Recent improvements of 1D models of volcanic plume rise: Implications for characterizing sulfur emissions by explosive volcanic eruptions and the subsequent sulfate aerosol forcing

Poster #333605

Thomas J. Aubry and A. Mark Jellinek

Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada

thom.aubry@gmail.com

I- Motivation and overview of 1D models of plume rise

1 - 0D/1D models of plume rise are useful tool to understand, predict and reconstruct volcanic sulfur injections into the atmosphere.

Three examples of application (Fig. 1):

1. Near real-time mass eruption rate (MER) from plume height measurement during eruptive crisis
2. Plume height from MER, e.g. when designing scenarios for future eruptions
3. Plume height from deposit when reconstructing the forcing of ancient eruptions

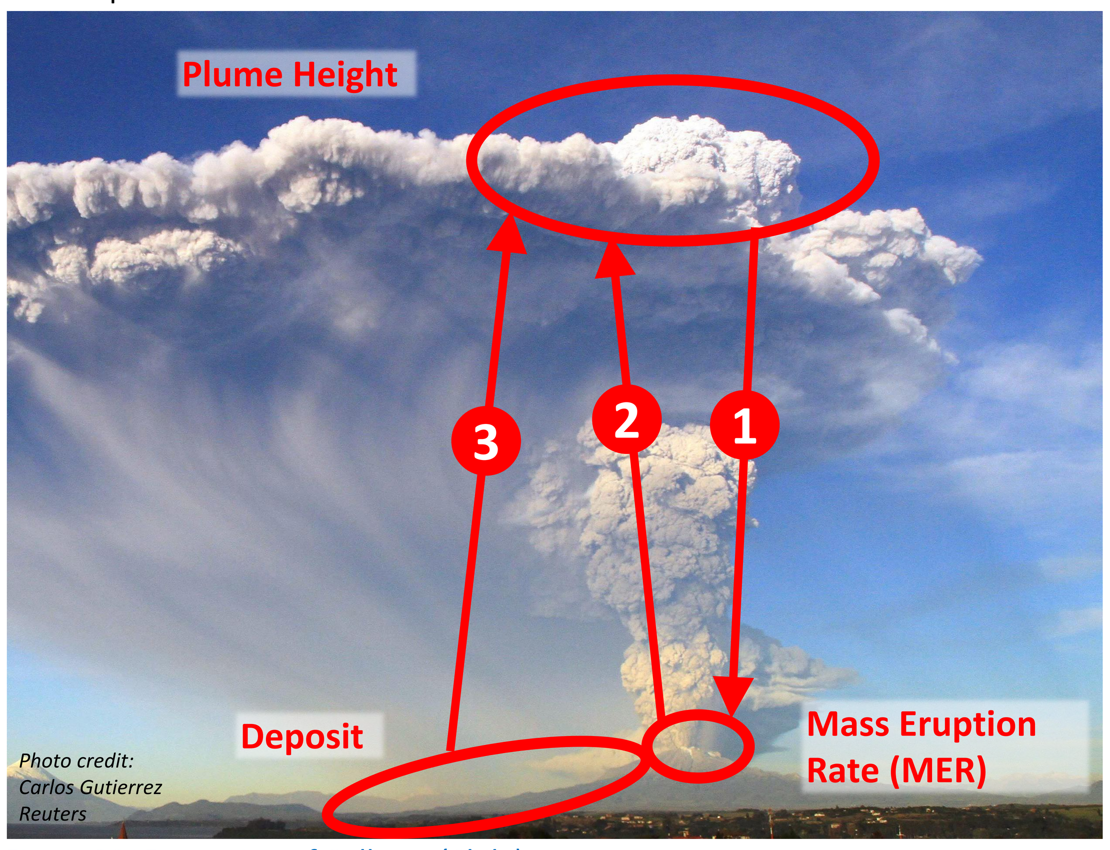

Fig. 1: 2015 eruption of Calbuco (Chile)

2- Effective model predictions are hindered by uncertainties related to parameter calibration.

Can you answer the following questions, for the Calbuco 2015 eruption, using the 1D models runs on Fig. 2:

- Given measured plume height, what is the order of magnitude of the MER?
- Given measured MER, is there a significant stratospheric injection of SO_2?

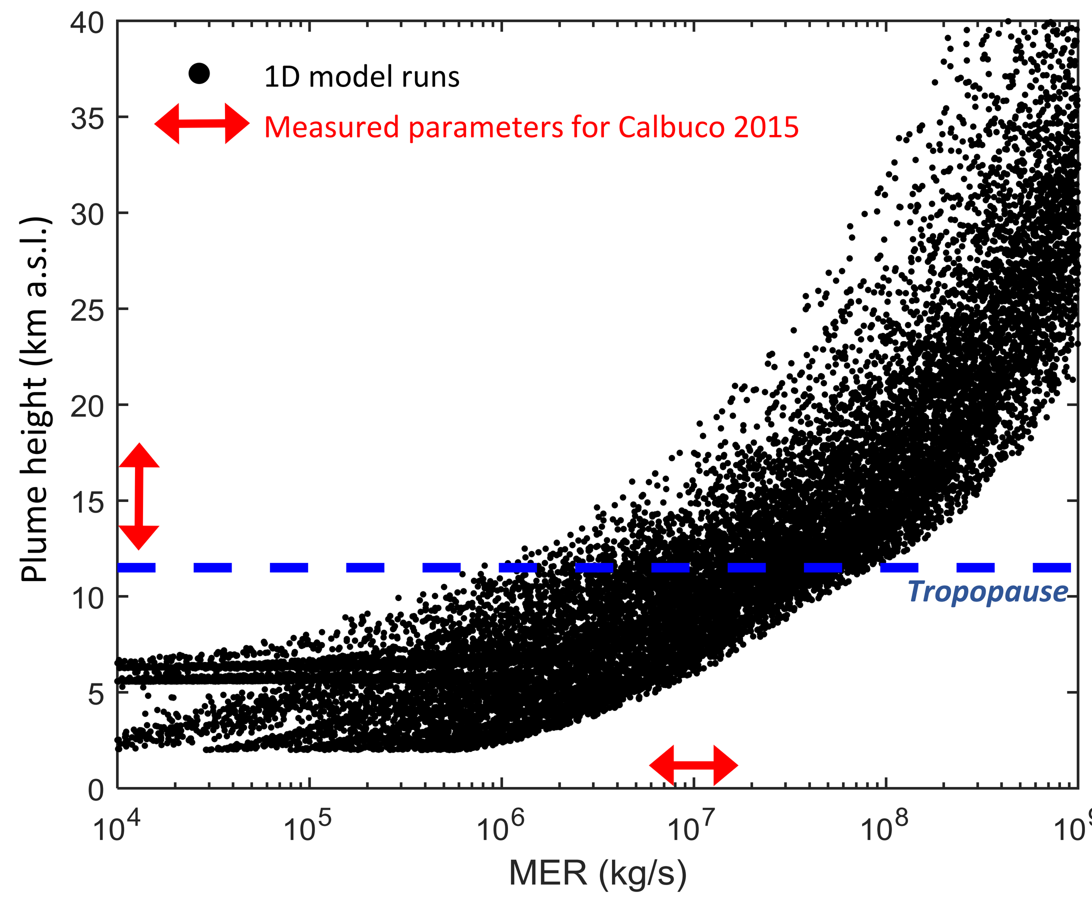

Fig. 2 (modified from ref. 1): 1D model runs with atmospheric conditions of the Calbuco 2015 eruption. The spread is due to model parameter uncertainties.

3 - The wind entrainment coefficient β and condensation rate λ are the major sources of uncertainty in 1D plume models.

Main assumptions of 1D models[1]:

- Mass/momentum/heat fluxes conserved along the plume centerline
- Steady source/atmospheric conditions
- Top-hat radial distribution of plume properties
- Entrainment: Influx of atmosphere at plume edge with velocity u_ε (Fig. 3)
- Condensation: Entrained atmospheric water vapor condensed at rate λ

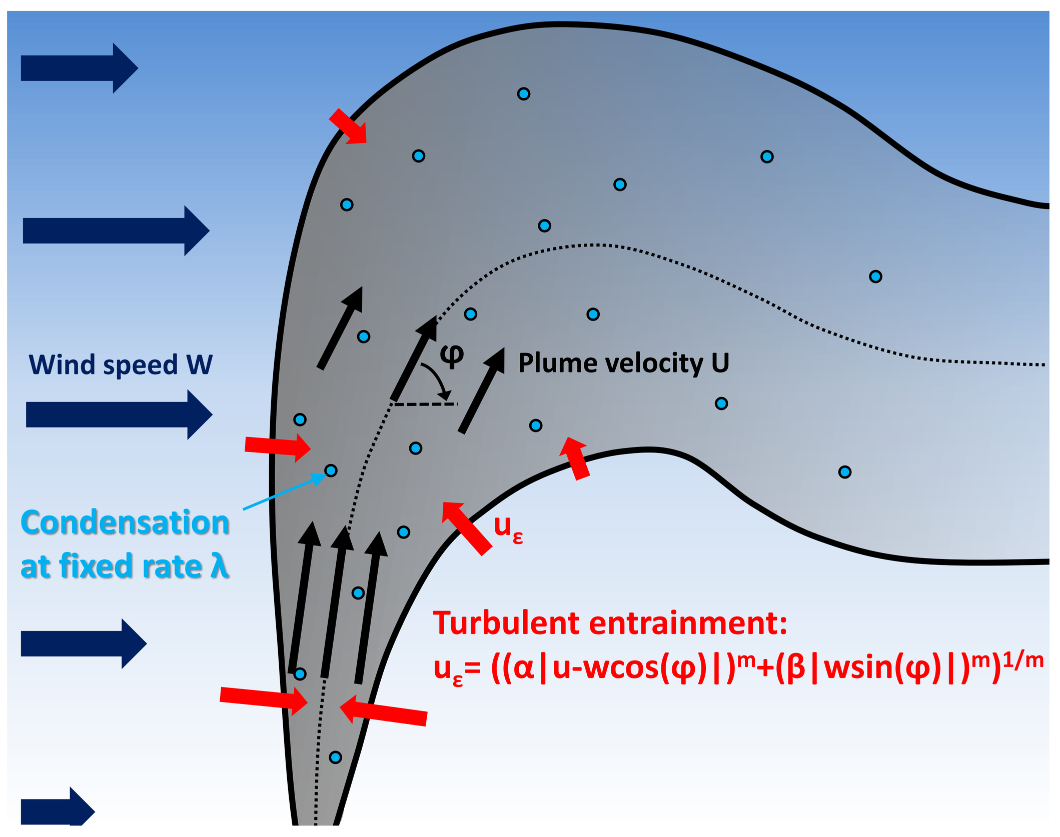

Fig. 3 (modified from ref. 1): Key concepts for 0D/1D plume models

II- New datasets to evaluate models for volcanic plume rise

1 – We compile an unprecedented database of plume heights and MERs constrained independently[2]:

- Largest database before our study[3]: 25 eruptive phases and no uncertainties
- New database: 94 eruptive phases and uncertainties on height and MER; atmospheric conditions from NCEP/NCAR reanalysis

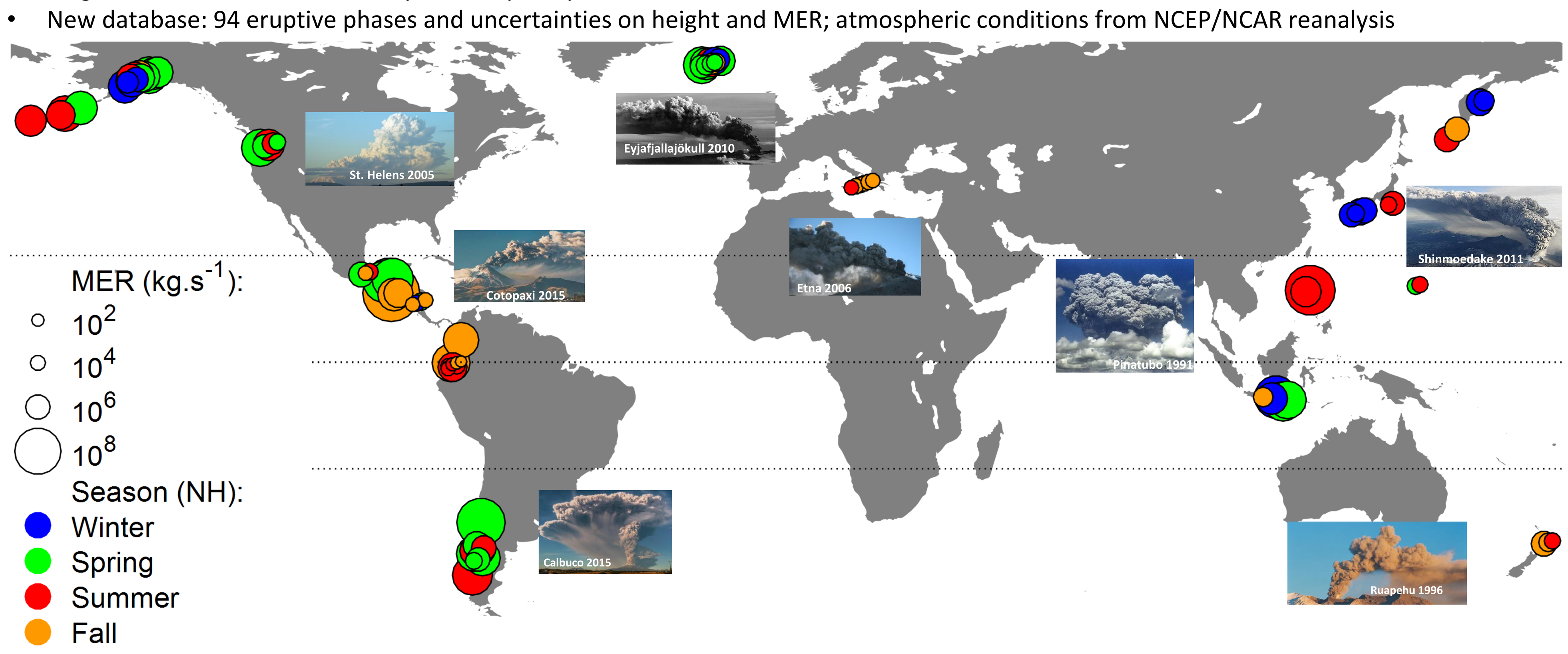

Fig. 4 (modified from ref. 1): Location, MER and season of the 94 eruptive phases of the new database. Pictures show a few select examples.

2 - New lab experiments covering the same dynamical regimes as explosive eruptions, overcoming a major limitation of previous studies[2,4]

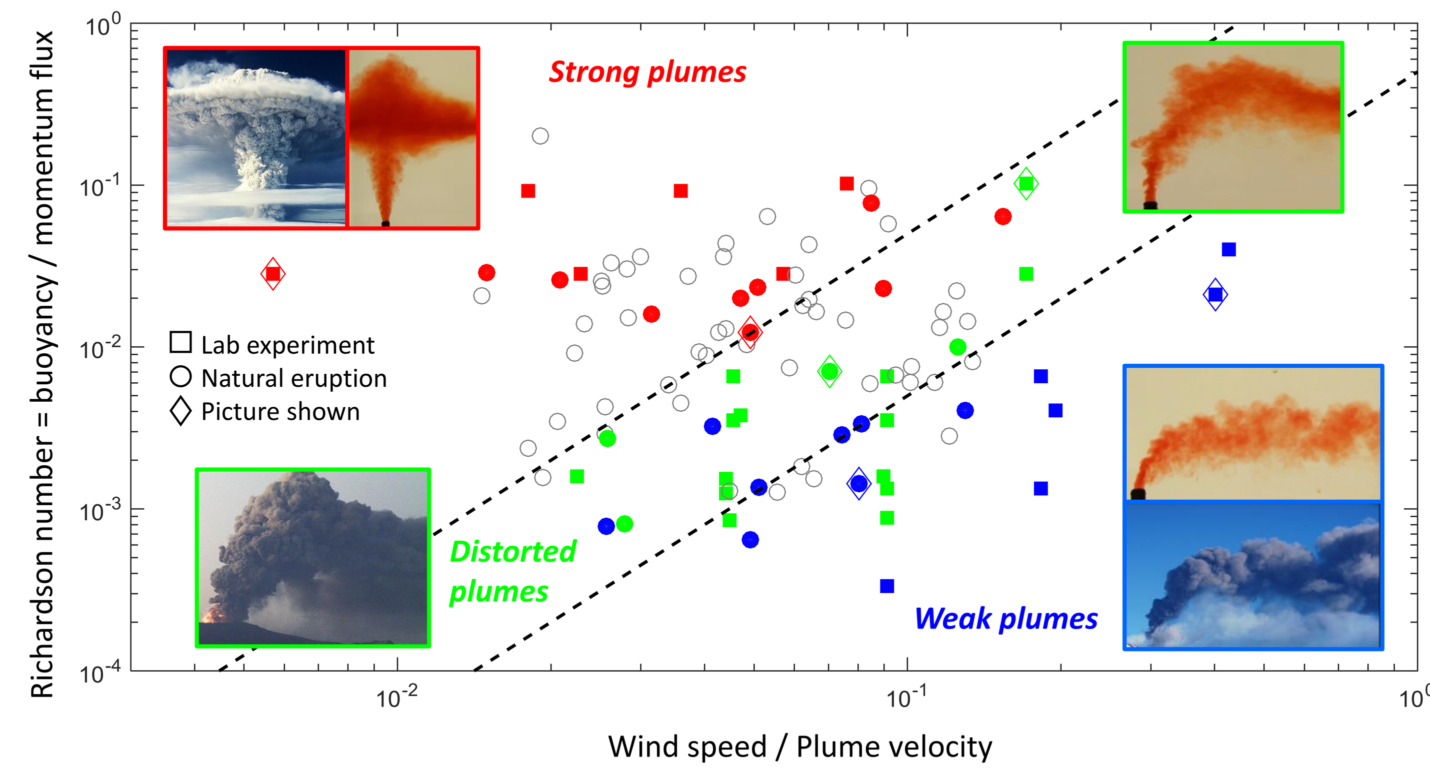

Fig. 5 (modified from ref. 2): Richardson number and velocity ratio for the new database of eruption source parameters and analog laboratory experiments. Colors highlight different plume shape regimes.

→ **We use the eruptive parameter database and lab experiments to constrain and evaluate 0D and 1D plume models, along with Monte Carlo simulations to account for uncertainties in both datasets[1,2,5]**

III- New insights on 1D and 0D models parameterizations and performance

1 – The wind entrainment coefficient β is small

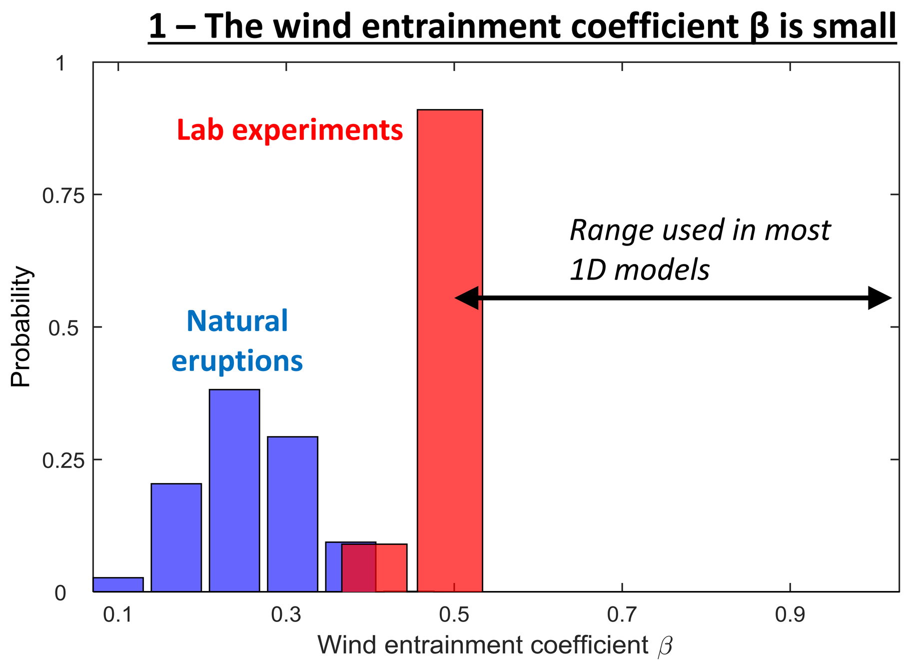

Fig. 6 (modified from ref. 1): Probability distribution of β obtained by minimizing error on plume height (natural eruptions) or trajectories (lab experiment) using a Monte Carlo strategy to account for observational uncertainties

2- Absent condensation OR negligible impact on plume buoyancy flux

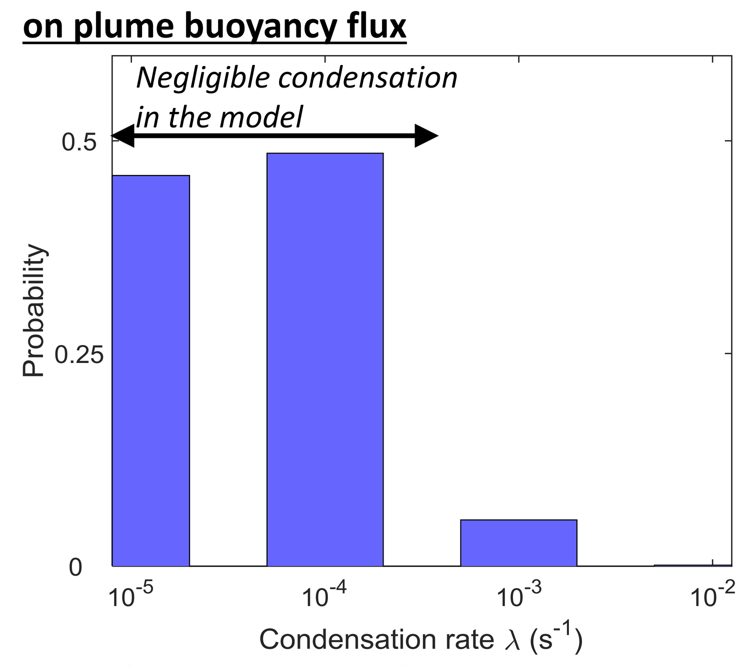

Fig. 7 (modified from ref. 1): Same as Fig. 6, but for λ and using only the database of explosive eruptions (no condensation in lab experiment)

3 – Refined calibration[2] of the most popular "model" for plume rise: PH= a x MER^b

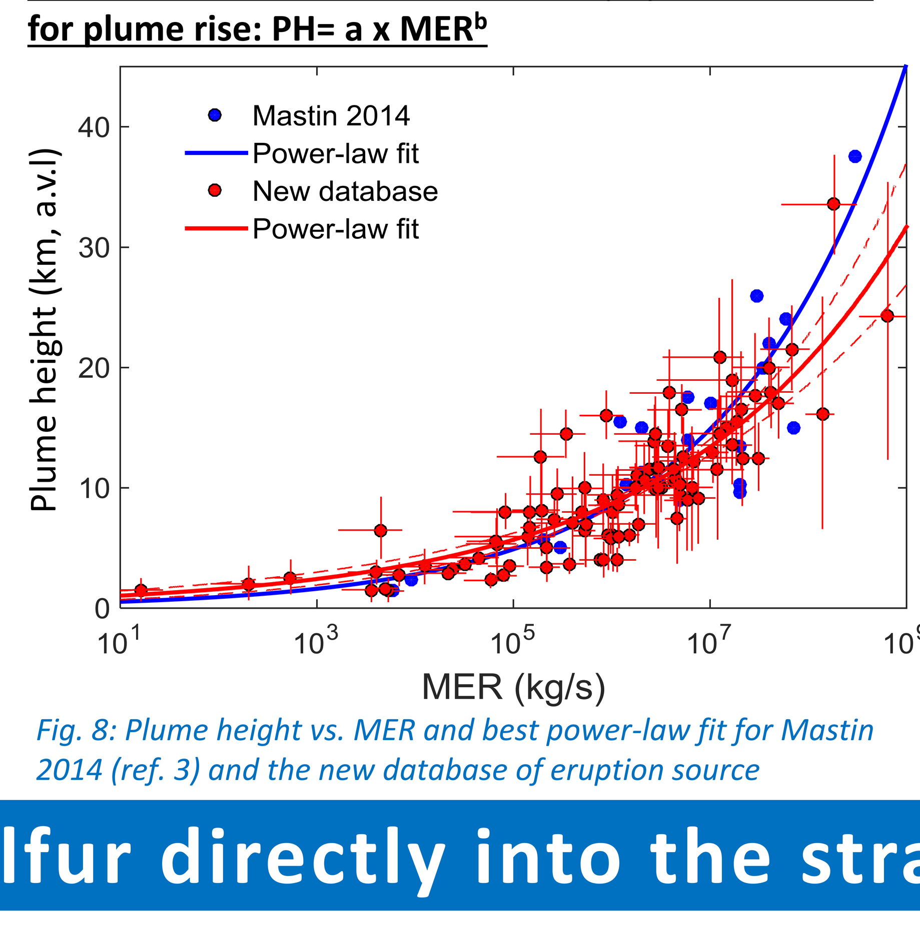

Fig. 8: Plume height vs. MER and best power-law fit for Mastin 2014 (ref. 3) and the new database of eruption source

4 – 1D models make significantly better plume height predictions than 0D models

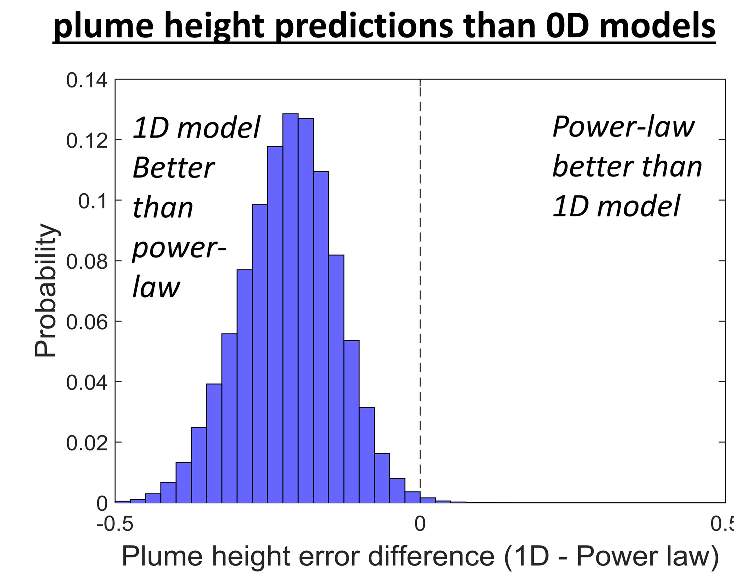

Fig. 9: Difference between error on plume height for a 1D model and a power law scaling. The error is a root mean squared error on predictions for natural eruption plume height normalized by observational uncertainties.

IV- What MER is required to inject sulfur directly into the stratosphere?

1 – New datasets enable to better constrain the critical MER for stratospheric injections

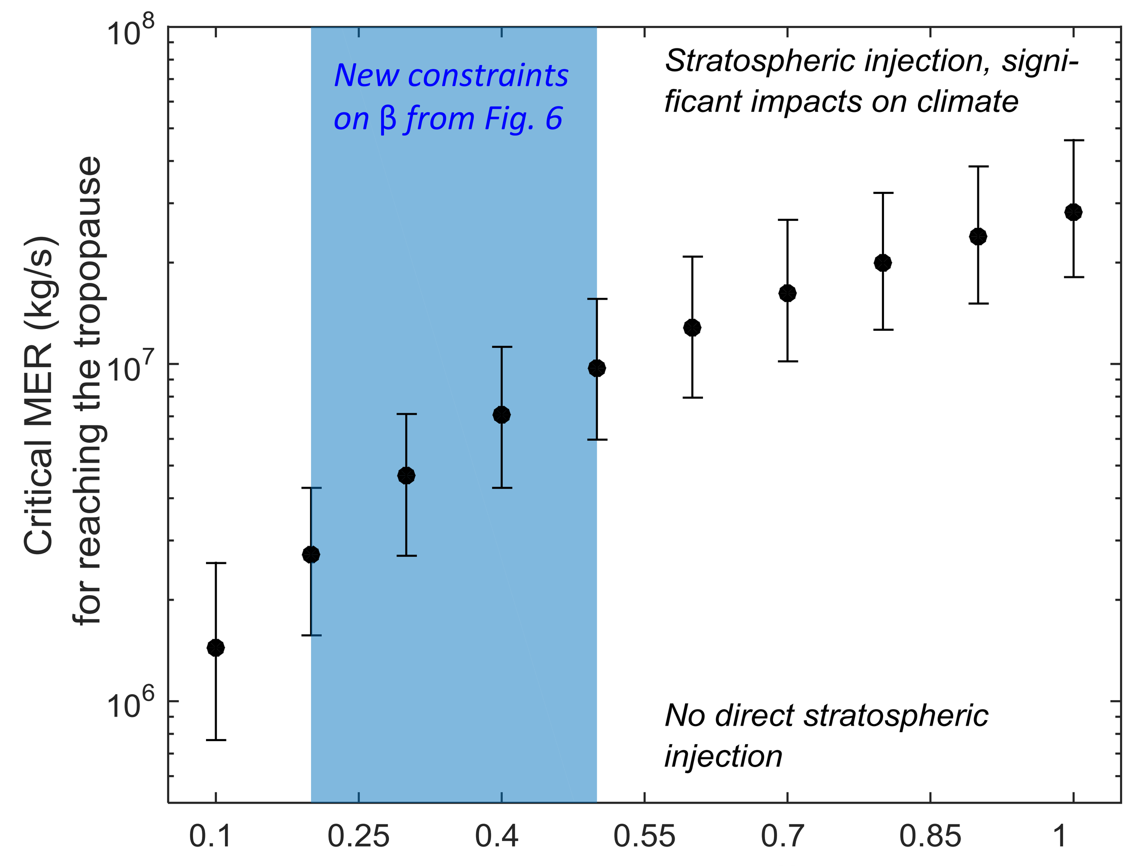

Fig. 10 (modified from ref. 5): Critical MER for stratospheric injection (right) vs β for the same atmospheric conditions as the 2011 Cordón Caulle eruption, and for a vent height of 1500m.

2 – Sensitivity of the critical MER to background climate: A new climate-volcano feedback?

- New constraints on condensation rate (Fig. 7) → relatively large MER are required to reach the tropopause
- Global warming → larger critical MER → less stratospheric SO2 injections → less cooling[6]? More Friday at 11.30am

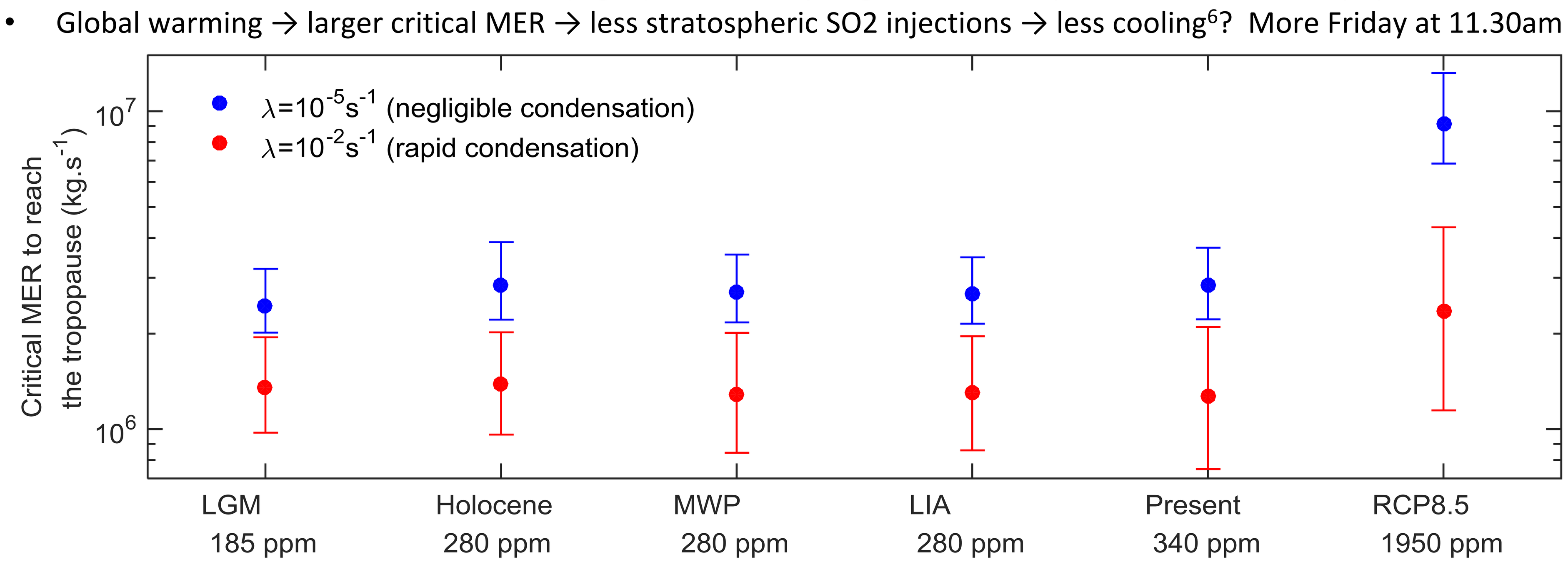

Fig. 11 (modified from ref. 1): MER required to reach the tropopause with/without condensation. Atmospheric conditions for Ecuador, from the MPI-ESM climate model and for various climates with CO_2 and surface temperature labeled. Vent height of 2000m. LGM= Last Glacial Maximum, MWP= Medieval Warm Period, LIA= Little Ice Age

References

1. Aubry, T. J. and A. M. Jellinek (2018), New insights on entrainment and condensation in volcanic plumes: Constraints from independent observations of explosive eruptions and implications for assessing their impacts, Earth and Planetary Science Letters, 490, 132-142, doi:10.1016/j.epsl.2018.03.028
2. Aubry, T.J., et al., A new analytical scaling for turbulent wind-bent plumes: Comparison of scaling laws with analog experiments and a new database of eruptive conditions for predicting the height of volcanic plumes, J. Volcanol. Geotherm. Res. (2017), doi: 10.1016/j.jvolgeores.2017.07.006
3. Mastin L. Testing the accuracy of a 1-D volcanic plume model in estimating mass eruption rate. J. Geophys. Res. Atmos , doi:10.1002/2013JD020604
4. Carazzo, G., et al. (2014) Laboratory experiments of forced plumes in a density-stratified crossflow and implications for volcanic plumes. Geophysi. Res. Let., 41, doi: 10.1002/2014GL061887
5. Aubry, T.J., Jellinek, A.M. and Carazzo, G. Turbulent entrainment in buoyant jet rising in a stratified crossflow: New constraints from laboratory experiments, Submitted to Geophys. Res. Lett.
6. Aubry, T. J., et al (2016), Impact of global warming on the rise of volcanic plumes and implications for future volcanic aerosol forcing, J. Geophys. Res. Atmos., doi:10.1002/2016JD025405.