



IUGG

MELBOURNE Australia 2011

Earth on the Edge: Science for a Sustainable Planet
28 June - 7 July 2011



Forecasting Volcanic Ash

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Eyjafjallajökull, volcanic clouds, and aviation - one year on

Melbourne, 8 June 2011

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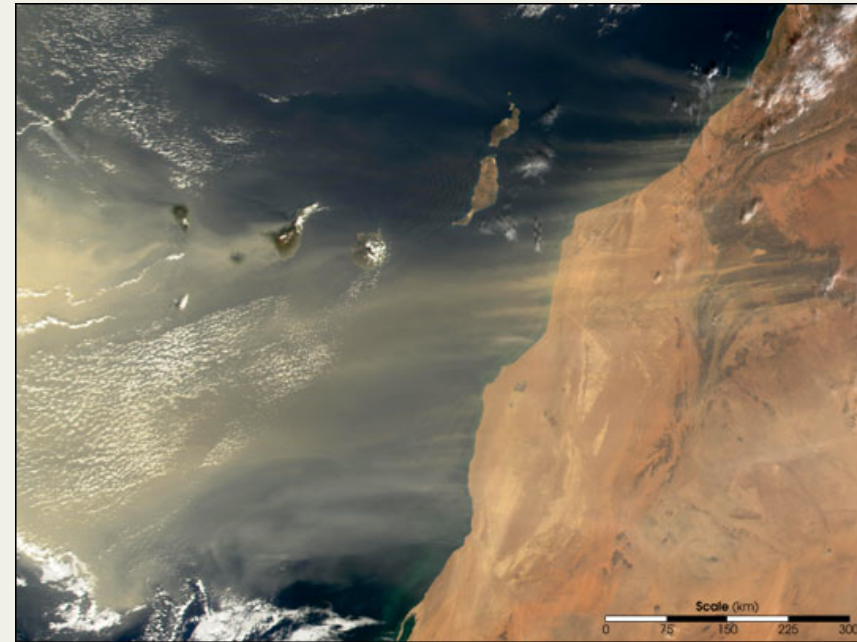
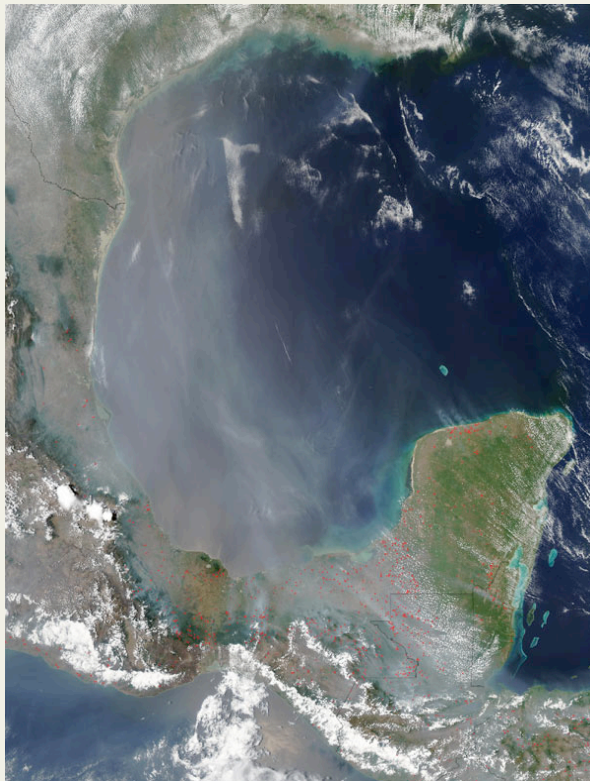
Model the transport of ash is similar to model the transport of other substances

1. Natural origin

- Mineral dust
- Volcanic ash and aerosols
- Sea salt

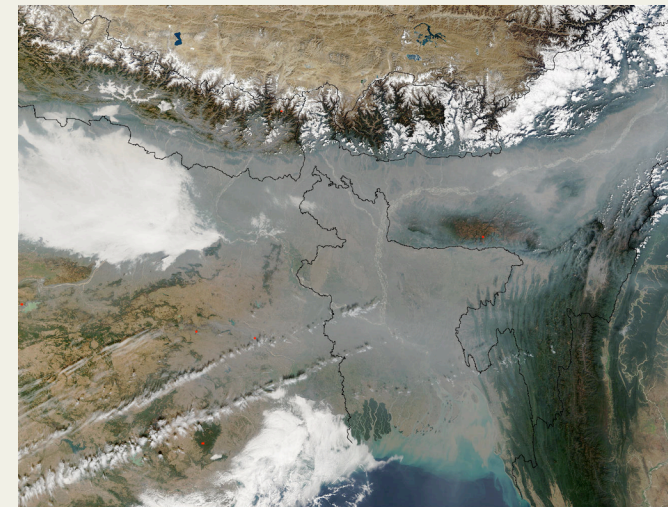
2. Biogenic origin

- Biomass burning



3. Anthropogenic origin

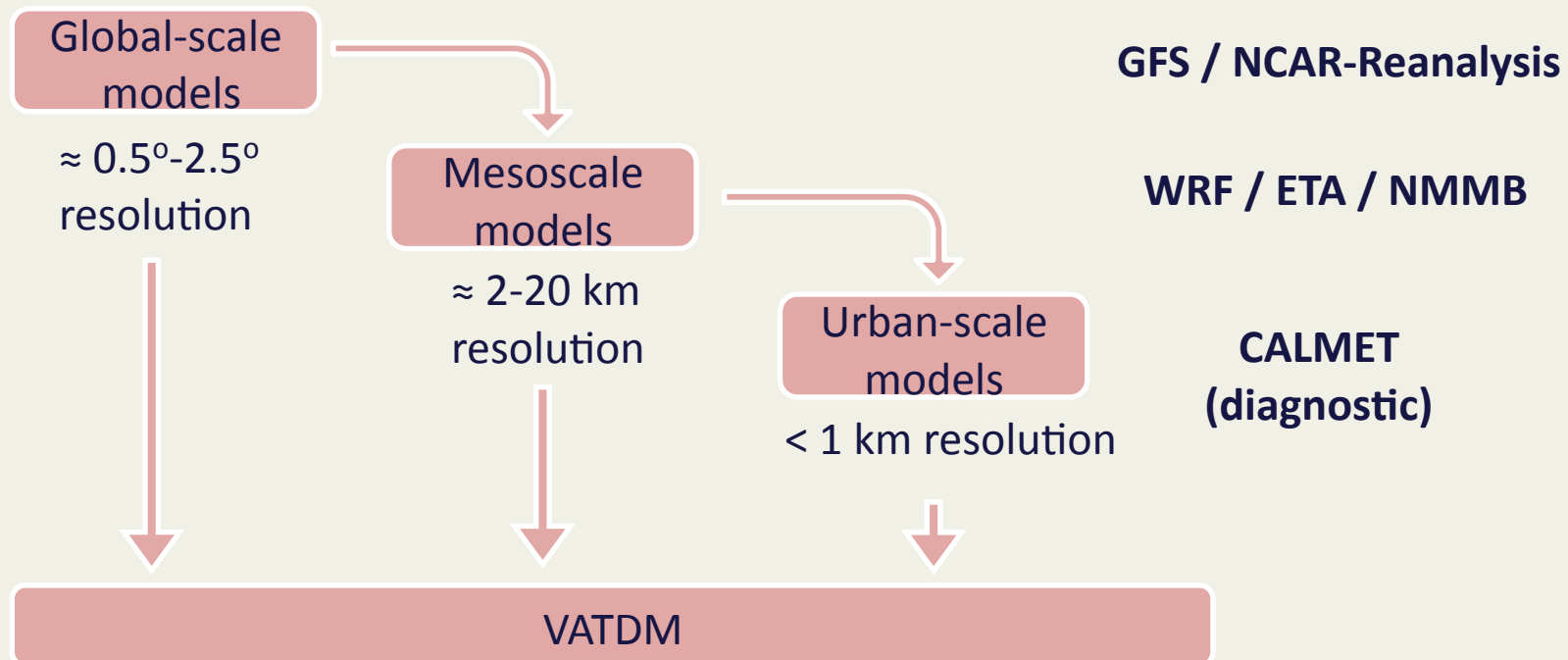
- Pollutants
- Radionuclide



Atmospheric transport of any substance always involves 3 different components

1. A meteorological or atmospheric model (NWPM)

- NWPM solve the atmospheric motion equations but using different approaches and/or parameterizations depending on the scale under consideration.
- Global-scale ($\approx 0.5^\circ$ - 2.5° resolution), Meso-scale (≈ 2 - 20 km resolution), Urban-scale (<1 km resolution).
- VATDM typically follow an off-line approach (on-line unpractical in forecast mode)



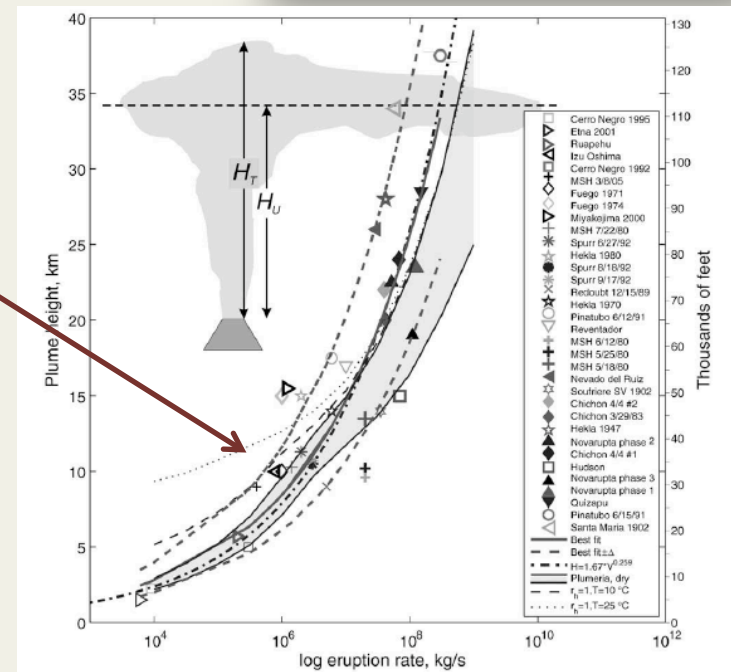
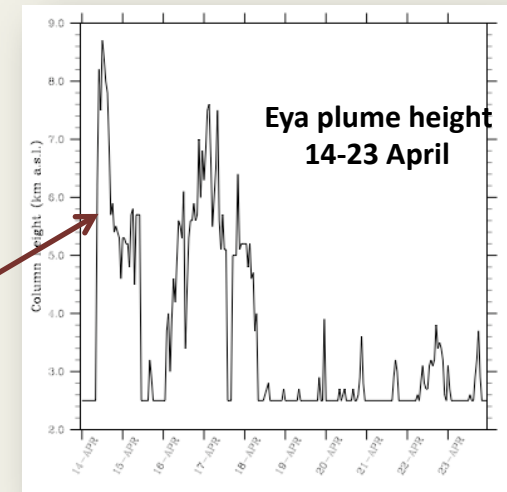
Atmospheric transport of any substance always involves 3 different components

2. An emission or source model (source term)

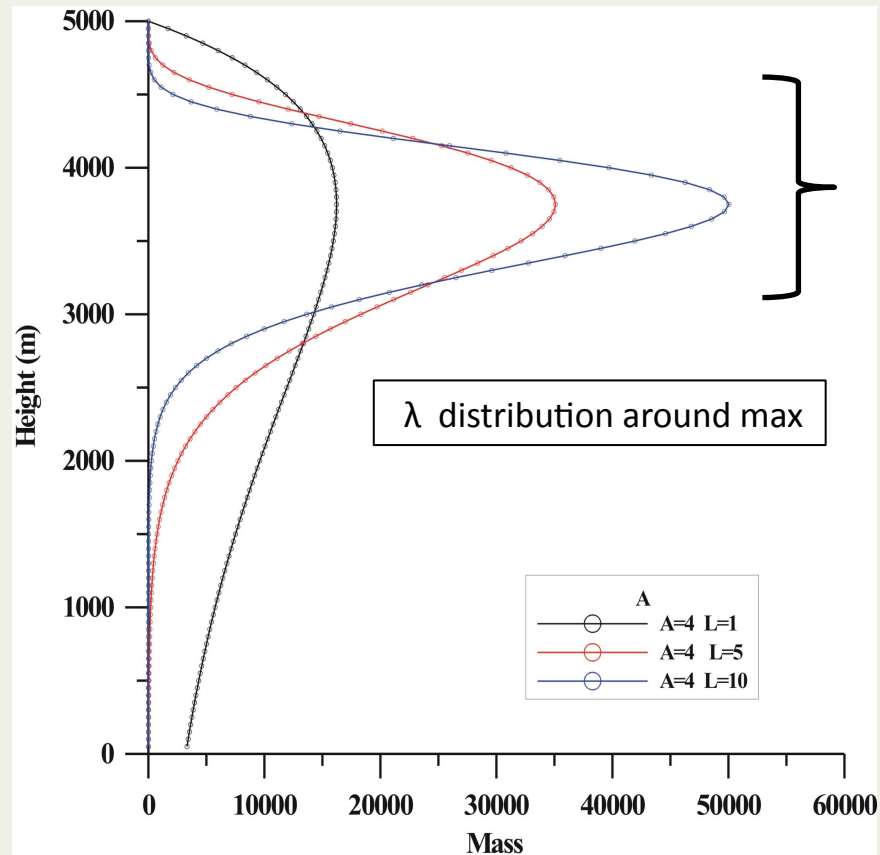
- Where the “contaminant” is released ?
- When the “contaminant” is released ?
- How the “contaminant” is released ?

In VATDM Source term is characterized by

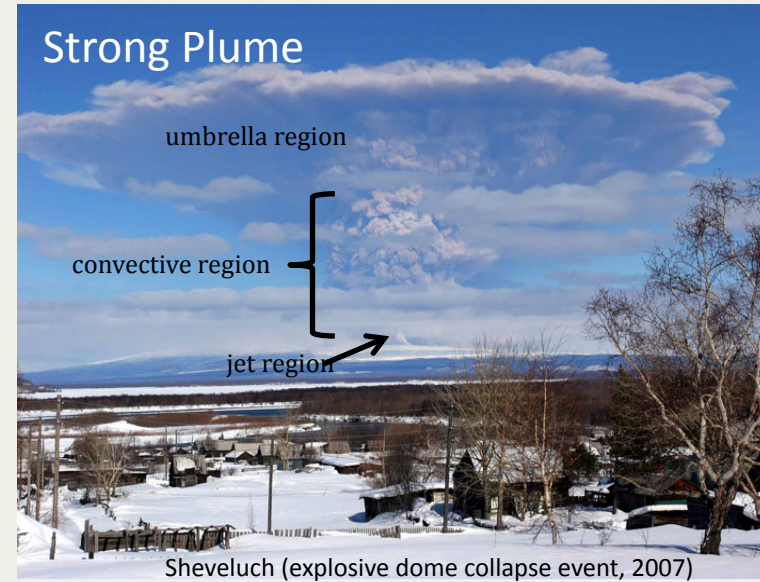
- 1) Plume height (H)
 - From observations (radar, sat, PiReps, etc).
- 2) Mass Eruption Rate (MER)
 - MER-H relationships exist but...
- 3) Vertical distribution of mass
 - Fine ash centred at the top



i) Vertical distribution of mass according to a Suzuki distribution



ii) Vertical distribution of mass solving The BPT equations



Atmospheric transport of any substance always involves 3 different components

3. A transport model *sensu stricto*

- Solve a transport equation switching on/off different terms accounting for different processes (deposition, chemical reactions, phase changes, etc.)

$$\frac{\partial C}{\partial t} =$$

$$-\frac{\partial(u_x C)}{\partial x} - \frac{\partial(u_y C)}{\partial y} - \frac{\partial(u_z C)}{\partial z} \quad \text{(advection)}$$

$$+ \frac{\partial}{\partial x} \left(k_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial C}{\partial z} \right) \quad \text{(diffusion)}$$

$$+ \frac{\partial(u_d C)}{\partial z} \quad \text{(sedimentation)}$$

+ *Source + Sink*

Very distinctive of VATDM

Includes:

- Gravitational settling
- Other dry deposition mechanisms
- Wet deposition

Gravitational settling dominates down to a certain size only...

$$+ \frac{\partial(u_d C)}{\partial z}$$

$$u_s(z, \phi) = \sqrt{\frac{4d(\rho_p - \rho_a)}{3C_D(Re)\rho_a}}$$

Air density

Given by atmosphere models

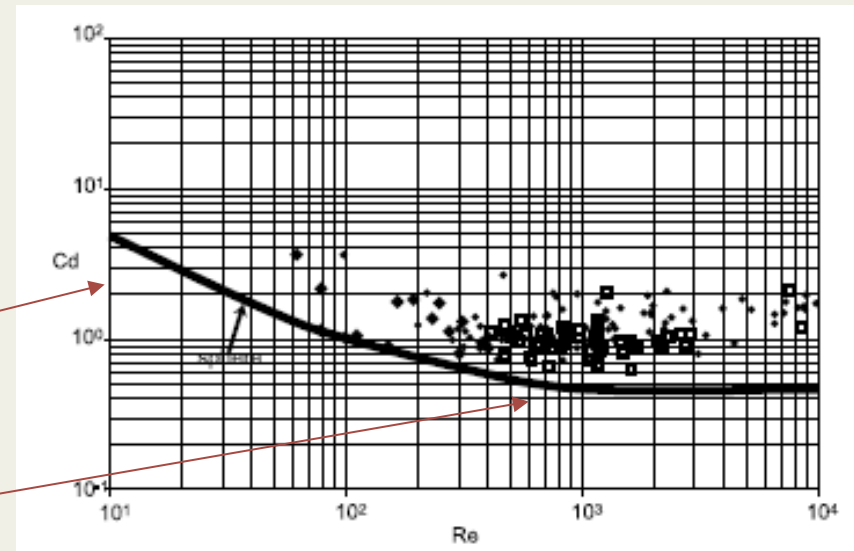
Drag coefficient

Experimental fits for non-spherical particles
[Ganser, 1993] and pumices [Dellino et al.2005]

Analytic expression
exists for spherical
particles only

$$C_D = \frac{B}{Re}, \quad B = 24$$

0.44 for spheres
1.2 for cylinders
0.8–1.05 for cubes



...but other (dry) deposition mechanisms can control sedimentation...

Actually, (dry) deposition velocity at SBL depends of different very size-dependent mechanisms:

- Brownian diffusion (aerosol nuclei mode)
- Inertial impaction (aerosol accumulation and coarse mode)
- Gravitational sedimentation. Dominates for particles > 100 μm

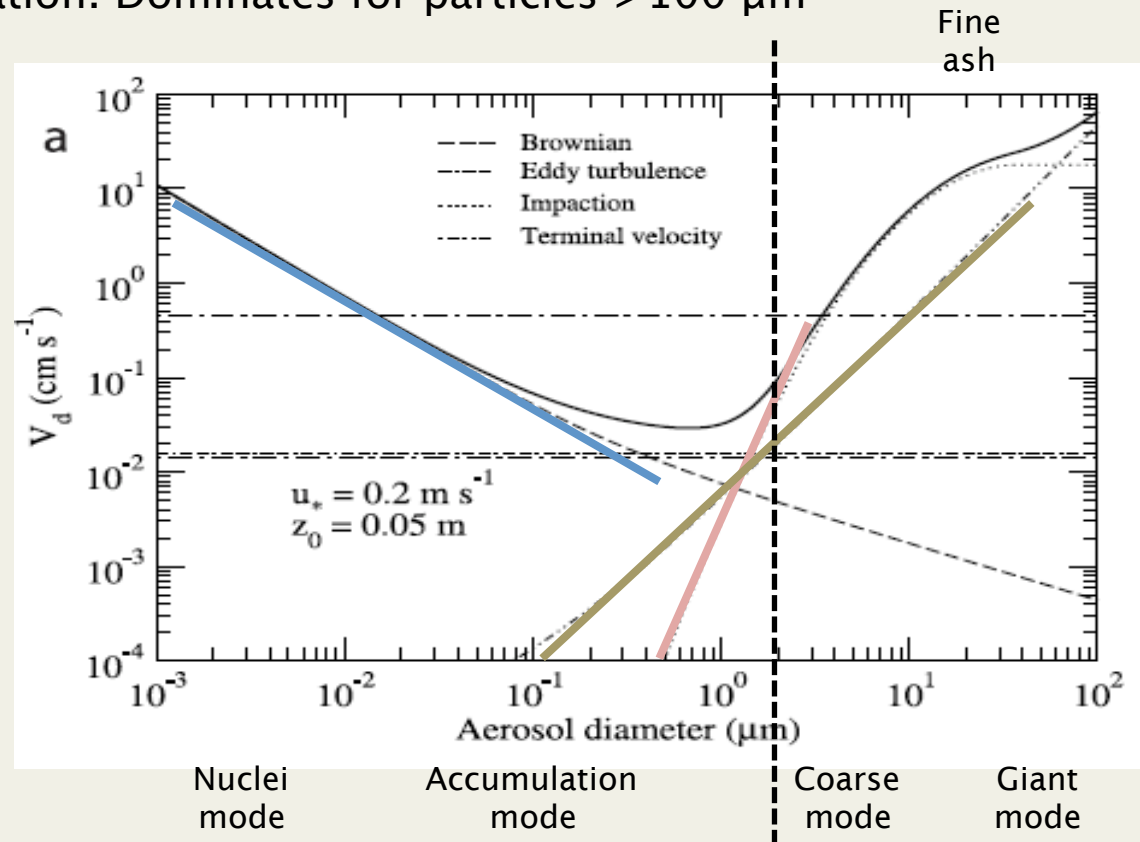
$$V_d = V_t + \frac{1}{r_a + r_s + r_a r_s V_t}$$

Brownian —

Inertial —

Gravitational —

After Feng (2007)



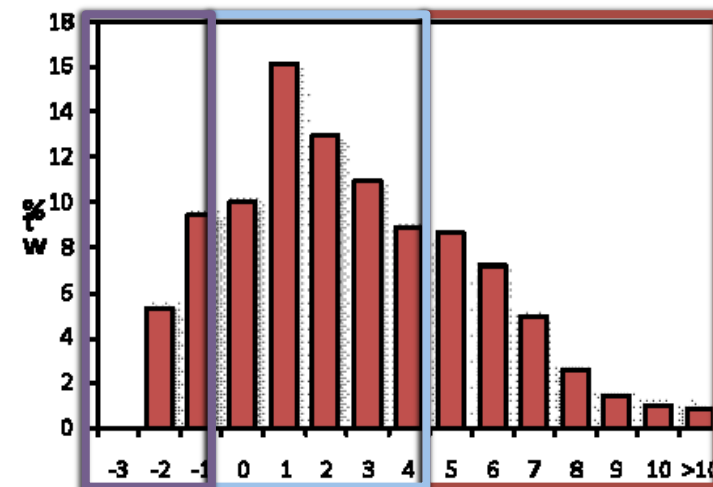
However, ATM of volcanic ash have some challenging particularities...

1. Wide particle-size spectrum



	bombs / blocks	lapilli	coarse ash	fine ash
Diameter	> 64 mm	(64 mm-2 mm)	(2 mm-64 μ m)	(<64 μ m)
Residence time	\approx sec	\approx min	\approx hours to few days	several days
Travel distance	proximal <10km	medial <50 km	distal <100 km	very distal <1000 km

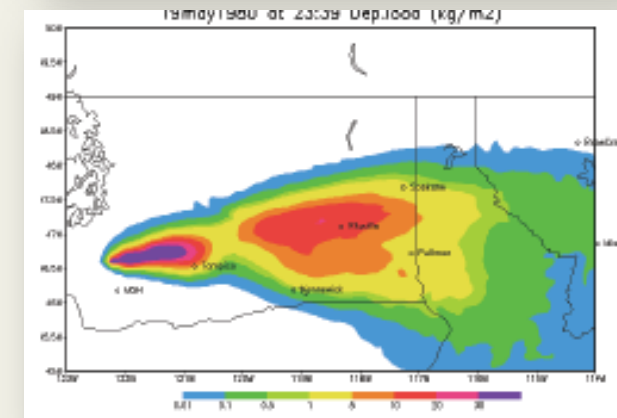
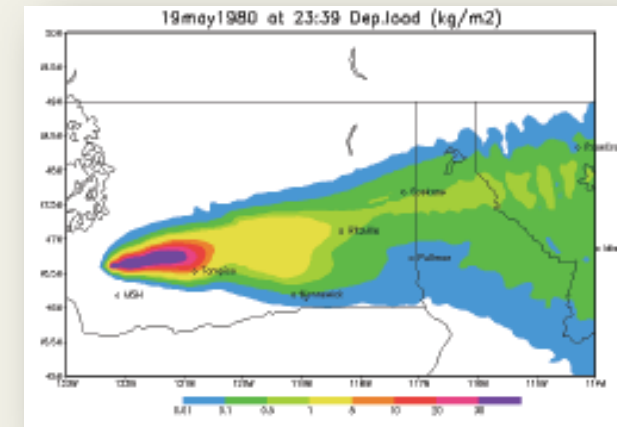
- Far-field transport involves “fine-ash” only.
- Erupted mass refers to the TOTAL mass.
- Fraction of fine ash (warning this term is often misleading or improperly used).



However, ATM of volcanic ash have some challenging particularities...

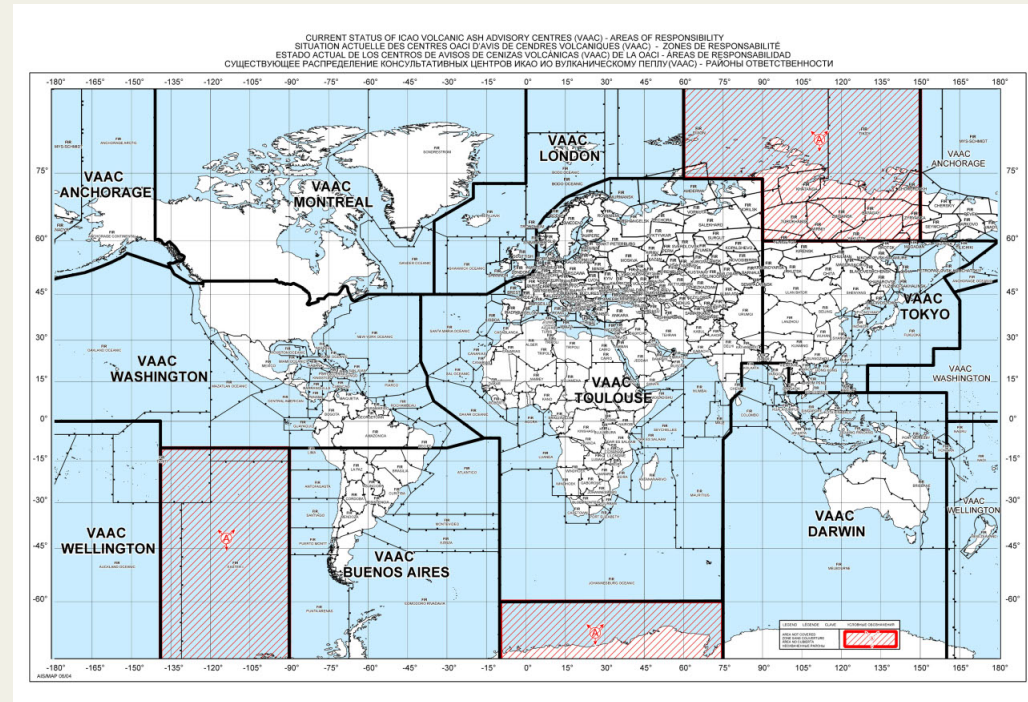
2. Fine ash often aggregates

- Premature ash cloud mass removal
- Formation of deposit and airborne concentration secondary maxima
- Aggregation is difficult to model
 - Computationally expensive
 - Lack of a comprehensive model
 - Depends on many parameters: existence of fine ash, moisture, residence time, etc.
- Difficult to discriminate if aggregation occurs in the vertical plume or in the spreading ash cloud
 - A compromise is to include aggregation in the source model rather than in the transport model
- ***The worst of aggregation is the loss of linearity in the transport equation !!***



VATDM currently operational at the 9 different VAACs

Anchorage:	PUFF HYSPLIT
Buenos Aires:	PUFF FALL3D
Darwin:	PUFF HYSPLIT
London:	NAME
Montreal:	MLDPO
Toulouse:	MOCAGE
Tokyo:	JMA model
Washington:	HYSPLIT
Wellington:	PUFF HYSPLIT



7 different models; 5 Lagrangian, 2 Eulerian

Differences between VATDM exist due to a number of reasons

	ASH3D	ATHAM	FALL3D	FLEXPART	HYSPLIT	JMA	MLDPO	MOCAGE	NAME	PUFF	TEPHRA2	VOL-CALPUFF
Operational												
Approach ⁽¹⁾	E/H	E	E	L	H	L	L	E	L	L	E	H
Method ⁽²⁾	N	N	N	N	N	N	N	N	N	N	A	S
Coverage ⁽³⁾	LRG	L	LR	LRG	LRG	G	LRG	G	LRG	LRG	L	LR
Physics												
Topography												
H wind advection												
V wind advection												
H atm. diffusion								See ⁽⁵⁾				
V atm. diffusion												
Particle sed.												
Other dry dep.												
Wet deposition												
Dry part. aggr.												
Wet part. aggr.												
Particle shape												
Gas species												
Chemic. processes												
Granulometry												
Variable size class.												
Variable GS distr.												
Variable size limits												
Source term												
Mass distribution ⁽⁴⁾	LN	O	ALL	PS/L/U/P/O	PS/L/U/P/LN	PS/L/U/P/LN	PS/L/U/LN	PS/L	PS/L/O	PS/L/U/P	L/U/LN	PS/BP

(1) L=Lagrangian, E=Eulerian, H=Hybrid

(2) A=Analytical, S=Semi-analytical, N=Numerical

(3) L=Local, R=Regional, G=Global

(4) PS=Point Source, L=Linear, U=Umbrella-type, P=Poisson, LN=Log-normal, BP=Buoyant Plume, O= Other (see Appendix).

(5) Neglected. Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5°.

What about operational forecasting?

During operational forecasting things are worst for a number of reasons...

1. VATDM source term

- Plume height measurement frequency (if any) ?
- Mass estimations (source concentration) ?

2. Granulometry

- No TGSD available at the eruption onset
- Very rare during the eruption
- “Fraction of fine ash” becomes in practice a mere “model tuning factor”

3. NWPM forecasts

- Vertical resolution decreases at high atmospheric levels
- Wet deposition and wet aggregation models

4. VATDM grid resolution

- Limited by operational requirements (e.g. deliver frequency)

The aftermath of the Eyjafjallajökull eruption: Implications for VATDM forecast

- To assess the source term in VATDM is crucial
 - In a “zero-tolerance” context the most important is the column height.
 - In the new context, a good estimation of the mass flow rate and vertical distribution of mass becomes essential.

- It is difficult (if not impossible) for current models to forecast concentrations of few mg/m^3 due to a number of reasons:
 - Inherent difficulty of the physical processes involved.
 - Insufficient definition of inputs (especially the volcanological).
 - Inherent uncertainty and transient behaviour of the eruptive phenomenon.

A fully deterministic approach will always find the limit of uncertainty

Cutting-edge scientific/operational aspects of VATDM

1. Model physics

- a) Theoretical modelling of plume dynamics, especially for the case of weak plumes
- b) Theoretical and experimental modelling of aggregation processes
- c) Experimental determination of terminal settling velocities of volcanic particles

2. Data assimilation: coupling models and monitoring

- Operational models run with pre-defined volcanological inputs and data from measurements is eventually incorporated (if available)
- Future advances in models should use near and far-source measurements
 - Characterize the source term
 - Infer some characteristics of the source term (e.g. injection height) through inverse modelling (e.g. FLEXPART inversion strategy at NILU)
 - Give an initial condition to models based on quantitative satellite retrievals (forecast initialization)

Cutting-edge scientific/operational aspects of VATDM

3. Develop of ensemble forecast techniques for VATDM

- a) Ensemble of multiple runs of a single model (each set of ESP is an ensemble member)
- b) Ensemble of multiple runs of different VATDM models
- c) The output could be deterministic (but with associated uncertainty)

4. Develop probabilistic forecast techniques for VATDM

- a) Produce range of probability by stochastically sampling probability density functions (PDFs) of input parameters

5. Implementation of techniques to improve numerical accuracy and performance of VATDM

- a) Strategies based on ensemble different models and scenarios imply an increase of the computational cost
- b) Adapt models to run in HPC or to use acceleration techniques (e.g. GPGPU)

CONCLUSIONS

1. Modelling atmospheric transport of volcanic ash is challenging because

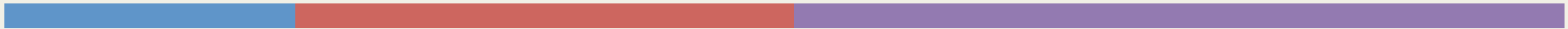
- Source term is complex and highly unsteady and uncertain
- Particle properties may vary with time and cover a wide size-range
- Aggregation phenomena

2. Models today...

- Best models can compute (in re-analysis) far-field concentrations within a factor 2-3 at most.
- In operational mode (forecast) models can capture the order of magnitude only
- Problem is actually not models themselves, but our incapacity to “feed” them

3. Models tomorrow...

- Forecasts will likely improve when using data assimilation
- However, some uncertainty will always remain
 - **End-users need to assume a probabilistic forecast output**



Questions?