`bent`: A model of plumes in crossflow

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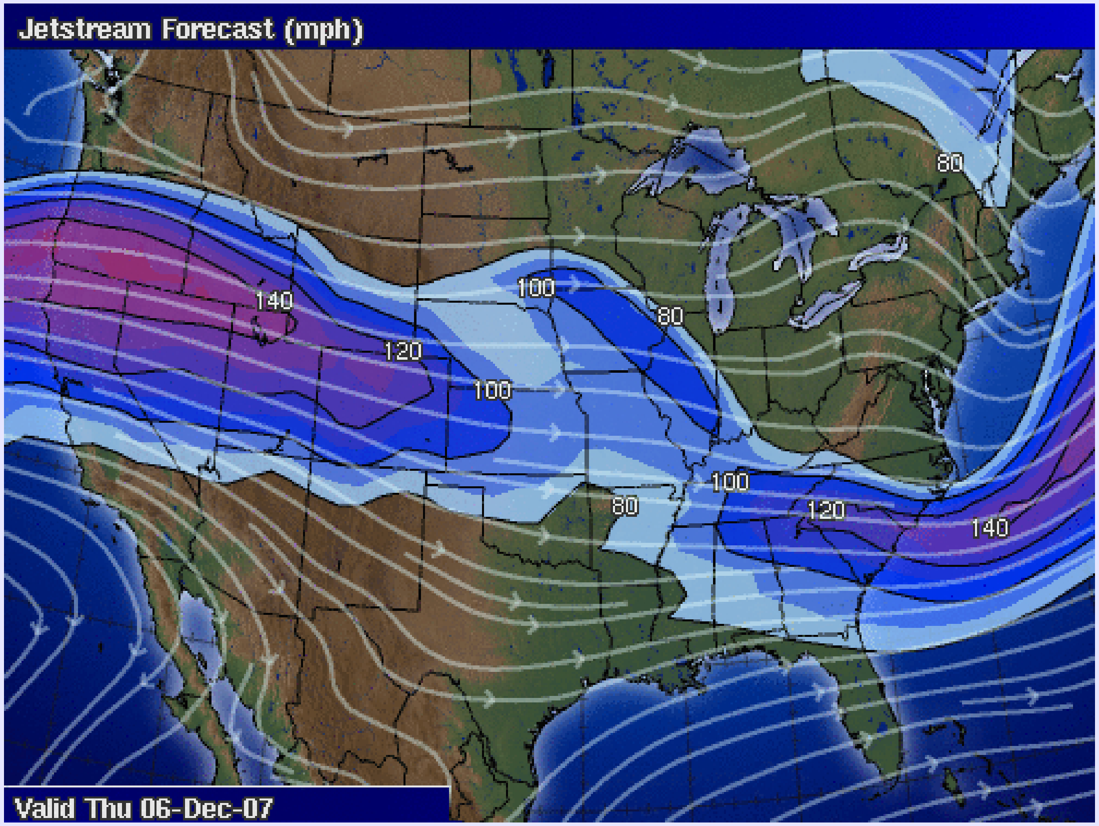
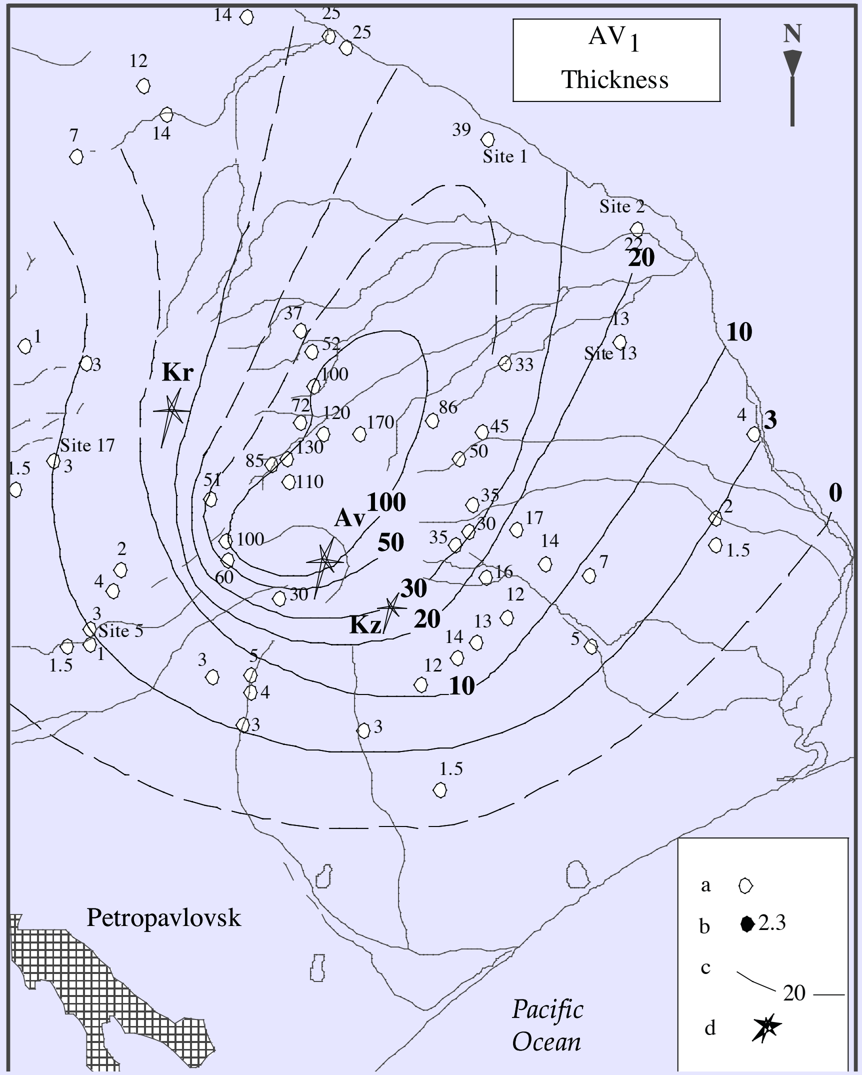
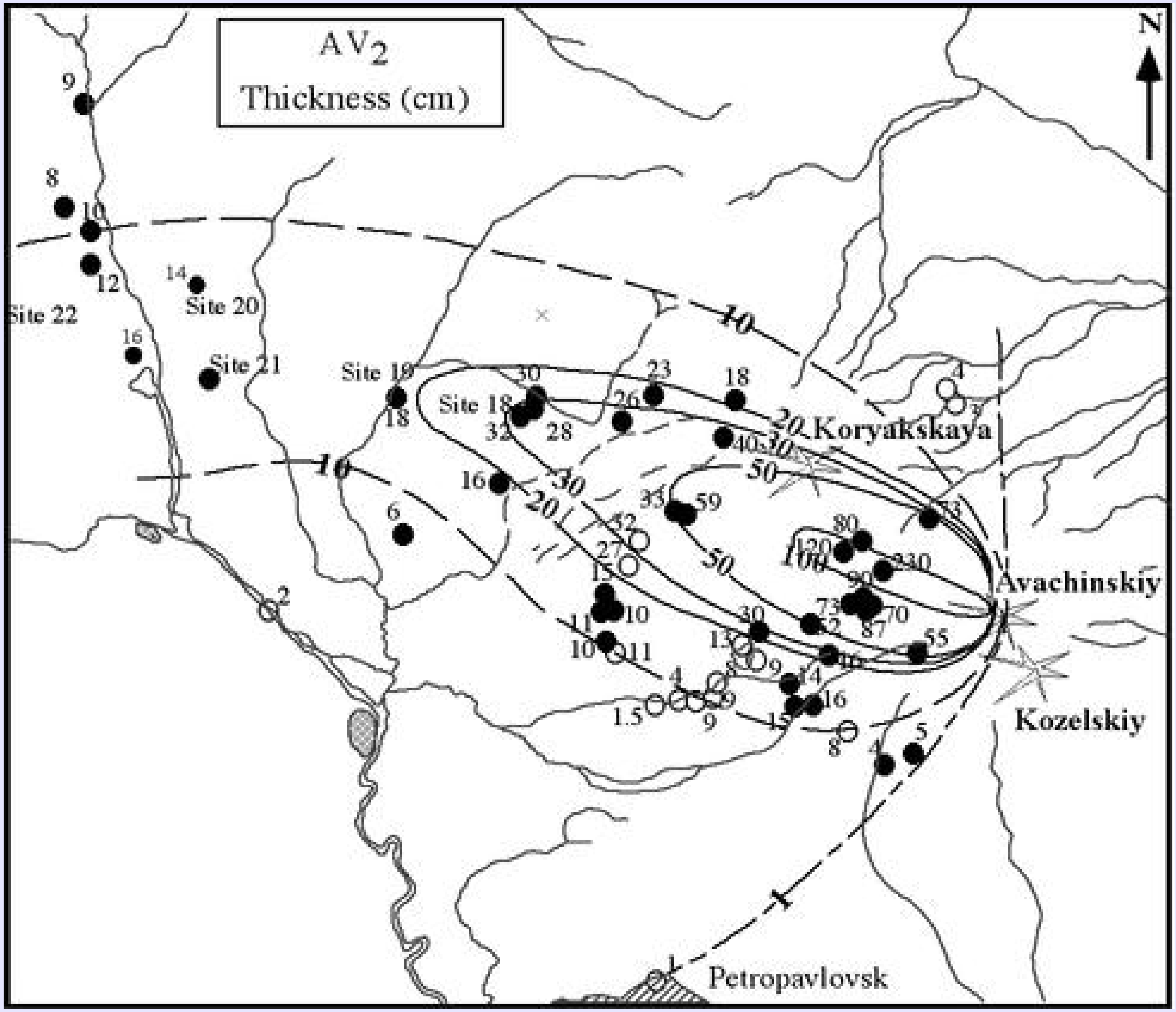
Introduction: Jetstream



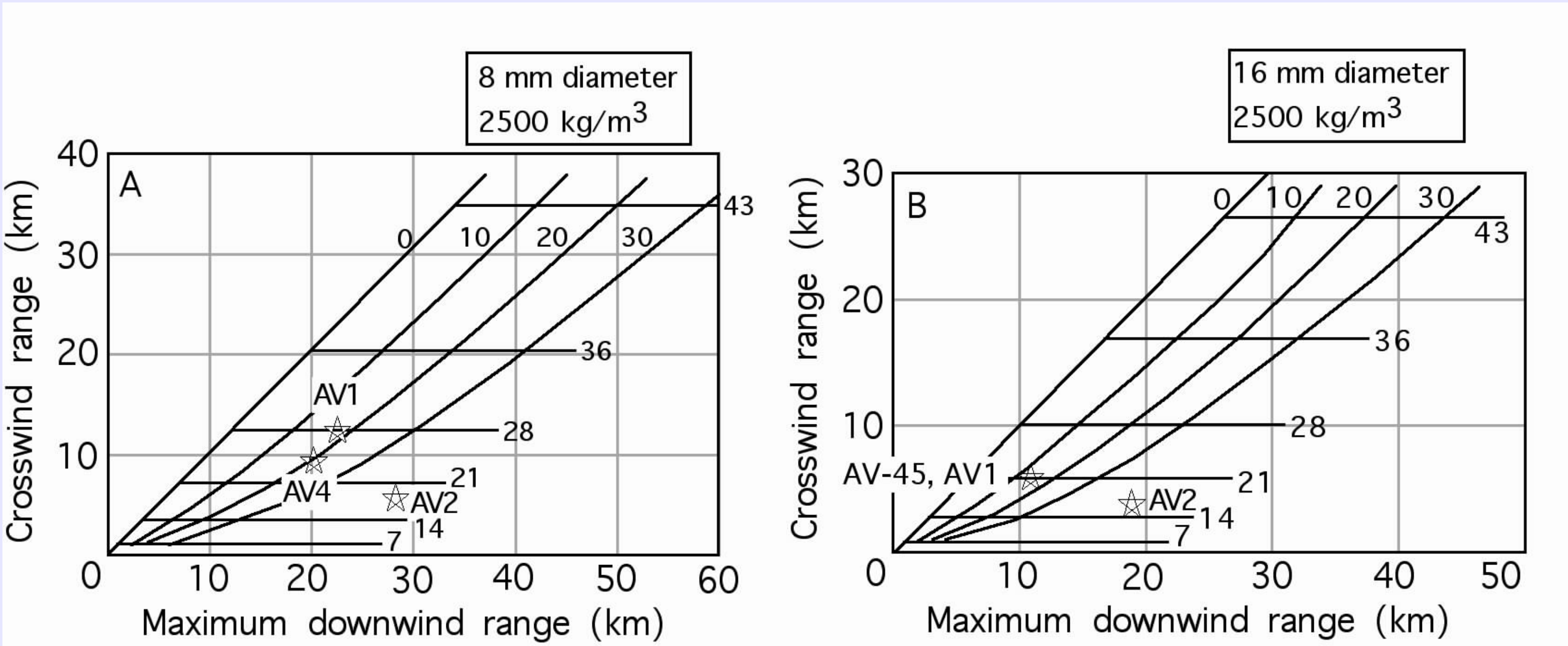
Polar jets or jetstreams are regions of high [eastbound] winds that span the globe from 30 to 60 degrees in latitude, centered at an altitude of about 10 km. They can be hundreds of kilometers wide, but as little as 1 km in thickness. Core windspeeds are up to 130 m/s. Modern transcontinental and transoceanic air routes are configured to take advantage of the jetstream, saving both time and fuel.

Observation: elongated isopachs


AV1 Thickness
N
Kr
Av
Kz
Site 1
Site 2
Site 13
Site 17
Site 5
Petropavlovsk
Pacific Ocean
a
b 2.3
c 20
d

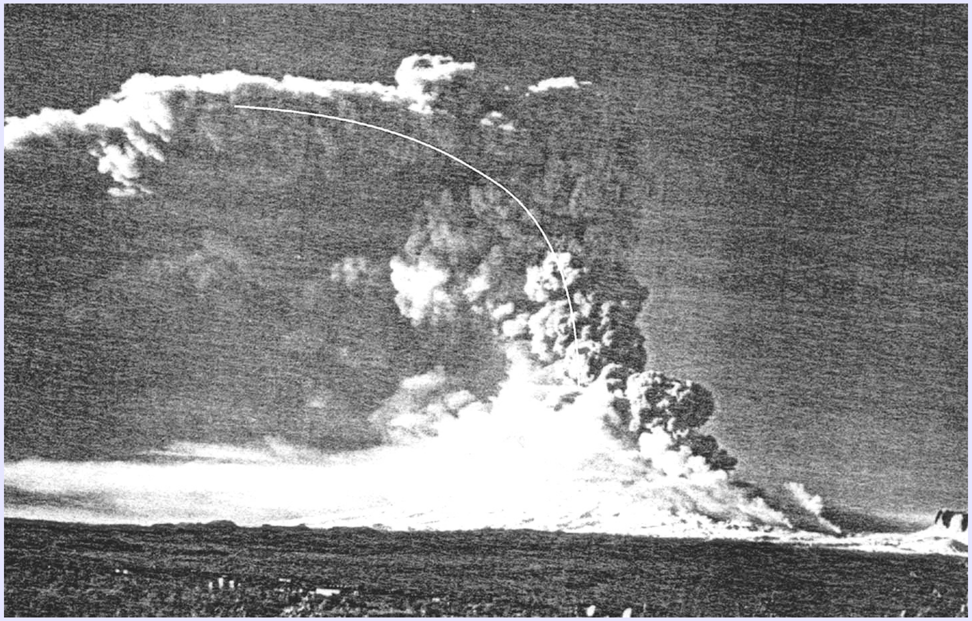

AV2
Thickness (cm)
N
Site 22
Site 20
Site 21
Site 19
Site 18
Koryakskaya
Avachinskiy
Kozelskiy
Petropavlovsk

Observation: anomalous dispersal



Clast dispersal data do not plot well on the nomograms from Carey and Sparks (1986)

Working hypotheses



– Plumes entering low polar jet entrain unusual amount of air mass as well as horizontal momentum as suggested in the photo of the Sept 30/Oct 1, 1994, eruption of Kliuchevskoy, Kamchatka, Russia
– The result will be lowering of column height because of entrainment, and anomalous dispersal of clasts from column
– **The numerical model used to test these hypotheses:** `bent`

BENT: coordinate system

`bent` is a trajectory model, calculated in a plume centered coordinate system

$$z = \int \sin\vartheta ds \quad (1)$$

and,

$$x = \int \cos\vartheta ds \quad (2)$$

$$U_\epsilon = \alpha|U - V\cos\vartheta| + \beta|V\sin\vartheta| \quad (3)$$

where $\alpha|U - V\cos\vartheta|$ is entrainment by radial inflow minus the amount swept tangentially along the plume margin by the wind, and $\beta|V\sin\vartheta|$ is entrainment from wind; α is the radial entrainment parameter, and β the wind-entrainment parameter.

Equations of motion

$$\frac{d}{ds}\left(\pi b^2 \rho U\right) = 2\pi \rho_a b U_\epsilon + \sum_{i=1}^{N} \frac{dM_i}{ds} \tag{4}$$

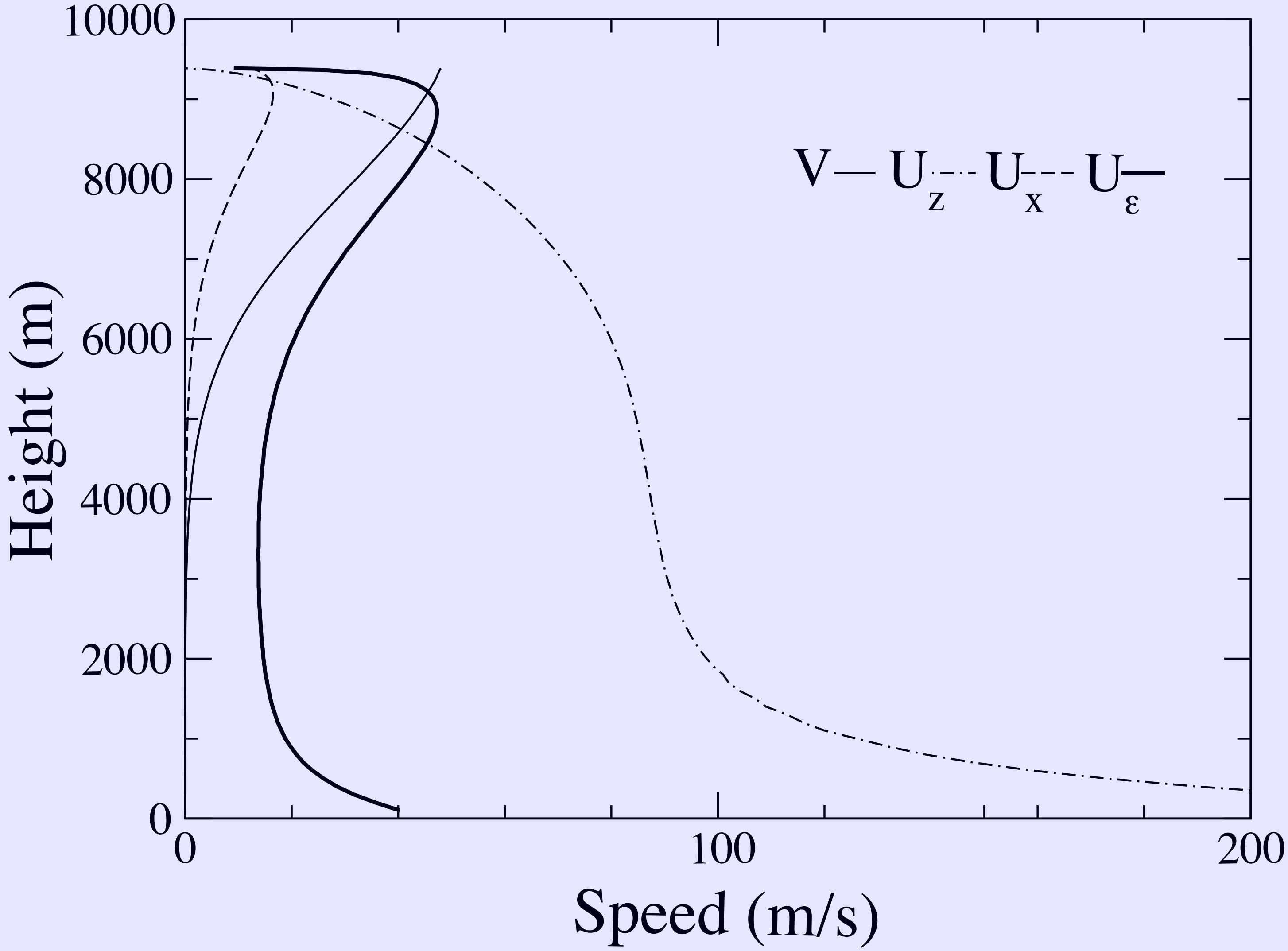
$$\frac{d}{ds}\left(\pi b^2 \rho U^2\right) = \pi b^2 \Delta\rho g \sin\vartheta + V \cos\vartheta \frac{d}{ds}\left(\pi b^2 \rho U\right) + U \sum_{i=1}^{N} \frac{dM_i}{ds} \tag{5}$$

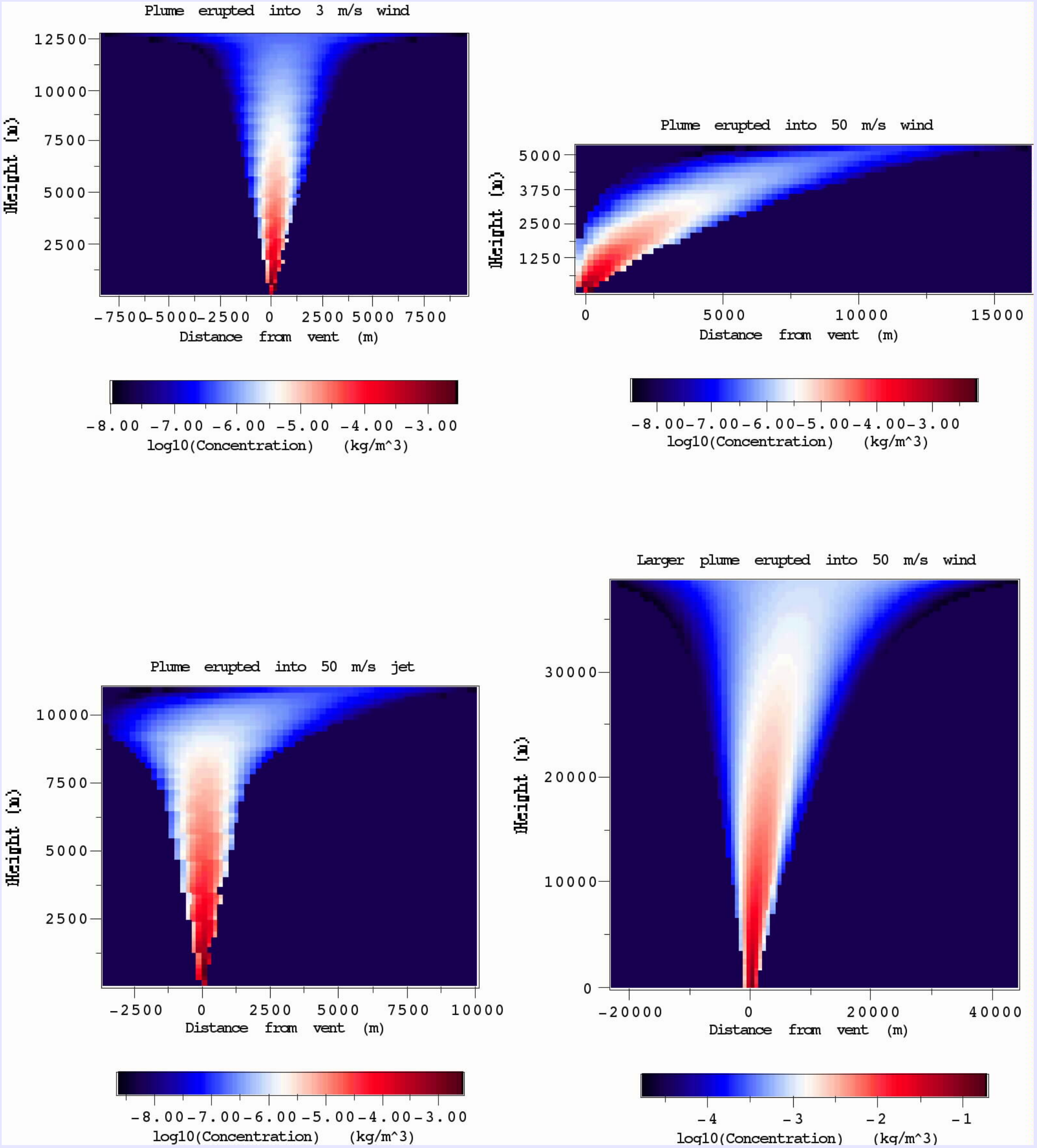
$$\left(\pi b^2 \rho U^2\right) \frac{d\vartheta}{ds} = \pi b^2 \Delta\rho g \cos\vartheta - V \sin\vartheta \frac{d}{ds}\left(\pi b^2 \rho U\right) \tag{6}$$

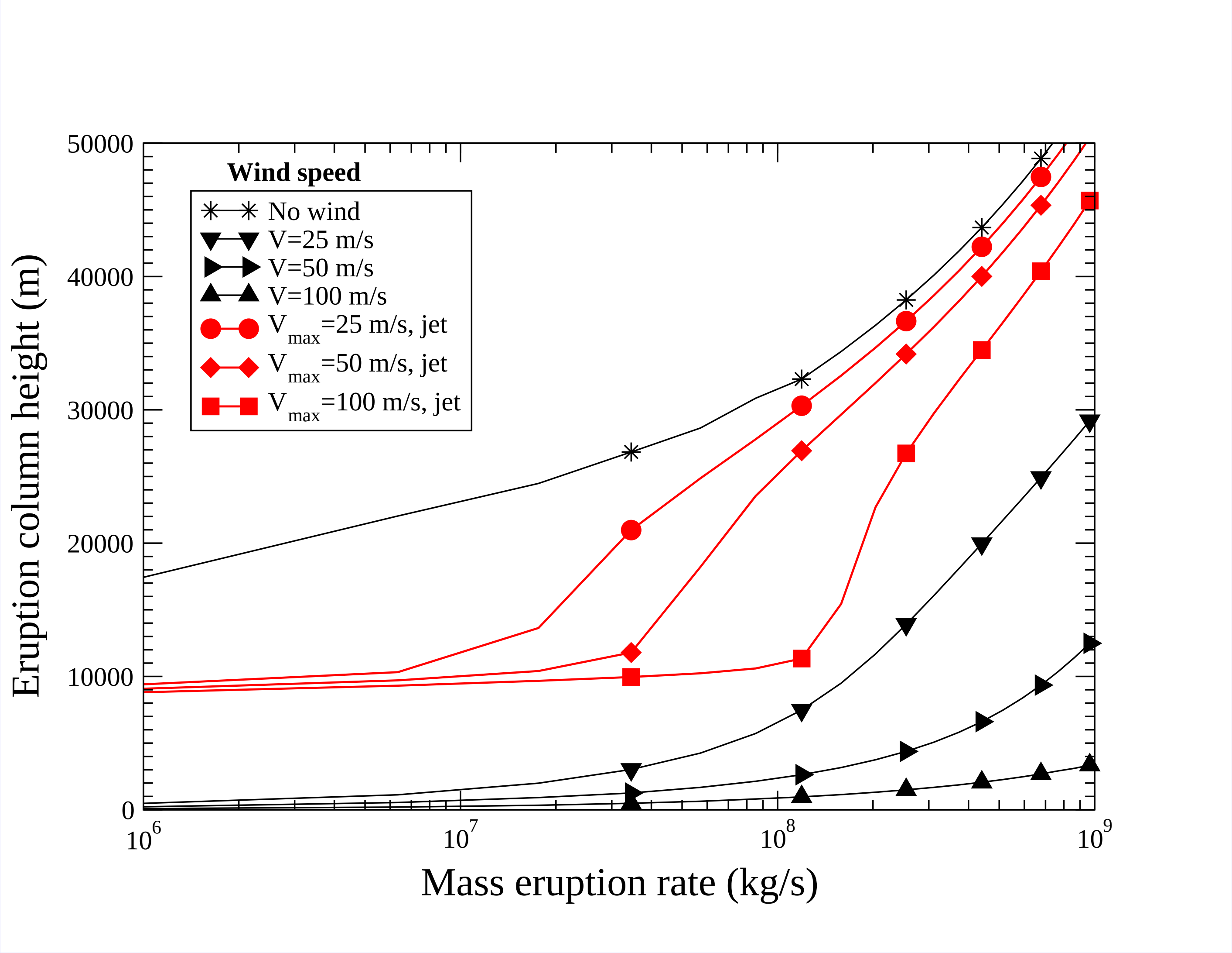
$$\frac{d}{ds}\left(\pi b^2 \rho U C_v T\right) = 2\pi b U_\epsilon \rho_a C_a T_a - \pi b^2 U g \sin\vartheta + C_p T \sum_{i=1}^{N} \frac{dM_i}{ds} \tag{7}$$

$$\frac{dM_i}{ds} = -\frac{p}{bU}\left(w_s - \frac{f U_\epsilon}{db/ds}\right) M_i \tag{8}$$

Discussion: wind entrainment causes plume bending and lowering of height

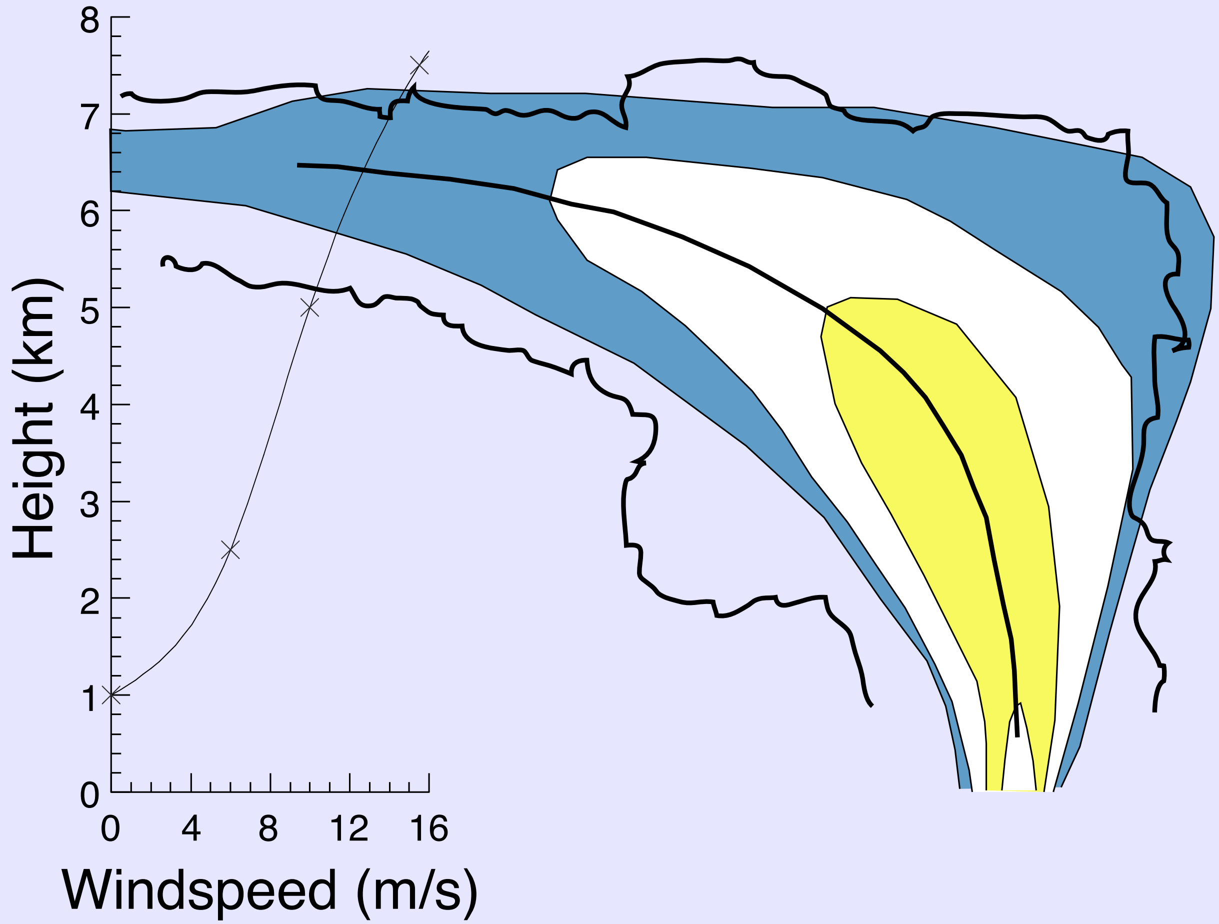



Plume erupted into 3 m/s wind
Height (m)
Distance from vent (m)
log10(Concentration) (kg/m^3)
Plume erupted into 50 m/s wind
Height (m)
Distance from vent (m)
log10(Concentration) (kg/m^3)
Plume erupted into 50 m/s jet
Height (m)
Distance from vent (m)
log10(Concentration) (kg/m^3)
Larger plume erupted into 50 m/s wind
Height (m)
Distance from vent (m)
log10(Concentration) (kg/m^3)



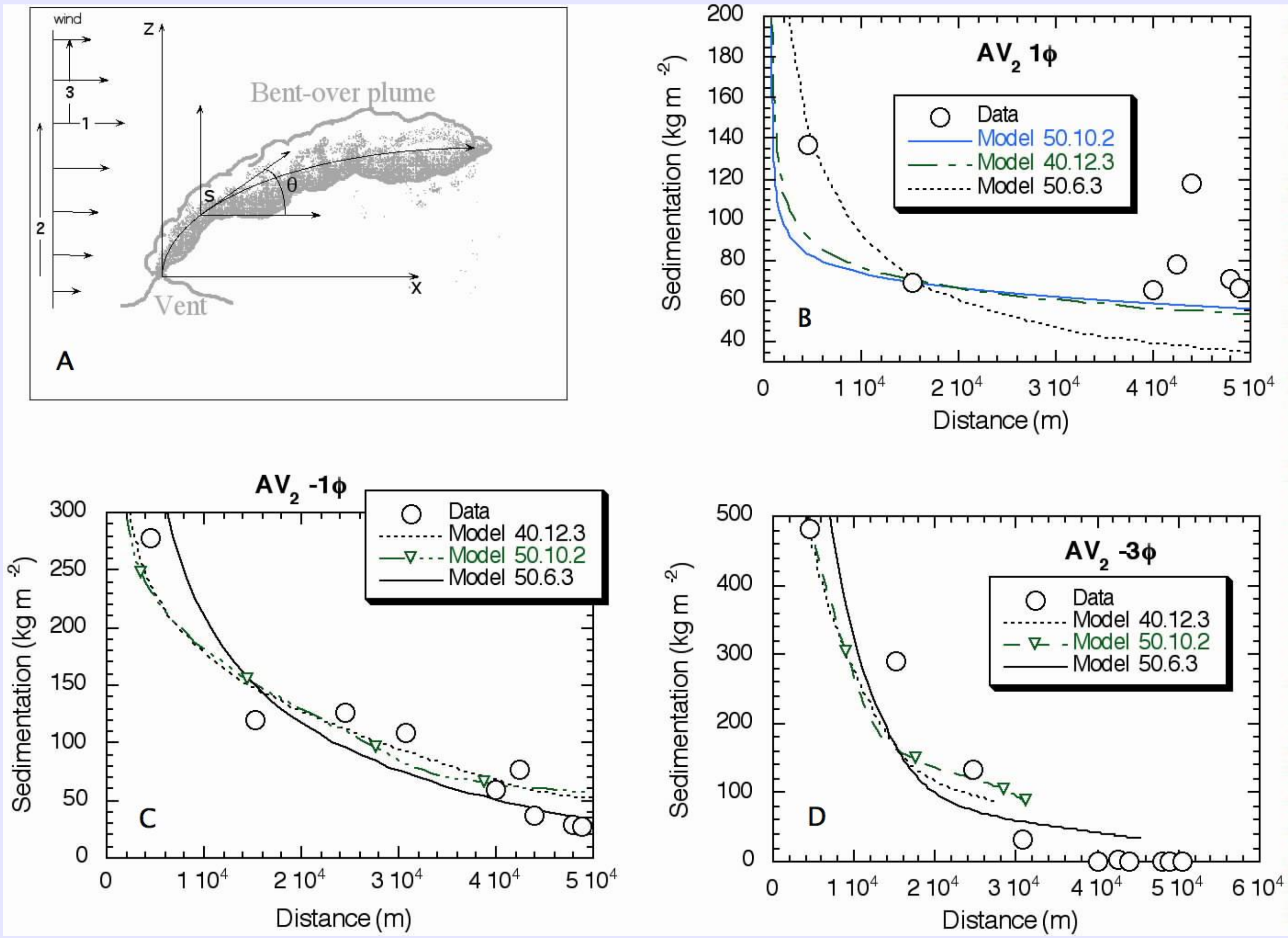
The numerical experiments suggest that over a wide range of mass eruption rates, from $\sim 10^6$ to $\sim 10^8$ kg/s, plumes rise between 9 and 11 km. In a still atmosphere, the rise height over this range of mass eruption rate increases from 17 to 33 km.

`bent` fit to Kliuchevskoy plume data



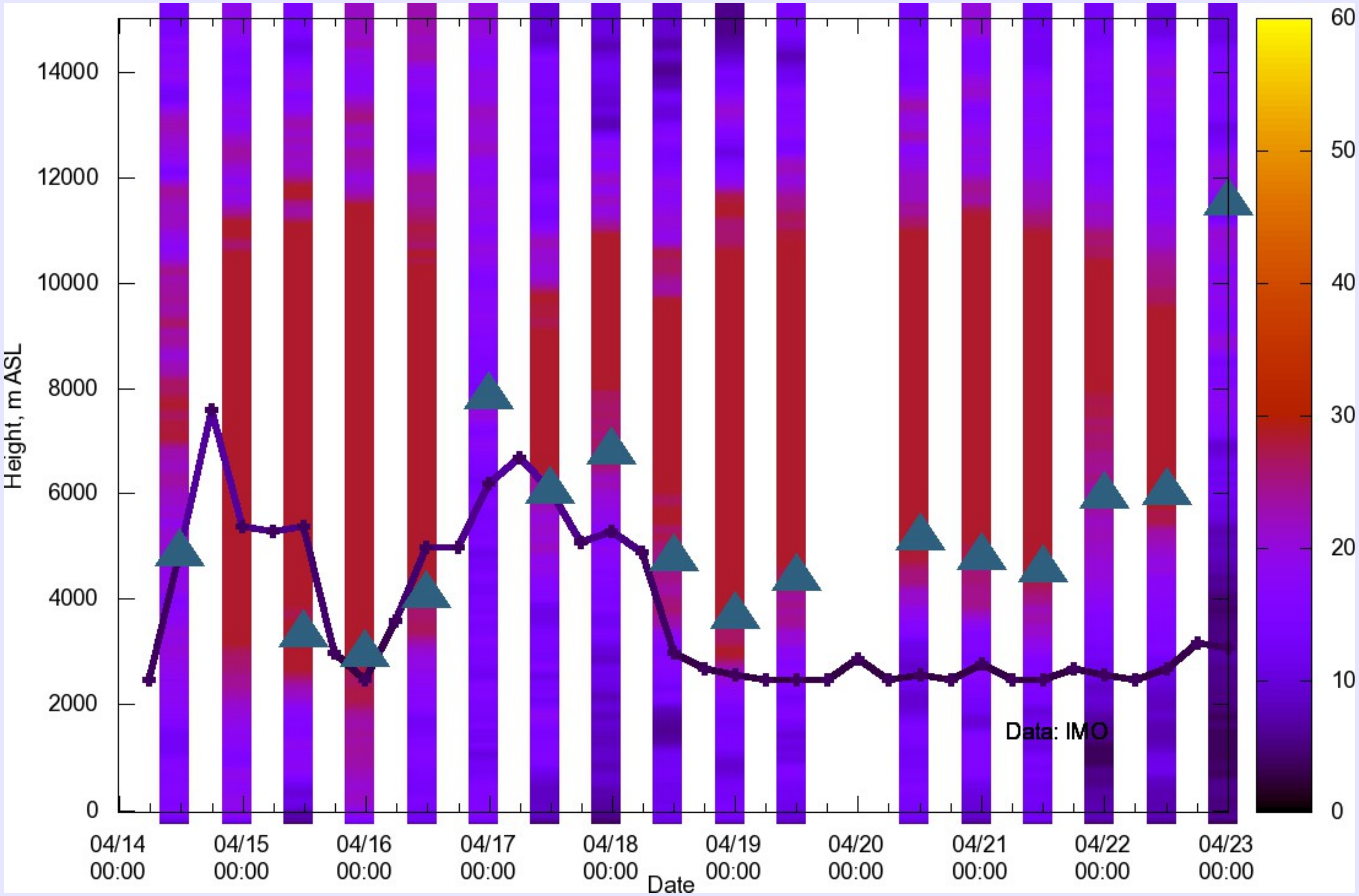
Model trajectories compare well with observed for the 1994 Kliuchevskoy eruption . . .

`bent` fit to Avachinskiy fall data



Tephra fall patterns for AV$_2$ although anomolously elongated, are modeled well by `bent`

`bent` fit to Eyjafjallajökull data



Calculated and observed H_T for Eyja. Model MER was held constant at 5×10^6 kg/s, so the variation in model height is caused only by wind.

Conclusions

– Presence of jet causes anomalously low plume height at a given eruption rate
– Jet causes anomalously distal deposition of tephra from column
– Estimates of mass eruption rate may be in considerable error in cases of high wind speed
– Changes in wind speed can alter plume height, with no changes in eruption strength at the vent
– Thus, eruptions with highly variable mass eruption rate pump volcanic particles into the jetstream, making it difficult to characterize the maximum size, grain size distribution and mass loading
– By taking advantage of the jetstream, aircraft are flying within an airspace that is preferentially occupied by volcanic eruption clouds and particles

References

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Carey, S. and Sparks, S., 1986, Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns, Bull. Volc. 48, 109-125.