An umbrella cloud model to explain thickness and grain size variation in tephra deposits: Pululagua (Ecuador)

Robert Constantinescu[1]

[1]University of South Florida, School of Geosciences

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Abstract

Tephra fallout hazard assessment relies on accurate reconstruction of eruption source parameters (ESPs) from tephra deposits. Models of tephra transport and sedimentation from a volcanic plume use ESPs (e.g. erupted mass, column height, mass eruption rate, total grain size distribution) that characterize the processes and the properties of the plume, particles and the atmosphere. We use Tephra2, an Eulerian model of tephra dispersion that simplifies atmospheric dynamics to reconstruct ESPs from mapped deposits. Tephra2 works well in reconstructing ESPs for some deposits, however it does not account for the geometry (i.e. shape) of umbrella clouds of large explosive eruptions. Since the accumulation of particles on the ground is calculated with respect to their release point in the atmosphere, we hypothesize that a modification of Tephra2 that accounts for umbrella clouds would better explain the deposit variations observed in the field associated with some large eruptions. We developed a Python version of Tephra2 that uses the advection – diffusion equation to calculate the mass accumulation of tephra released from an umbrella cloud. We tested three different geometries (i.e. point, vertical line and horizontal disk) against field data from the deposit of the 2450 BP Pululagua (Ecuador) eruption that occurred in absence of wind. Our preliminary results indicate three important aspects of tephra modeling: i) a disk geometry characterizing an umbrella cloud fits the data better than the line and point sources, the last two being highly sensitive to the atmospheric diffusion coefficient; ii) a disk geometry is sensitive to the volume of tephra and the radius of the disk and, iii) different discretization of disk geometries show little sensitivity in deposit geometry with change in the release height, suggesting that disk radius is a more sensitive parameter in modeling large umbrella clouds than the release point or release height. Since large explosive eruptions are characterized by large laterally spreading umbrella clouds even when advected by wind and the umbrella diameter is controlled by eruption rate, as is plume height in vertical plumes,, we suggest the modeling of large deposits with alternative models of the cloud geometries is an important step in analysis of ESPs associated with mapped deposits.

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R. Constantinescu[1], A. Hopulele-Gligor[2], L. Connor[1], C. Connor[1], C. Bonadonna[3], A. Volentik[4], S. Charbonnier[1], J. M. Lindsay[5]

The model

Hypothesis

- tephra transport and sedimentation models use ESPs (e.g. total mass, column height, MDR, TGSD) to characterize the processes and the properties of the plume, particles and the atmosphere;
- the accumulation of particles on the ground is calculated with respect to their release point in the atmosphere and most models, like Tephra2, work well with sub-vertical plumes but do not account for the geometry of large umbrella clouds;
- we developed a Python version of Tephra2 that uses the advection – diffusion equation to calculate the mass accumulation of tephra released from an umbrella cloud;

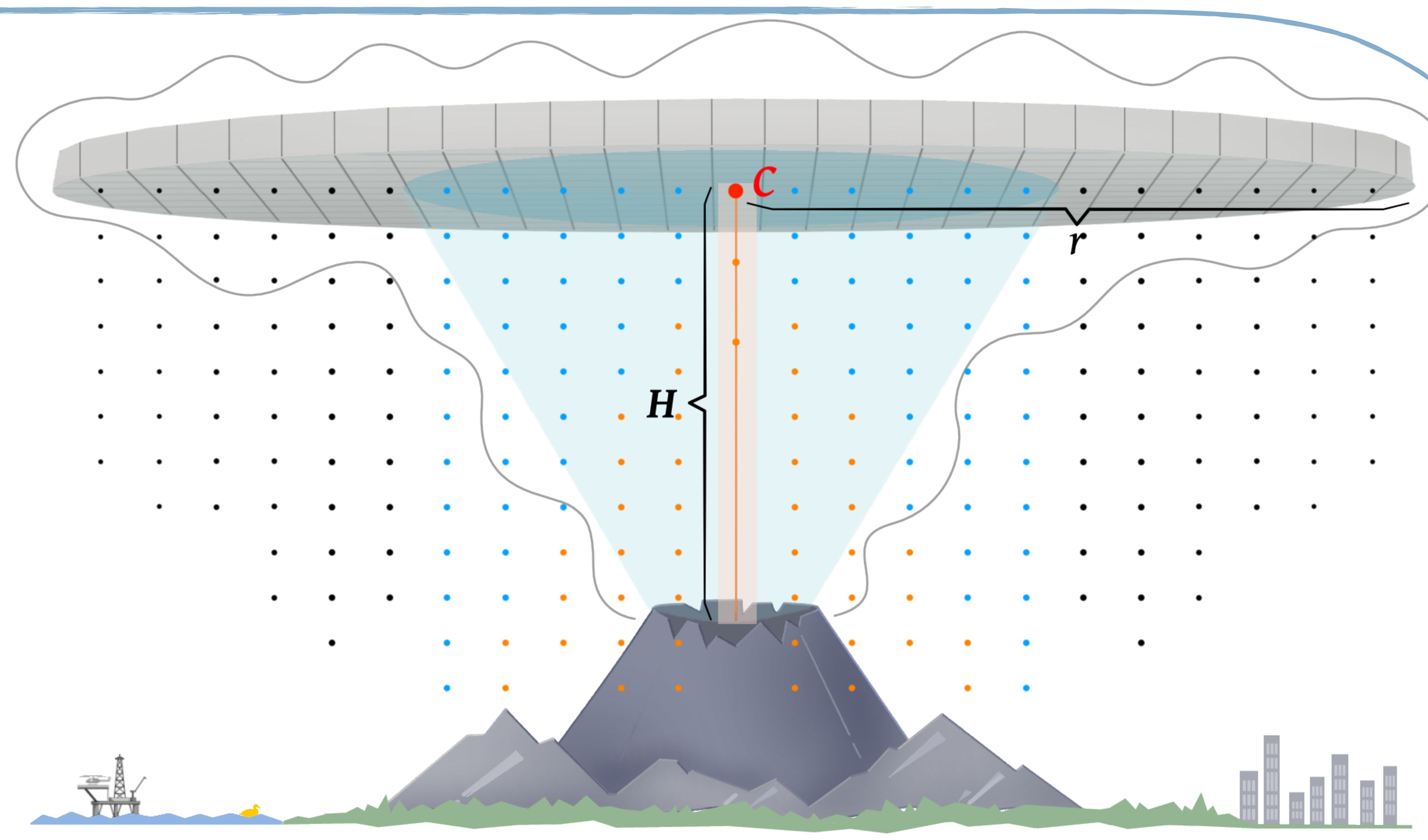

Figure 1. Schematic representation of an umbrella cloud emplaced during large explosive eruptions. Four source geometries used in tephra sedimentation models are represented: - i) a point source marked C; ii) a line source represented as a series of stacked points atop the volcano marked with orange (upper 20% of the column); iii) a reversed cone source as used by Tephra2 code representing a sub-vertical plume with blue; and iv) a disk source representing an umbrella cloud. The disk is discretized in grid cells of equal mass. Column height (*H*) might reach up to 40km and the radius (*r*) up to ~400 - 500 km (e.g. Pinatubo).

The pyTephra2 pseudocode

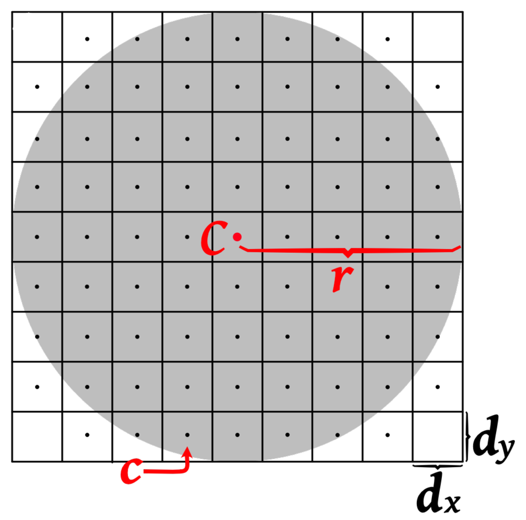

Figure 2. Discretization of umbrella cloud grid. C is the center of the disk located at (X_vent, Y_vent). c is the center of the grid cell *i* and *r* is the radius. m_{ci} is the mass released from each grid cell i.

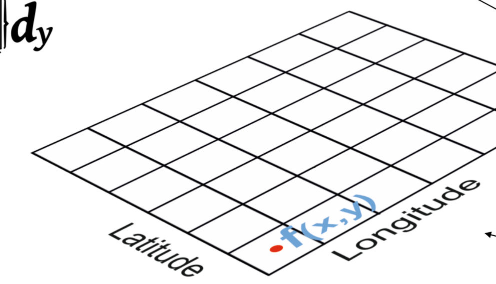

Figure 3. Ground grid to calculate tephra load.

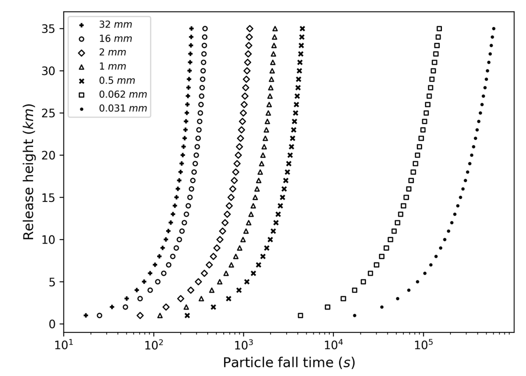

Figure 4. Total particle fall time depends on release height (*H*) and settling velocity (*S*). *S* depends on grain size (*phi*) and density (ϱ). Particles were assumed spherical and drag is dependent on flow regime (Bonadonna et al., 1998).

$$f_{i,j}(x,y) = \frac{Sm_{c_i}}{4\pi HK}\exp\left[-\frac{\left(x-\left(X_0+\frac{uH}{S}\right)\right)^2-(y-Y_0)^2}{4K\frac{H}{S}}\right]$$

$$M(x,y) = \sum_{C=1}^{C_{max}}\sum_{\phi_{min}}^{\phi_{max}} f_{i,j}(x,y)$$

Begin: The model inputs

Specify the map boundaries and the vent location

Specify the constants for calculations: *column height (H), particle density (ϱ), diffusion coefficient (K), atmospheric properties, gravitational constant (g); disk radius, total erupted mass, TGSD* μ, σ

Specify simulated *phi ()* classes: e.g. *[-6, ..., 6]* or *[x] for a specific phi class*

Internal variables

Generate umbrella disk grid: C(*X_vent, Y_vent*), *step (dx, dy), radius (R)*

Generate ground grid to calculate tephra load: Longitude, Latitude (*x_max, x_min, y_max, y_min*)

Calculate phi mass fraction, particle density and settling velocity (S) for each *phi* class

Loop: Do for each grid location *(x, y)*

a) Initialize mass accumulation:*tephra_load* = 0

b) For each phi in phi classes *[-6, ..., 6]*

c) Initialize variable for the mass of each phi classes

d) For each disk cell

e) Calculate tephra load: - advection - diffusion equation

f) Integrate tephra load across all phi classes

g) Integrate tephra load across all grid locations

h) write output file: *x, y,* $f_{i,j(x,y)}$

End: Output: total tephra load at *f(x, y)*

Pululagua eruptive history and the 2450 B.P. eruption

Background info

- Dacitic caldera in the Northern Volcanic Zone of the Andean chain, 15km North of Quito (Ecuador).
- At least ten explosive eruptions preceded the caldera forming event in 2450 B.P.

The 2450B.P. event

- The caldera forming eruption was of dacitic composition with estimated DRE volume of 5-6 km^3.
- Eruption occurred in no-wind conditions(e.g. Papale and Rosi, 1993; Volentik et al., 2010).
- The eruption started with a series of small phreatomagmatic eruptions (BGA) continued by the initiation of the Plinian explosion (BF1). The **climactic phase (BF2)** deposited ~4.5 x 10^{11}kg of tephra and had a ~27-29 km column height (i.e. estimated using inversion techniques with Tephra2 (Volentik et al., 2010)). The climactic phase fallout was followed by a thinner deposit (BF3) and a fine white-ash (WA) marking the end of the eruption.
- Here we model, using the new umbrella cloud model (pyTephra2), the climatic phase deposit (i.e BF2) using the total erupted mass and column height from Volentik et al. (2010).

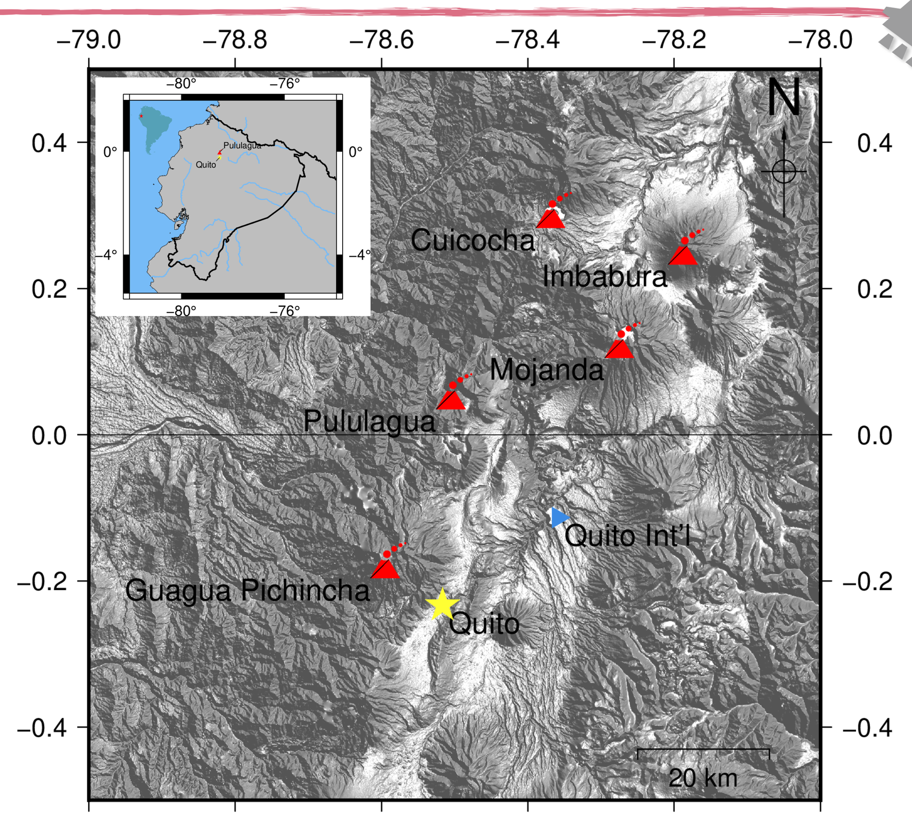

Figure 5. Location map of Pululagua volcano and the near-by volcanos. The capital Quito and the international airport are highlighted. Inset: - location of the enhanced area in Ecuador.

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Question: *can we improve tephra models to explain variation in grain size by modeling the umbrella region?* This means modeling all grain sizes with constant disk radius(*r*), constant column height (*H*) and constant diffusion (*K*).

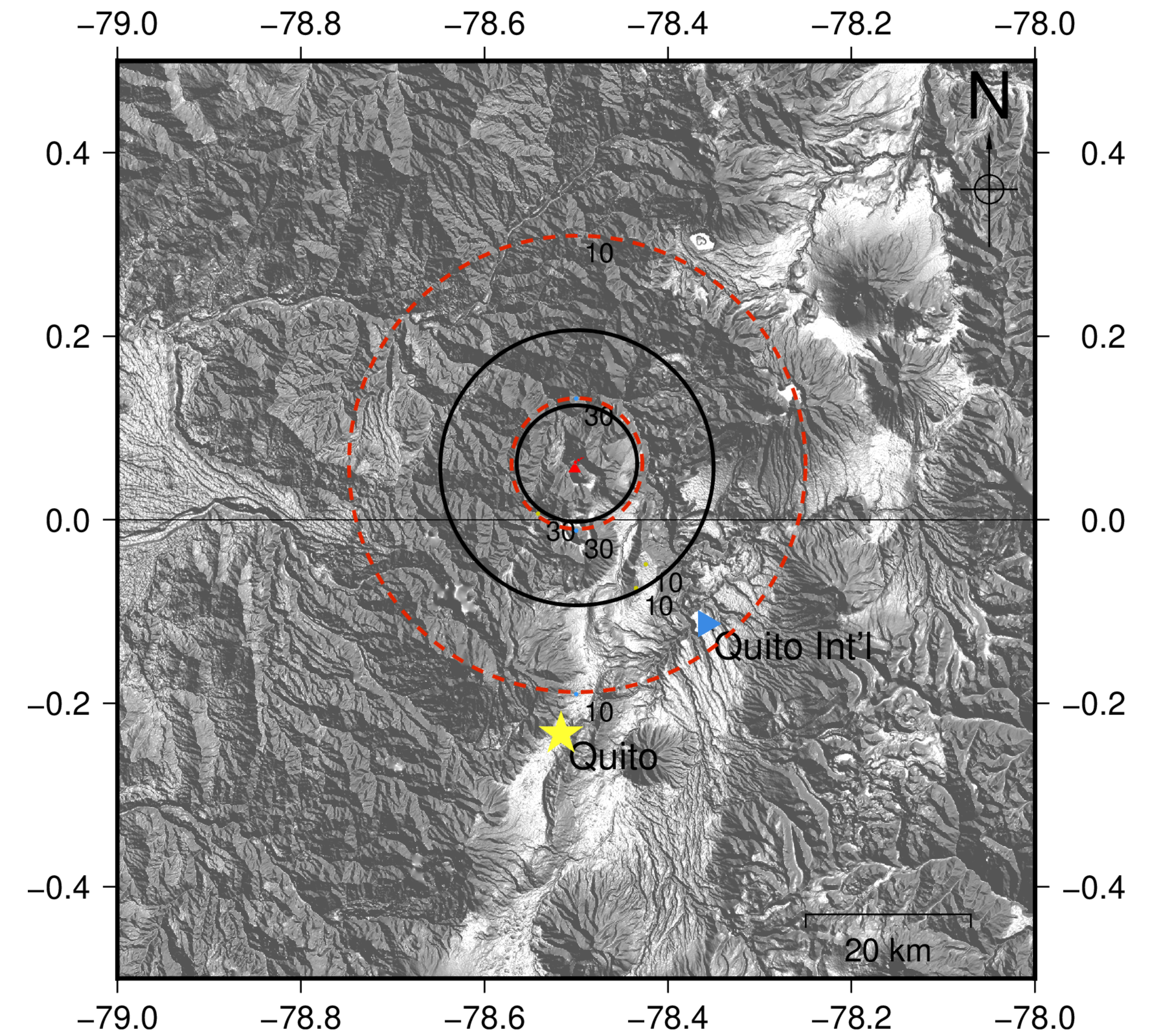

Figure 6. Isopach map for 30cm and 10cm thickness. Black lines represent isopachs as calculated with pyTephra2 umbrella cloud model and the red dotted line represent isopach lines as inferred from field data.

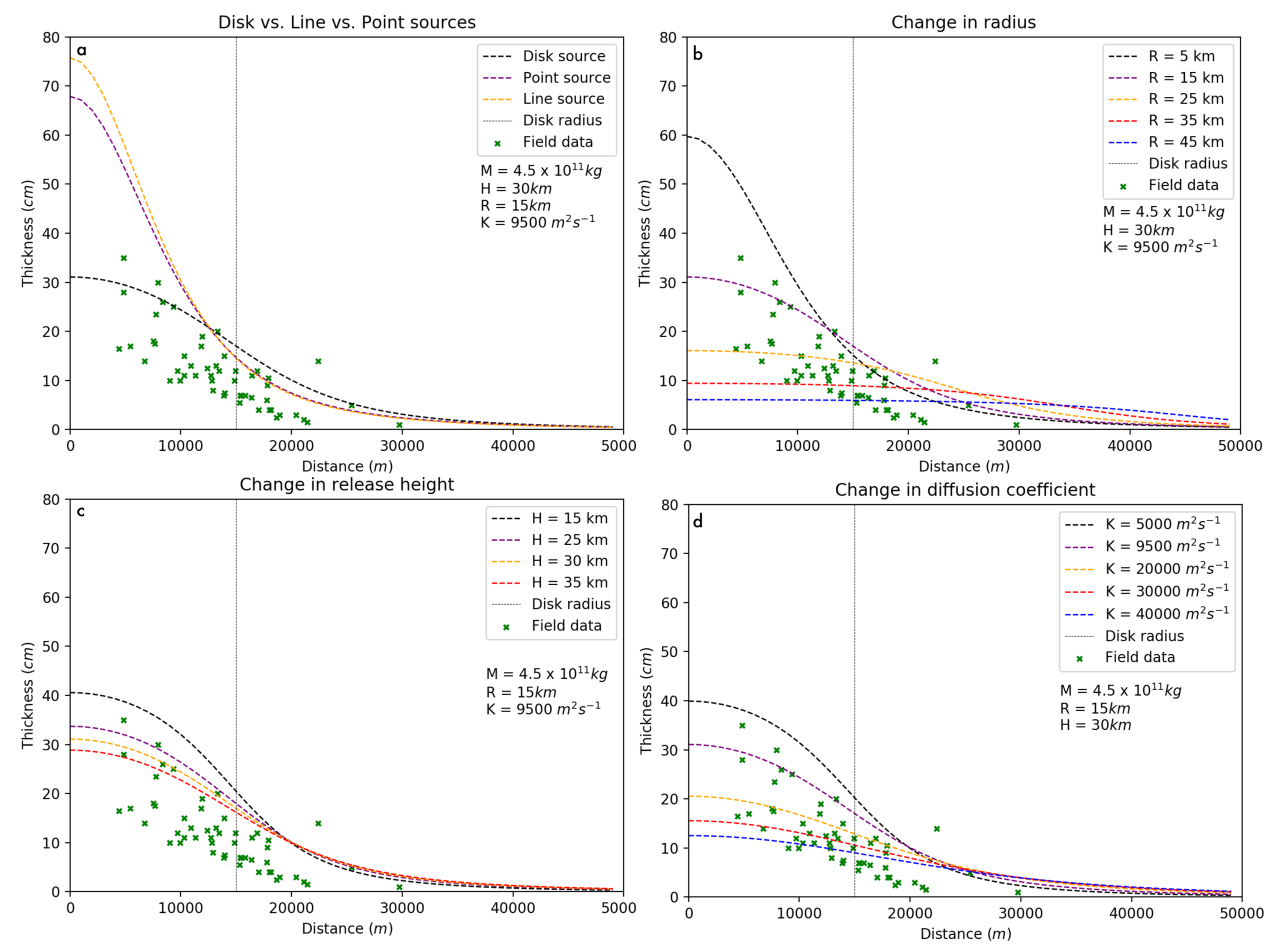

Figure 7. Tephra thickness vs distance plots: a) tephra simulated from a point, a line and a disk source; b) tephra simulated with a disk source with varied radii; c) tephra simulated with a disk source with varied release heights and d) tephra simulated with a disk source with varied

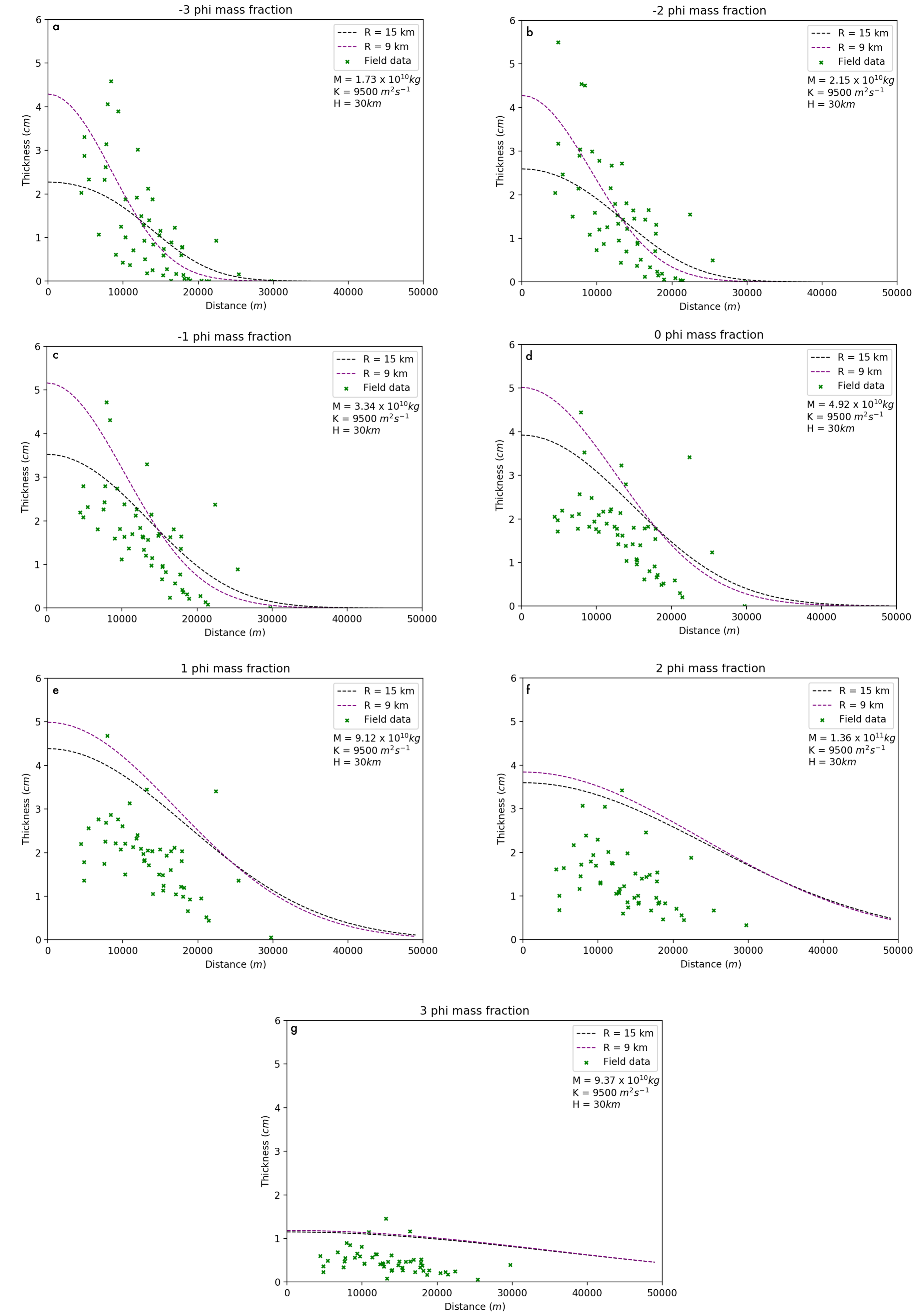

Figure 8(a-g). Tephra thickness vs distance plots for selected individual phi classes. Green crosses represent the field data published in Volentik et al. (2010).

Concluding remarks

- a disk geometry characterizing an umbrella cloud fits the data better than the line and point sources, the latter two requiring very large atmospheric diffusion coefficient;
- a disk source shows little sensitivity in deposit geometry with change in the release height, suggesting that disk radius is a more sensitive parameter in modeling large umbrella clouds;
- since large explosive eruptions are characterized by large laterally spreading umbrella clouds even when advected by wind and the umbrella diameter is controlled by eruption rate, as is plume height in vertical plumes, we suggest the modeling of large deposits with alternative models of the cloud geometries is an important step in analysis of ESPs associated with mapped deposits;
- our model shows that sedimentation from a lateral spreading umbrella cloud can match the widespread tephra deposits without using exceptionally large diffusivity values in order to increase the dispersal of fine ash;
- with an umbrella cloud geometry we can model tephra deposits using a constant radius, release height and diffusion coefficient for all grain sizes.

Authors affiliation

[1] University of South Florida, U.S.A. | [2] Freelance software engineer, Romania | [3] University of Geneva, Switzerland | [4] ExxonMobil, U.S.A. | [5] University of Auckland, New Zealand. | Corresponding author: *R. Constantinescu* | *e-mail:* robertc1@mail.usf.edu