May 6th @13:14 UTC. Photo: Þórdís Högnadóttir


↑ Radiosonde



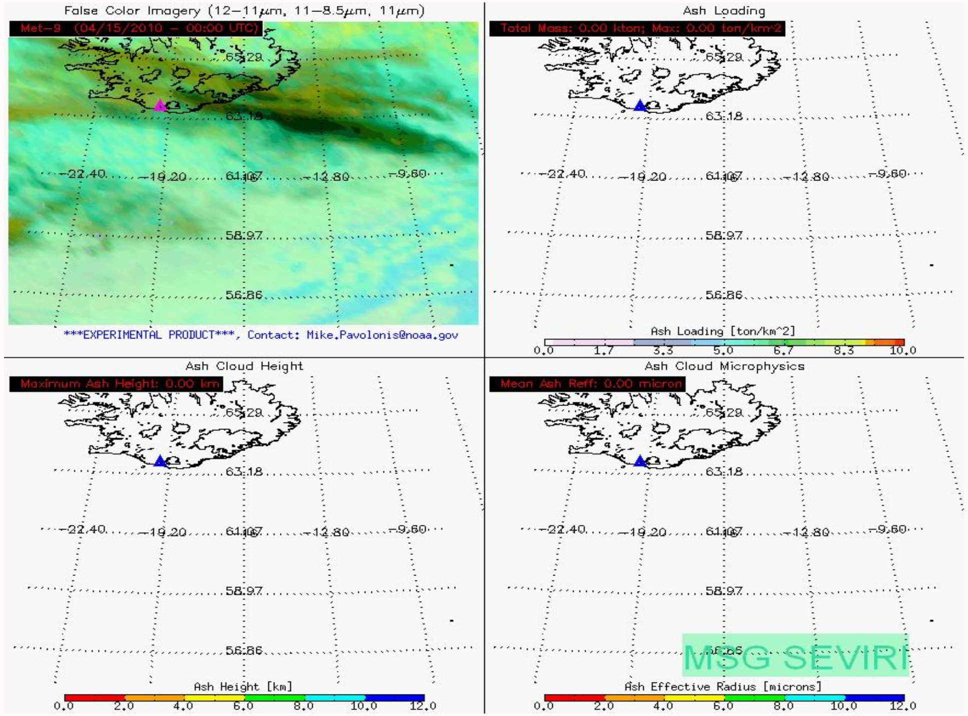

↑ Radiosonde

# 8. Source Model




↑ Expanded view

# 9. Validation with Satellite Retrievals



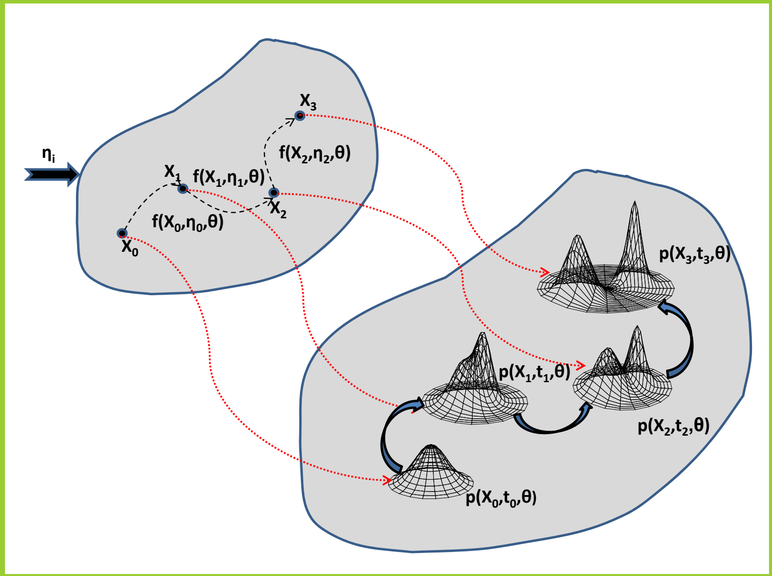

SEVIRI and CALIPSO will be used

## 10. Conclusions and Future Directions

- Use case approach might help characterize errors in different, general situations
- Trying to couple three models – difficult – but we are getting results
- Validation against good data – SEVIRI and CALIPSO – is necessary
- If we have good data on source, can we estimate long-range transport?
- Can ensemble approach provide probabilistic concentrations useful in VAAs?
- Statistical approaches for analyzing and comparing ensemble runs: What are they?
- Comparisons of ensemble members to satellite data: How do we do it?
- Use – NCEP Reanalysis. Have – WRF (nested grid), GFS (0.5 deg) and FNL (1 deg)
- `Bent` is VATD agnostic – could ensemble other VATDs

## 10.1. PCQ: More Details

- Bent + puff Model: $\mathbf{x}_{k+1} = f(\mathbf{x}_k) + \boldsymbol{\eta}_k,\ \mathbf{x}(t_0) = \boldsymbol{\mu}_0$.
- Source of uncertainties: system parameters, initial conditions, input to the system.
- Robust modeling of the propagation of these uncertainties is important to accurately quantify the uncertainty in the solution at any future time




State and pdf transition

## 10.2. Motivation

- Main challenge: characterizing the uncertainty in the system states due to *both parametric and input uncertainties* simultaneously
  - Approximate solution to exact problem: Multiple-model estimation method, Monte Carlo (MC) methods
  - Exact solution to approximate problem: Gaussian closure, Equivalent Linearization, and Stochastic Averaging.
- Main Objective: *develop analytical means to accurately characterize the state pdf of a linear system subject to initial condition uncertainty, and possibly non-Gaussian parametric uncertainty*

## 10.3. Proposed Approach: Polynomial Chaos Quadrature

Polynomial Chaos

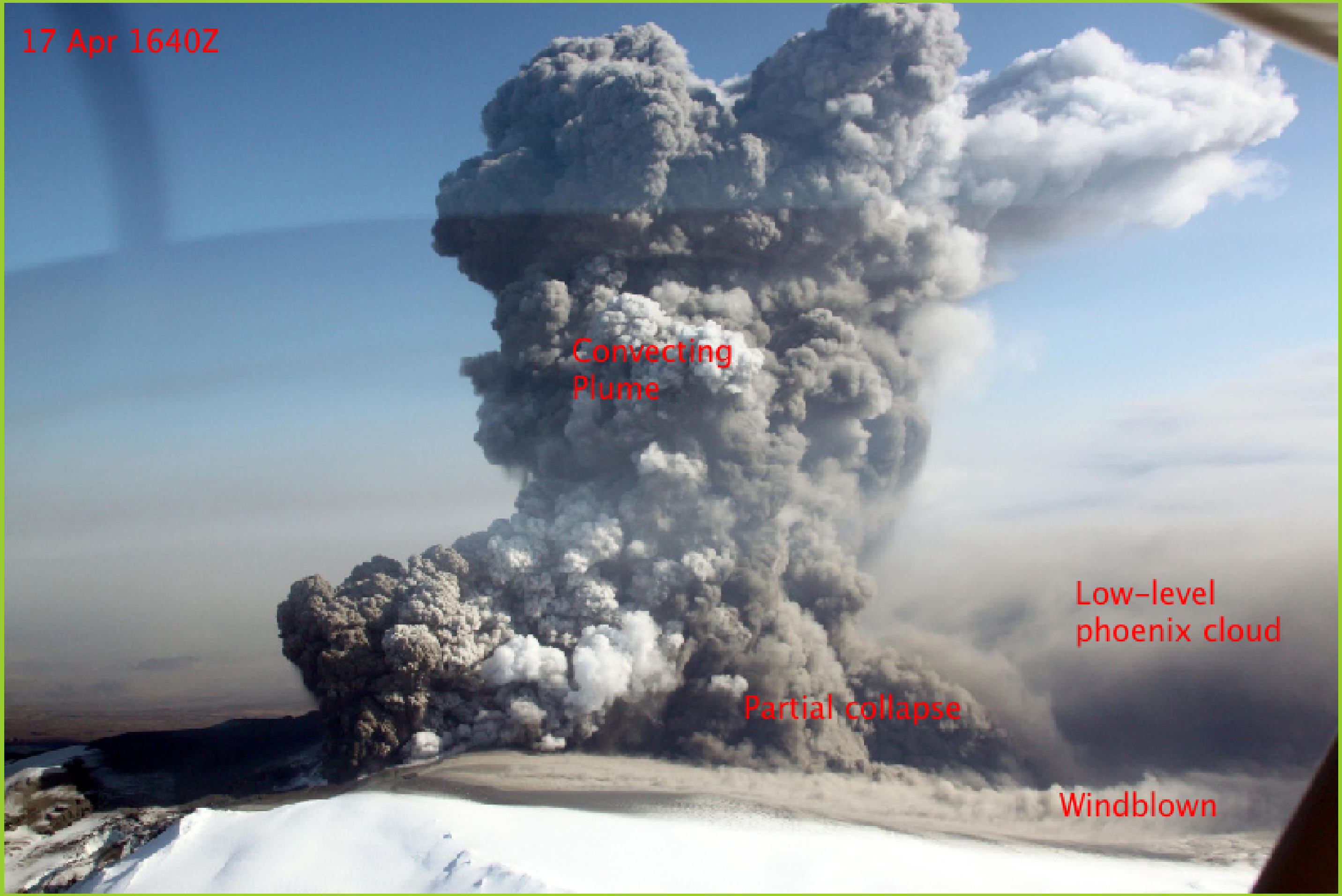
- Polynomial chaos (PC) is a term originated by Norbert Wiener in 1938, to describe the members of the span of Hermite polynomial functionals of a Gaussian process
  - PC has been generalized by Xiu et al. (2002) to efficiently use the orthogonal polynomials from the Askey-scheme to model various probability distributions
- PC involves a separation of random variables from deterministic ones in the solution algorithm for a stochastic differential equation
- The random variables are expanded in a polynomial expansion associated with the assumed pdf for the input variables
  - Hermite polynomials for normally distributed parameters, Legendre for uniformly distribution, etc.

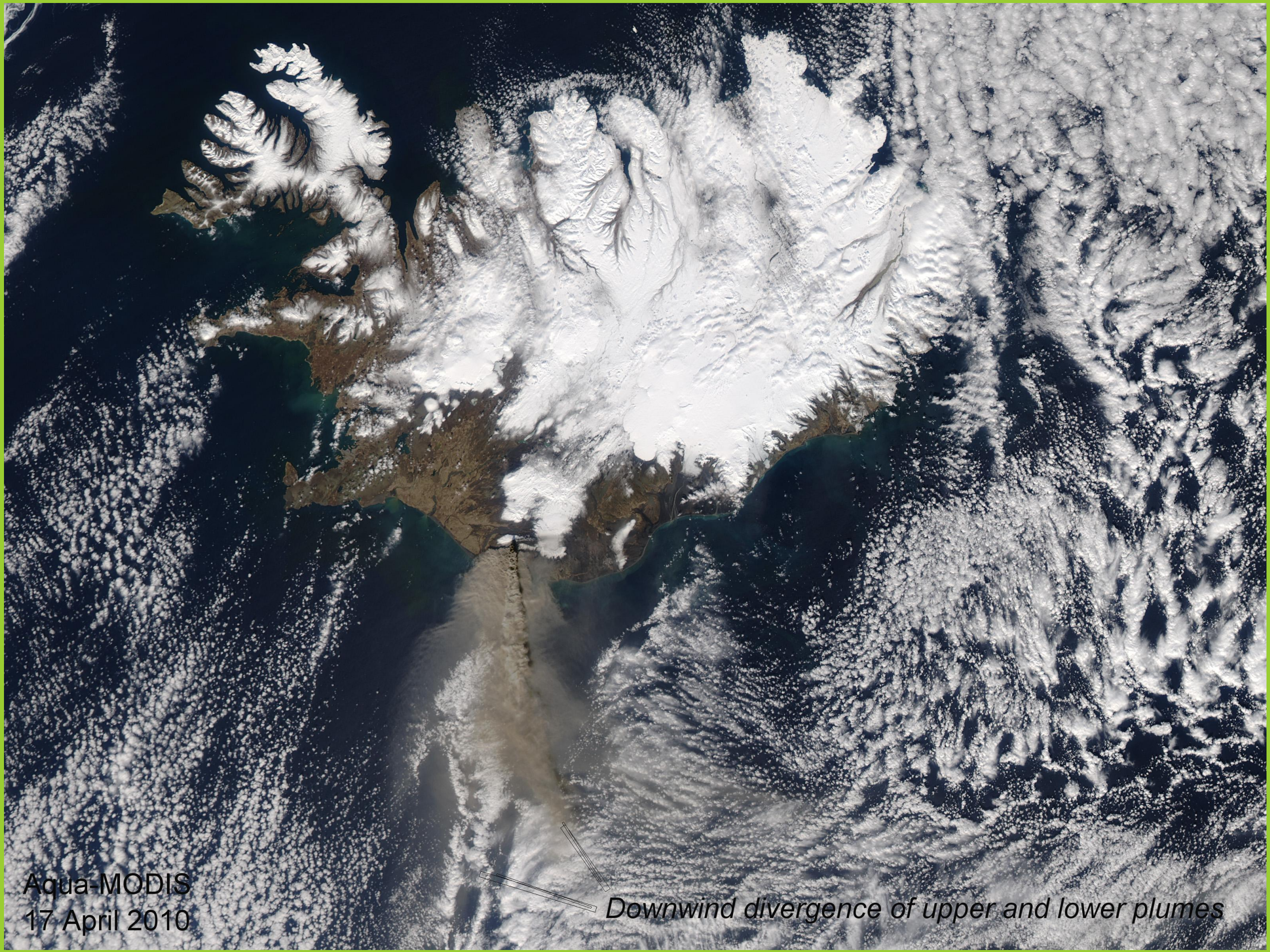
## 10.4. Proposed Approach: Polynomial Chaos Quadrature

Polynomial Chaos

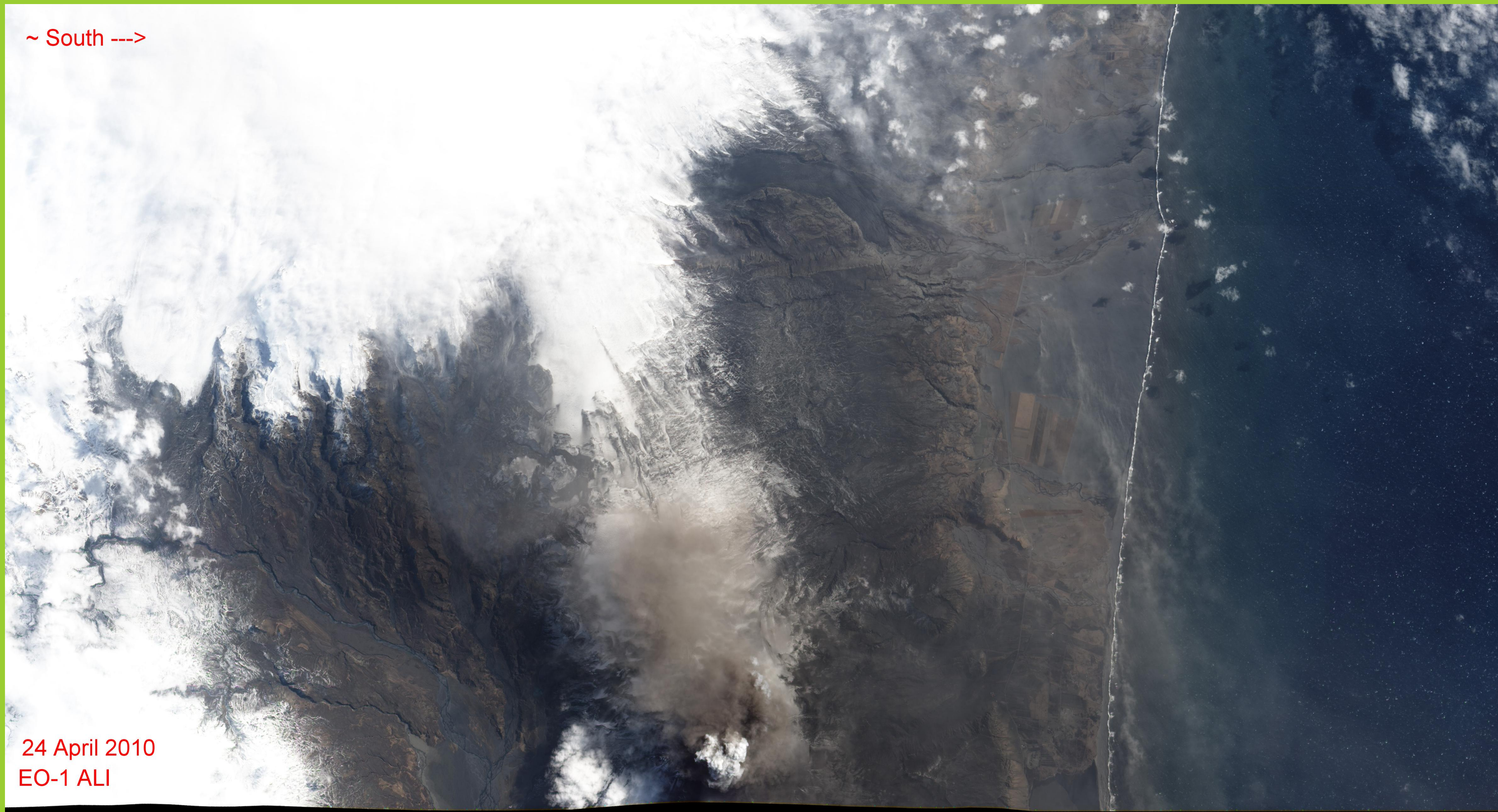
- Galerkin collocation is used to generate a system of deterministic differential equations for the expansion coefficients.
  - The Galerkin collocation step fails when applied to problems with non-polynomial nonlinearities, and can produce non-physical solutions.
- PCQ is an extension of the polynomial chaos idea and replaces the projection step of PC with numerical quadrature
  - The resulting method can be viewed as a Monte-Carlo-like evaluation of system equations, but with sample points selected by quadrature rules

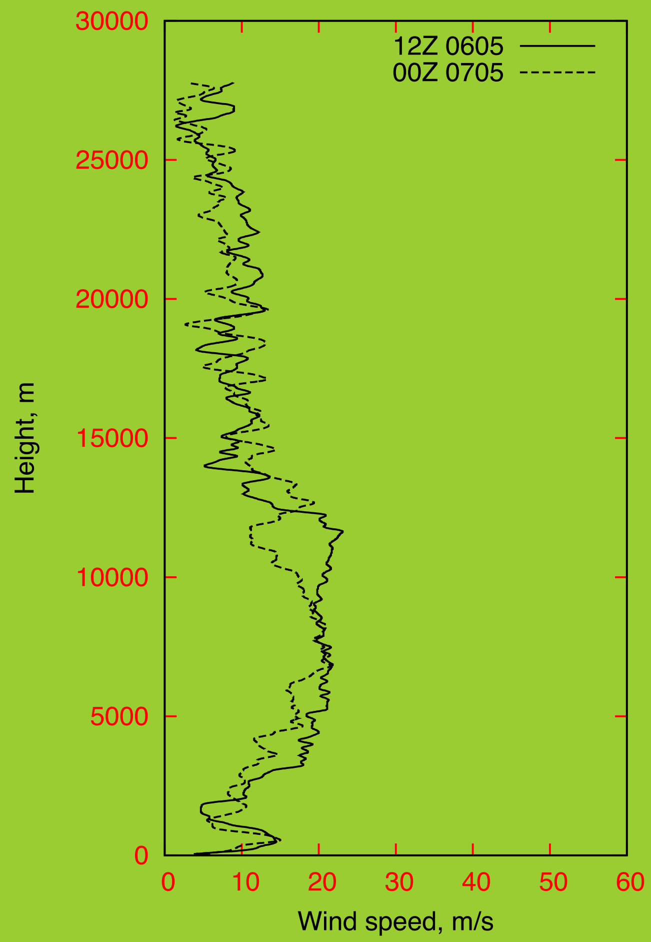

17 April 1712Z


17 Apr 1640Z
Convecting
Plume
Low-level
phoenix cloud
Partial collapse
Windblown


Aqua-MODIS
17 April 2010
Downwind divergence of upper and lower plumes


17 April 2000Z


~ South --->
24 April 2010
EO-1 ALI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00Z 0705
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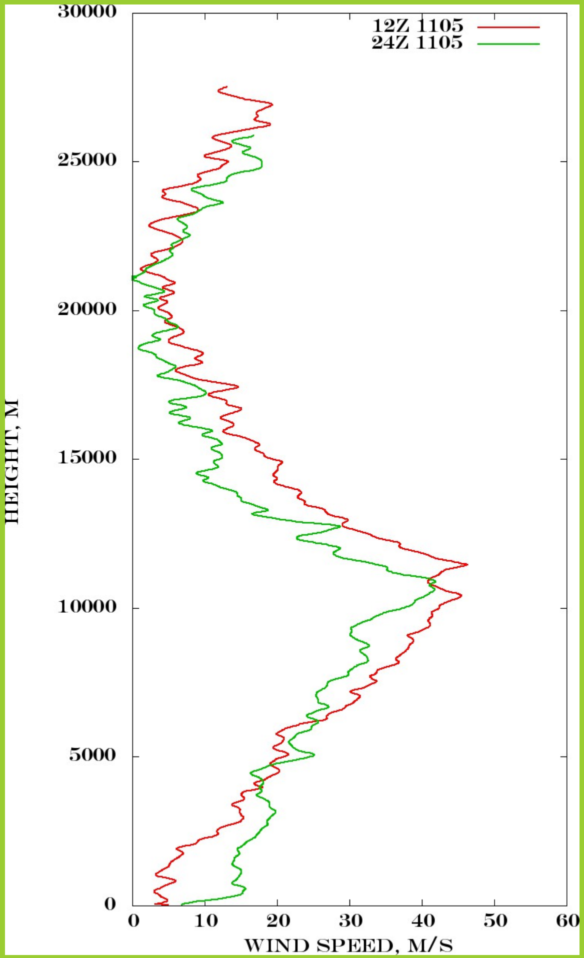
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24Z 1105
HEIGHT, M
WIND SPEED, M/S
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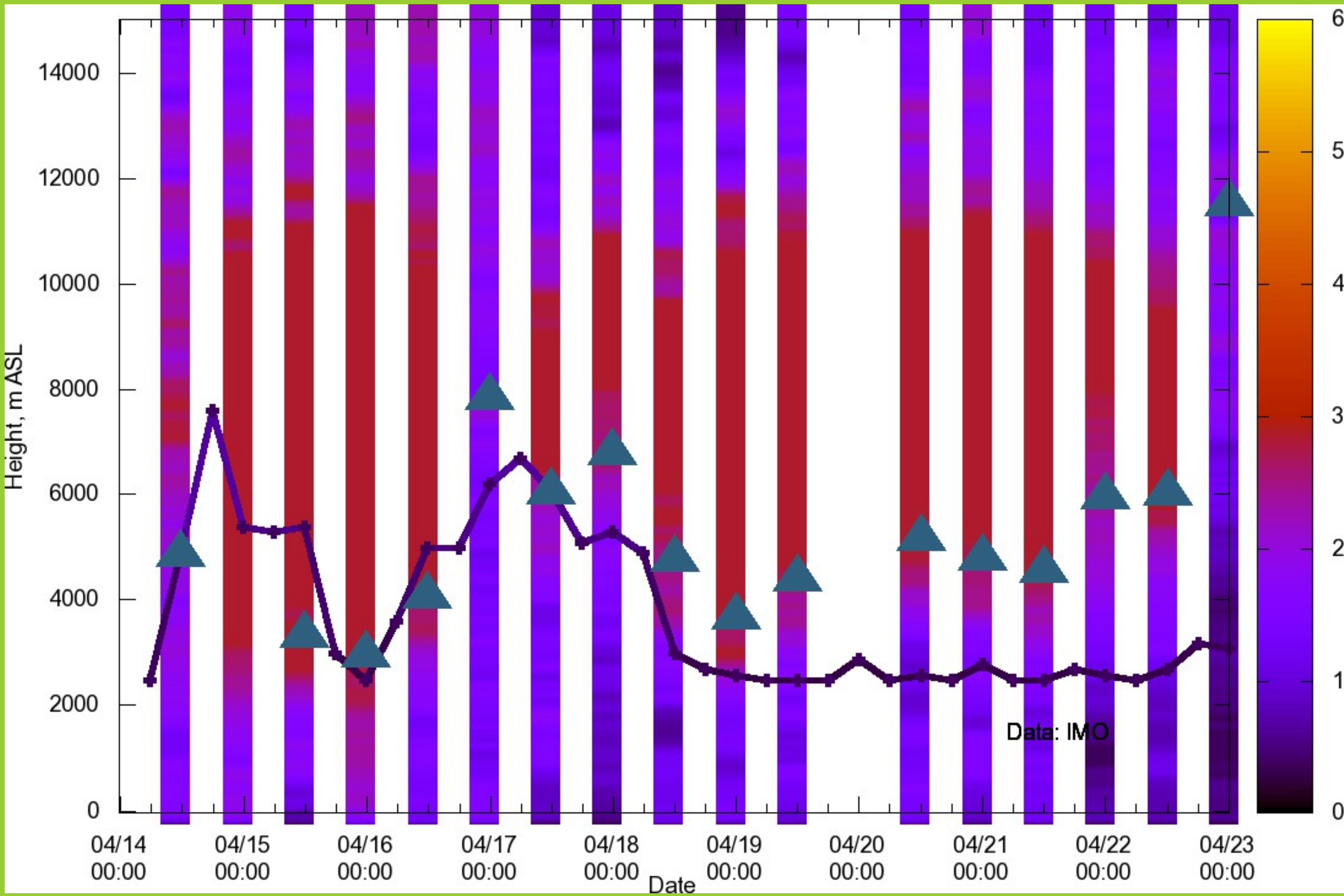

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04/18 00:00
04/19 00:00
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04/23 00:00
Date
Data: IMO
60
50
40
30
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10
0