Modeling Volcanic Ash Impacts of the 2010 Eyjafjallajökull Eruption

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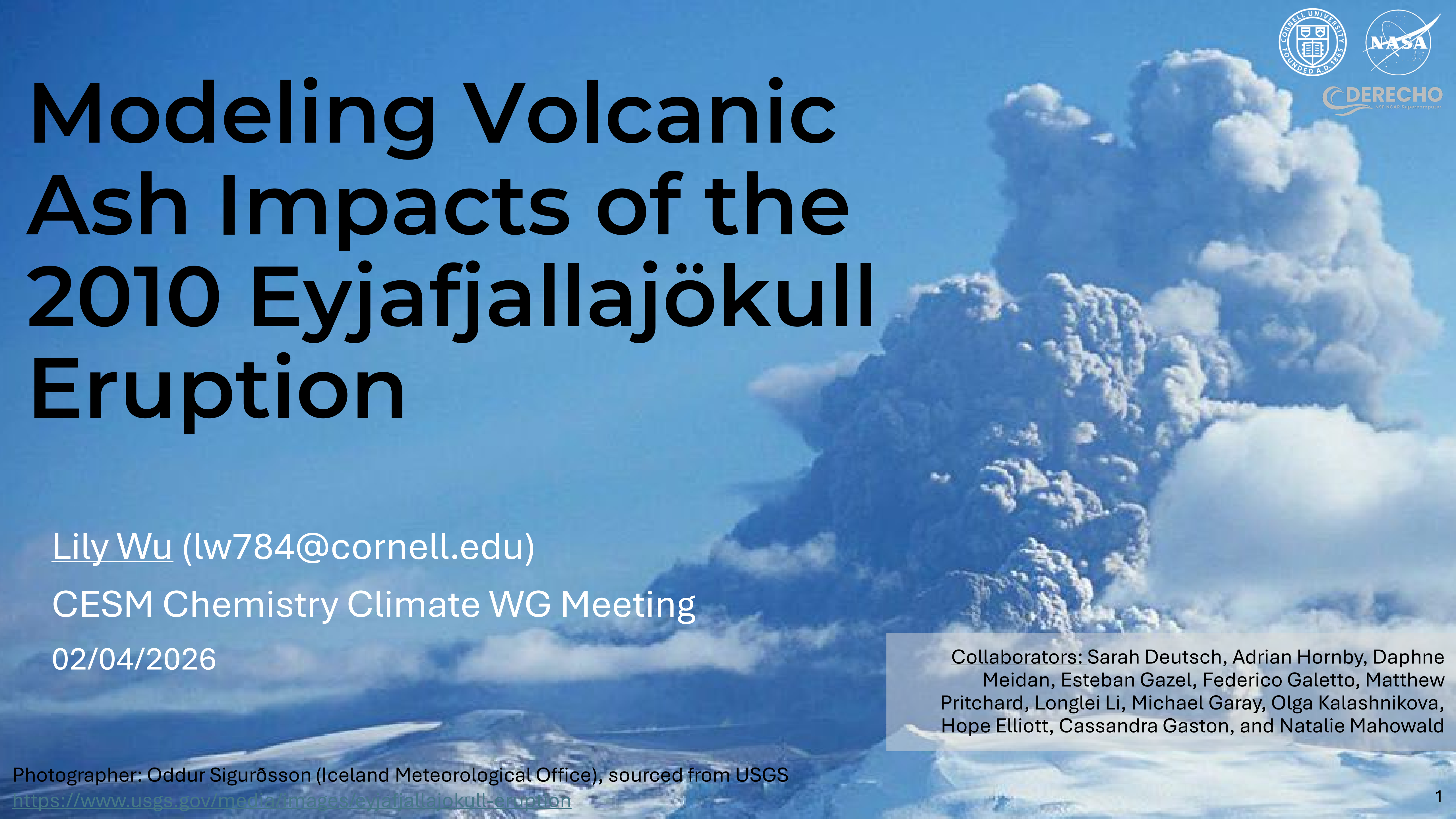
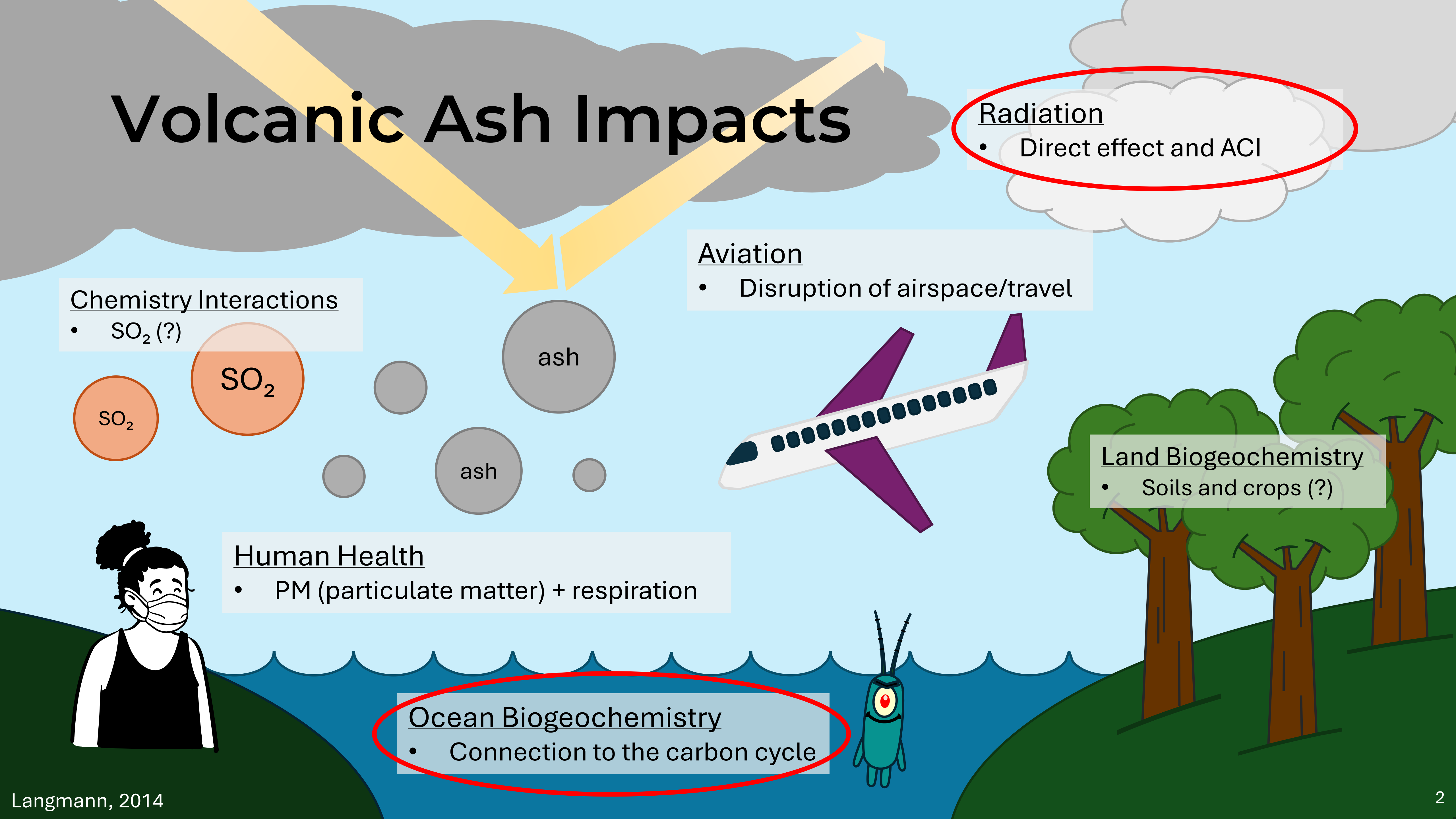


Photographer: Oddur Sigurðsson (Iceland Meteorological Office), sourced from USGS
https://www.usgs.gov/media/images/eyjafjallajokull-eruption


Volcanic Ash Impacts
Radiation
• Direct effect and ACI
Aviation
• Disruption of airspace/travel
Chemistry Interactions
• SO2 (?)
SO2
SO2
ash
ash
Land Biogeochemistry
• Soils and crops (?)
Human Health
• PM (particulate matter) + respiration
Ocean Biogeochemistry
• Connection to the carbon cycle
Langmann, 2014

Why Model? + Volcano Case Study

- Volcanic ash was previously neglected in global climate models like CESM in favor of volcanic sulfate aerosols
  - Ash particles are larger and assumed to be shorter lived -> impact is limited to smaller scales (temporally and spatially)
- **<u>NEW volcanic ash tracer!</u>**
- <u>2010 Eyjafjallajökull (Eyja) eruption</u>
  - April 14 – May 17
  - 4 eruptive phases with different ash chemistry
  - Observations of the eruption
    - Emissions
    - Impact on Europe

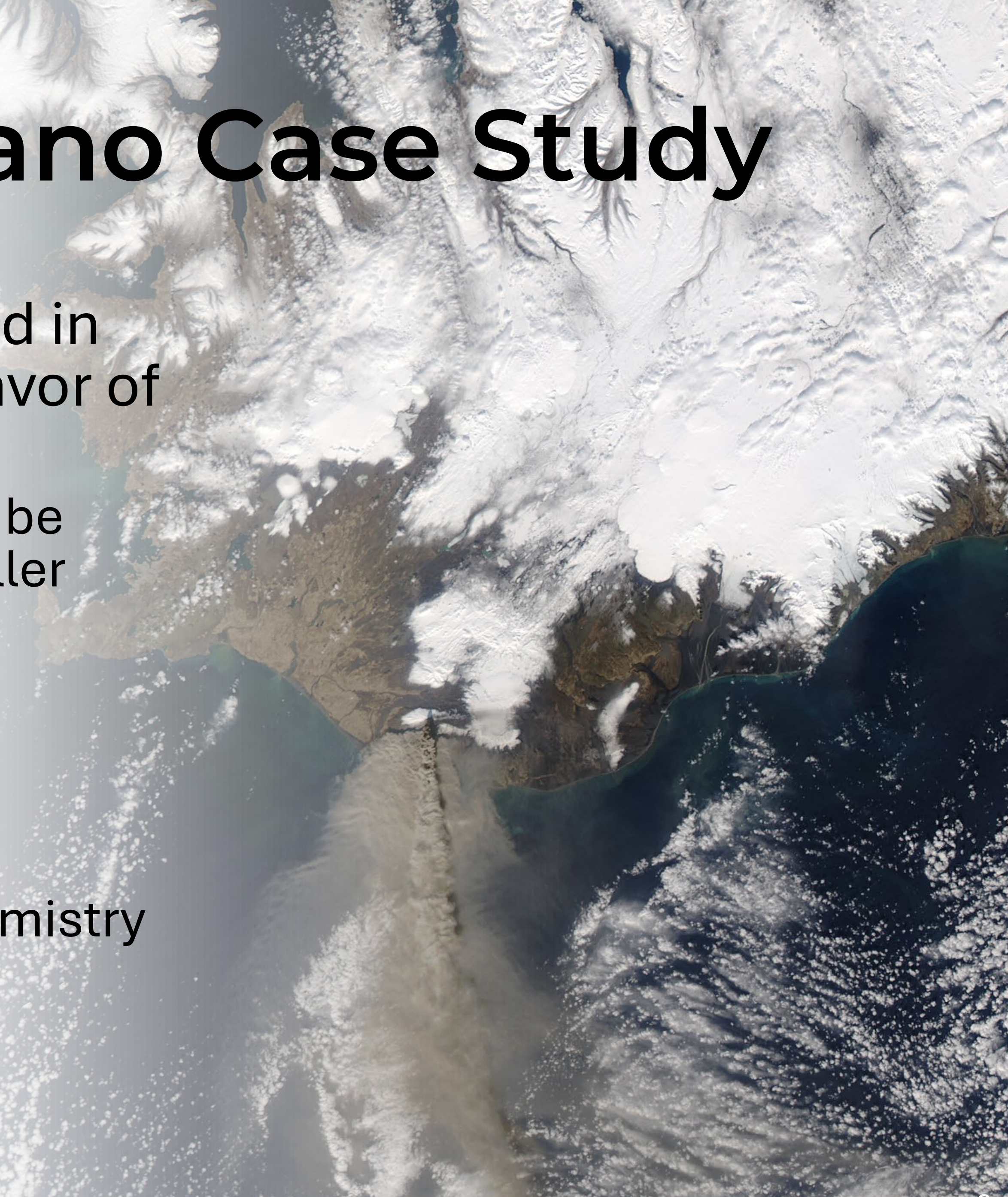


Photo from NASA Earth Observatory; Langmann, 2014; Gudmundsson et al., 2012

Model Setup

- CESM 2.1.0 Community Atmosphere Model 6 (CAM6)
  - Modal Aerosol Model v4 (MAM4)
  - Mechanism of Intermediate Complexity for Modelling Iron (MIMI)
- Dust framework
  - 8 dust tracers
    - Not all 8 needed to capture radiative forcing of dust -> condense into 4
  - Use remaining 4 for NEW ash tracers
    - Divided based on minerology from Eyja ash observations in Paque et al. (2016)

Tracer	Phase 1 % mass (April 14 – April 18)	Phase 2 % mass (April 18 – May 4)	Phase 3 % mass (May 4 – May 17)
Ash 1 (Iron oxides)	1.8	3.6	2.7
Ash 2 (All other iron bearing minerals; pyroxenes, amphibole, olivine, silicon dioxide, salts, smectite, zeolite)	73.6	64.8	63.8
Ash 3 (Plagioclases; feldspars)	24.5	31.5	33.5
Ash 4 (Phosphate)	9e-4	9e-4	9e-4

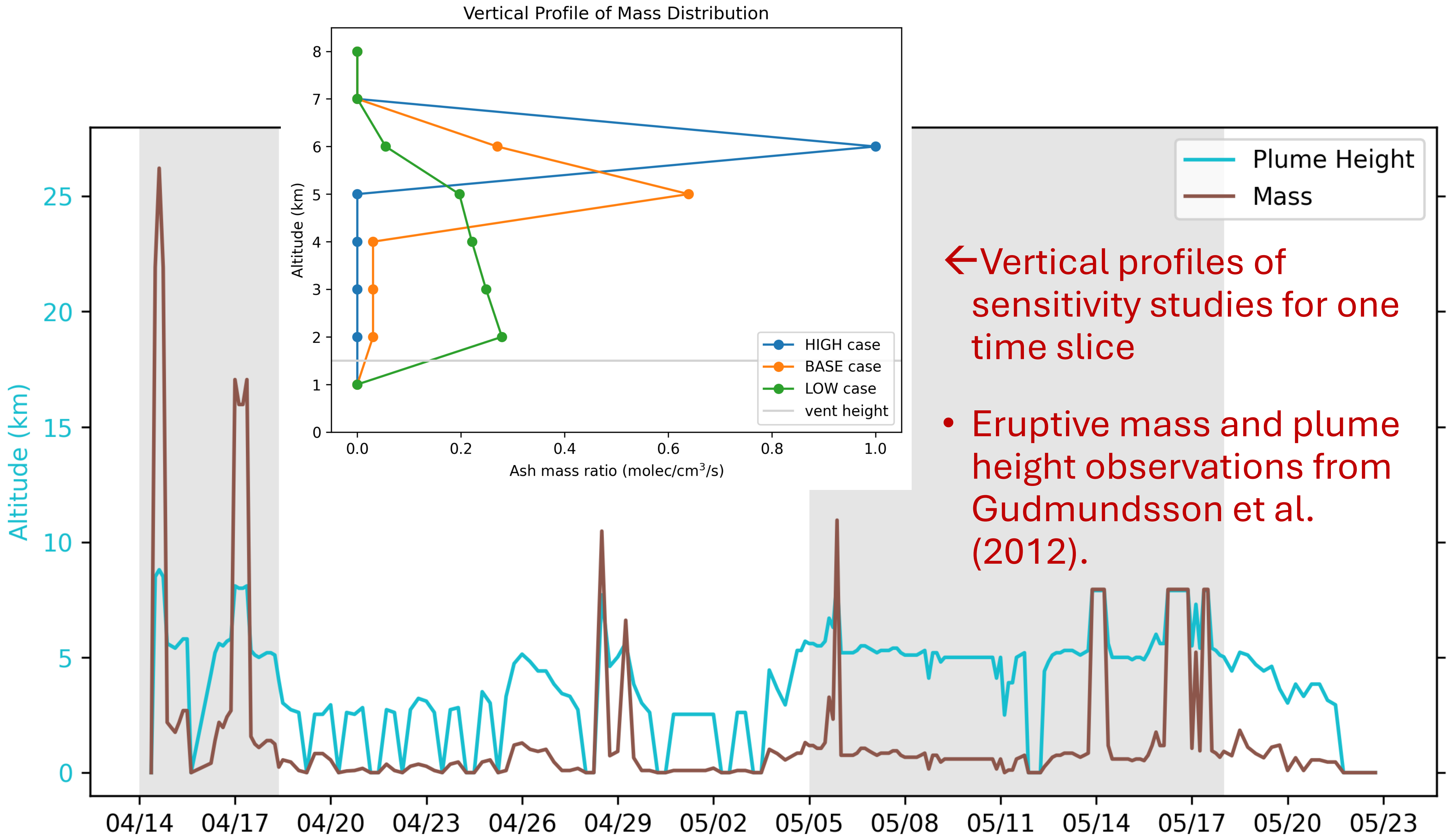
Ash tracers are divided based on their role in the atmosphere. Ash 1 iron oxides are separated for connections to ocean biogeochemistry, and Ash 2 iron minerals are for optics. Ash 3 feldspars are separated for their role as an ice-nucleating agent, and Ash 4 phorsphorus is for chemistry. Each of these four ash tracers contains a percentage of the total mass based on X-ray diffraction (XRD) measurements.

Liu et al., 2012, 2016; Hamilton et al., 2019; Li et al., 2021, 2022; Paque et al., 2016; Elliott et al., 2025

Sensitivity Studies

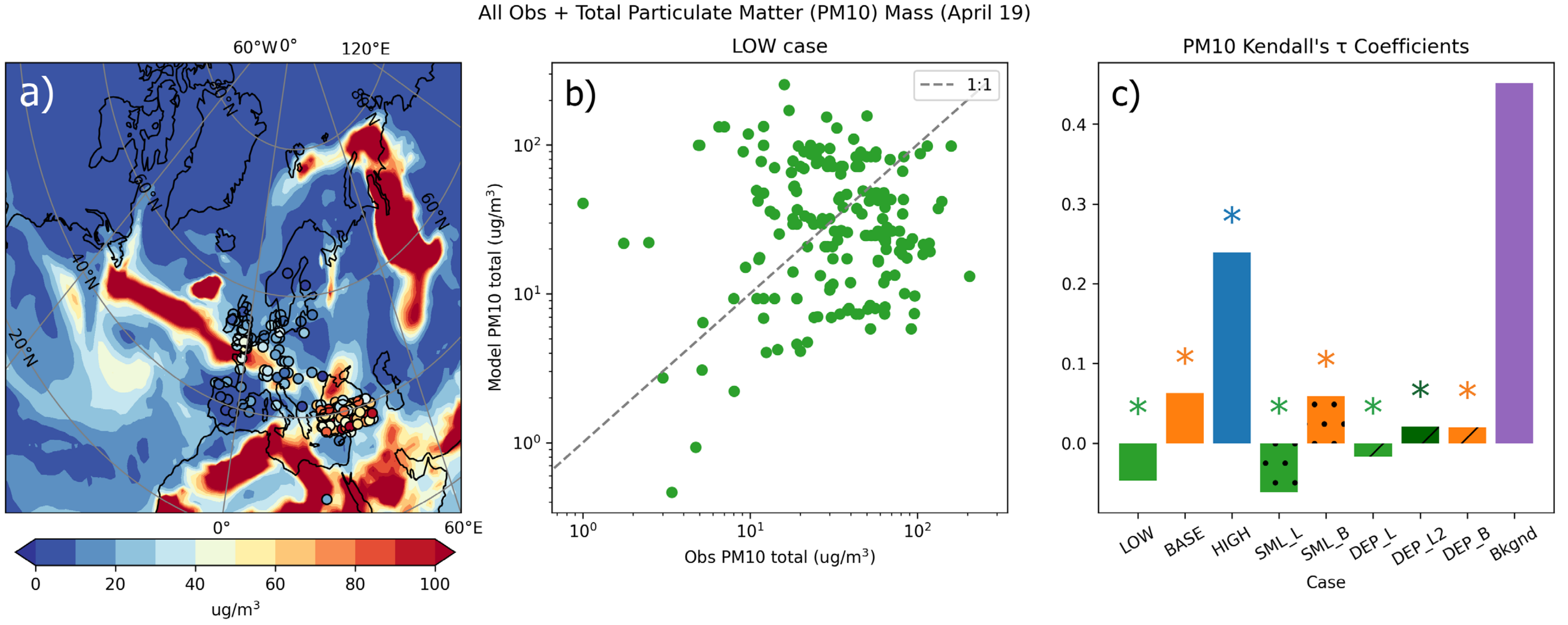
- Plume height vs. particle size distribution vs. deposition velocity
  - These parameters are poorly known
- **LOW** – constant mass mixing ratio throughout the ash plume
- **BASE** – 90% of mass in the top 1km, 10% evenly in the bottom
- **HIGH** – 100% mass at the maximum plume height
- **SMALL_LOW** (SML_L) – more mass in the accumulation size bin
- **SMALL_BASE** (SML_B) – more mass in the accumulation size bin
- ***DEP_LOW*** (DEP_L2) – increasing deposition velocity by 1.5X
- ***DEP_LOW2*** **(**DEP_L2) – increasing deposition velocity by 2X
- ***DEP_BASE*** (DEP_B) – increasing deposition velocity by 1.5X

Hirtl et al., 2019; Devenish et al., 2012; Kok et al., 2014; Elliott et al., 2025



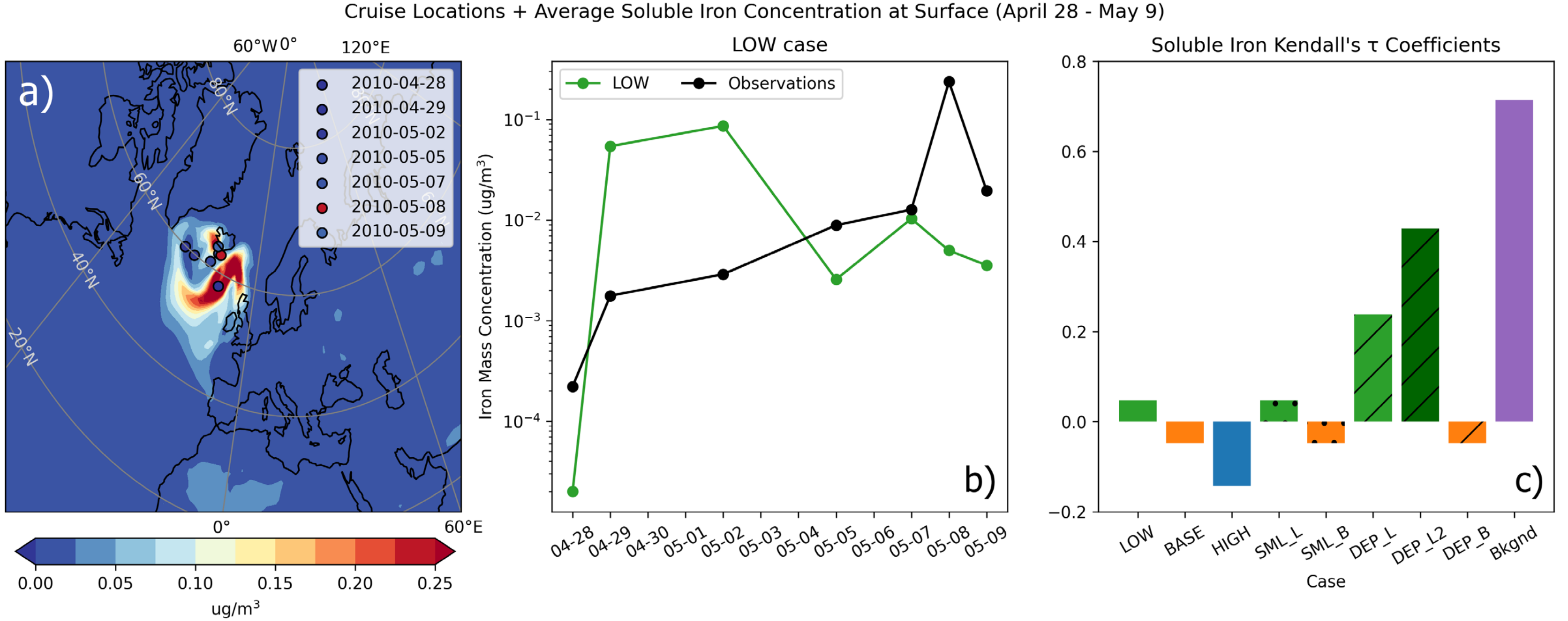
←Vertical profiles of sensitivity studies for one time slice

- Eruptive mass and plume height observations from Gudmundsson et al. (2012).



Particulate Matter (PM10)

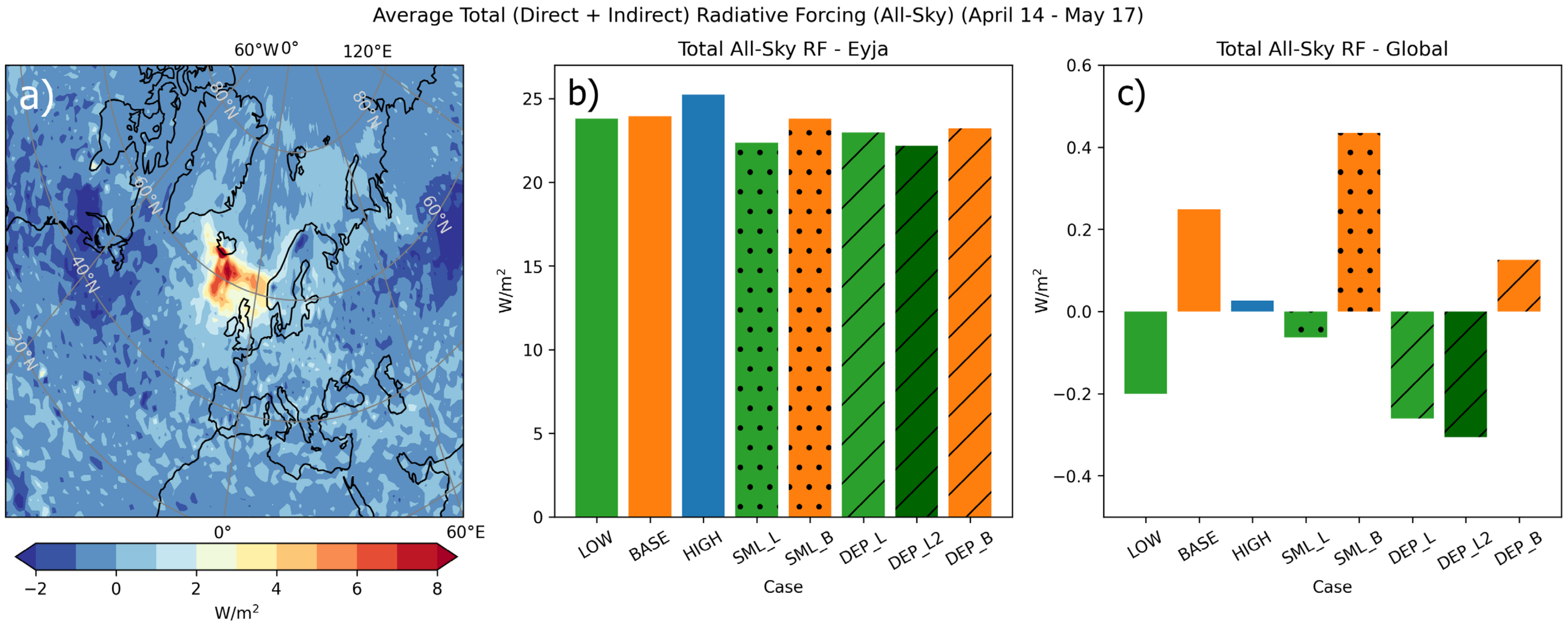
- Station observations from the AERO-MAP dataset (Mahowald et al., 2025)
- Long-range transport of volcanic ash to Europe
  - Model performs relatively poorly compared to the "Background" case without ash
- Model spatial resolution issues?



Soluble Iron at the Surface

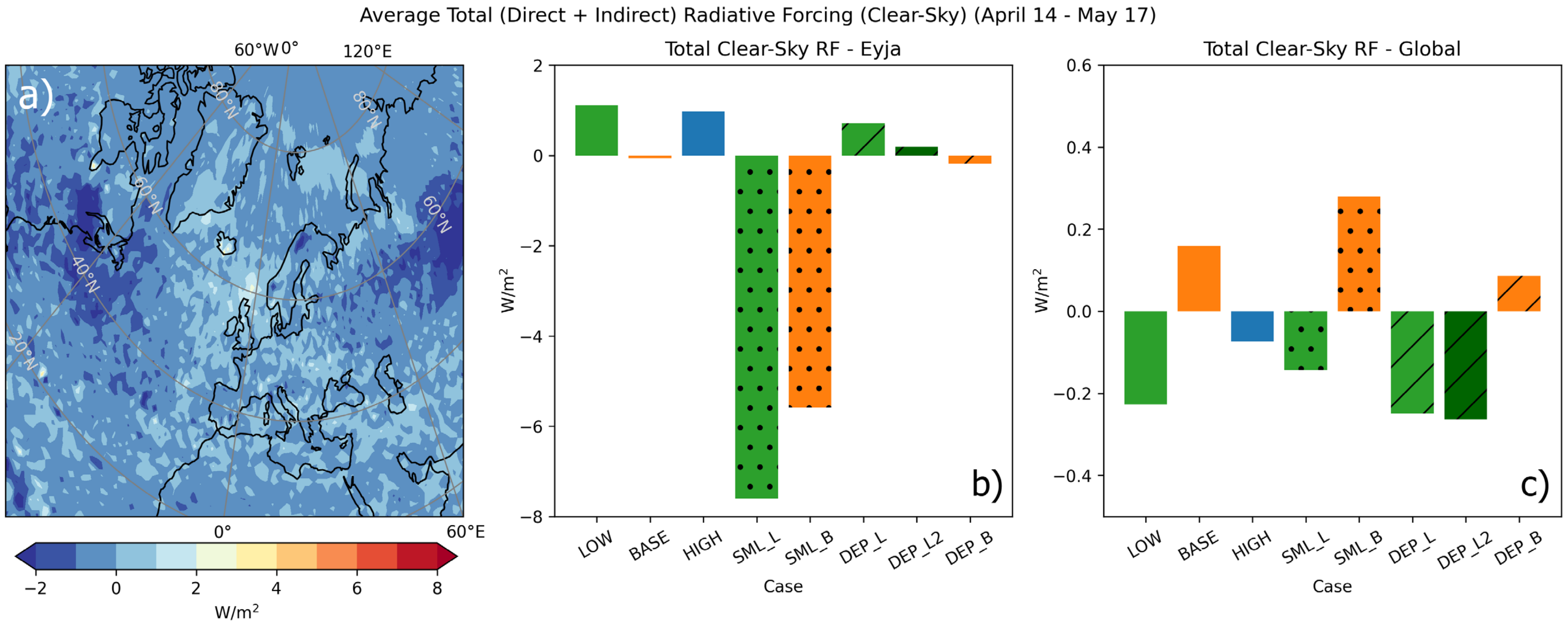
- Observations from the RRS *Discovery* (Achterberg et al., 2013)
- Local iron concentration from ash
  - Model performs relatively poorly compared to the "Background" case without ash
  - There is a 3-day timing delay (not shown), which captures the observed peak on 5/8/2010 better?

** Top of atmosphere (TOA) RF



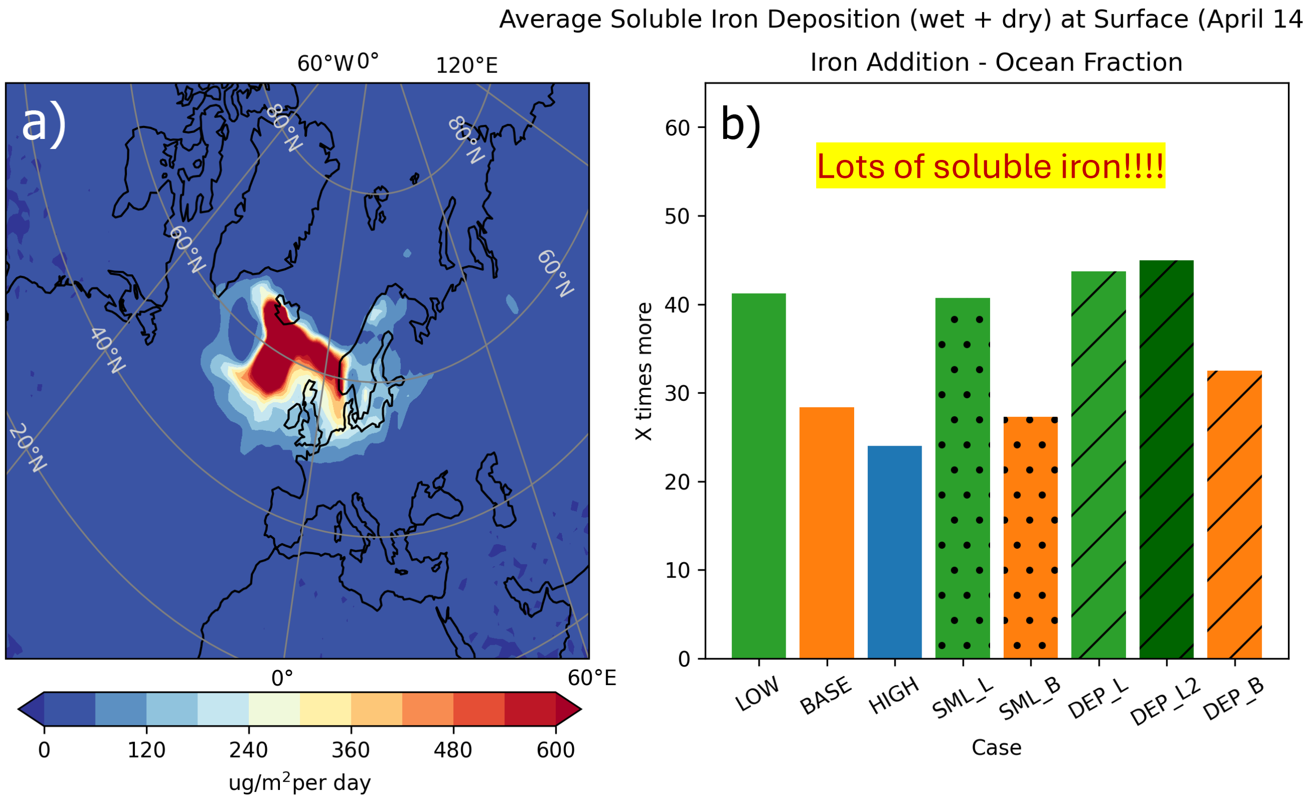
All-Sky (with clouds)

- Very strong POSITIVE local RF
  - Warming (b)
- Minimal global RF (c)
- **Not very sensitive to plume height, particle size, or deposition velocity!**



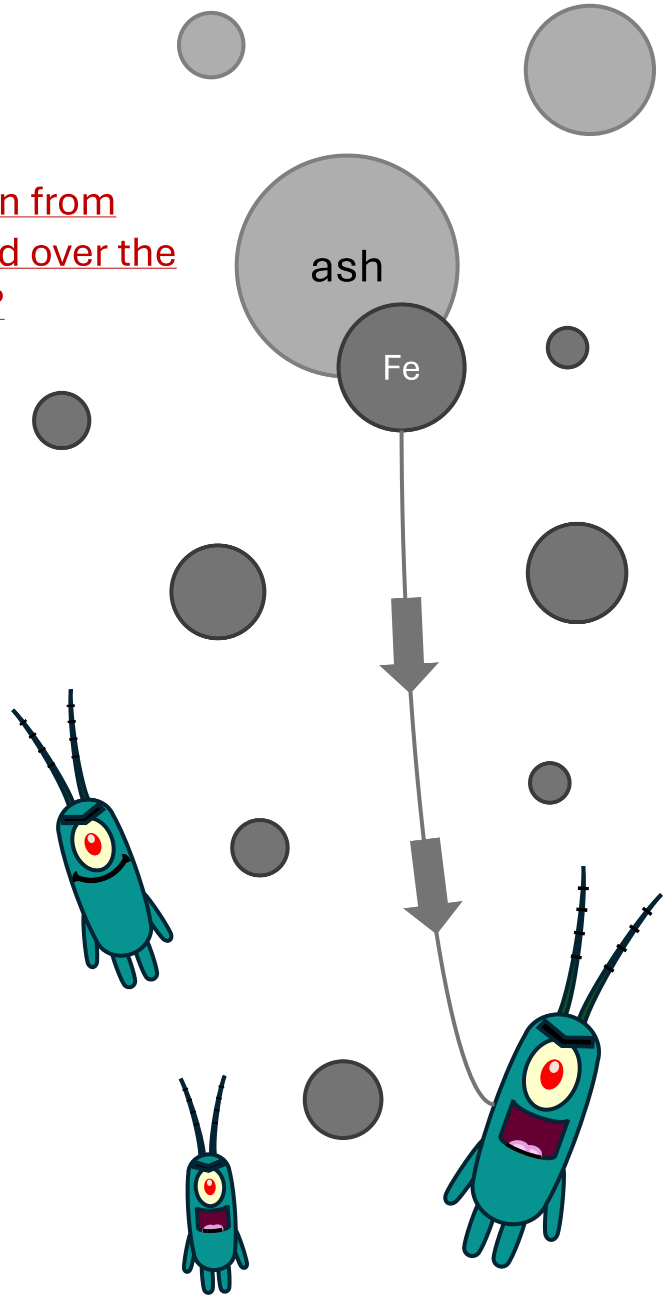
Clear-Sky (without clouds)

- Less strong local RF than All-Sky
  - Very strong NEGATIVE RF for the "SMALL" cases with more mass in the smaller aerosol size bins (b)
- Minimal global RF (c)
- **Senstive to particle size!**



How much soluble iron from volcanic ash deposited over the North Atlantic Ocean?

LOW: 66 Gg
BASE: 45 Gg
HIGH: 38 Gg
SMALL_LOW: 65 Gg
SMALL_BASE: 43 Gg
DEP_LOW: 69 Gg
DEP_LOW2: 71 Gg
DEP_BASE: 52 Gg



Why Plankton from SpongeBob?

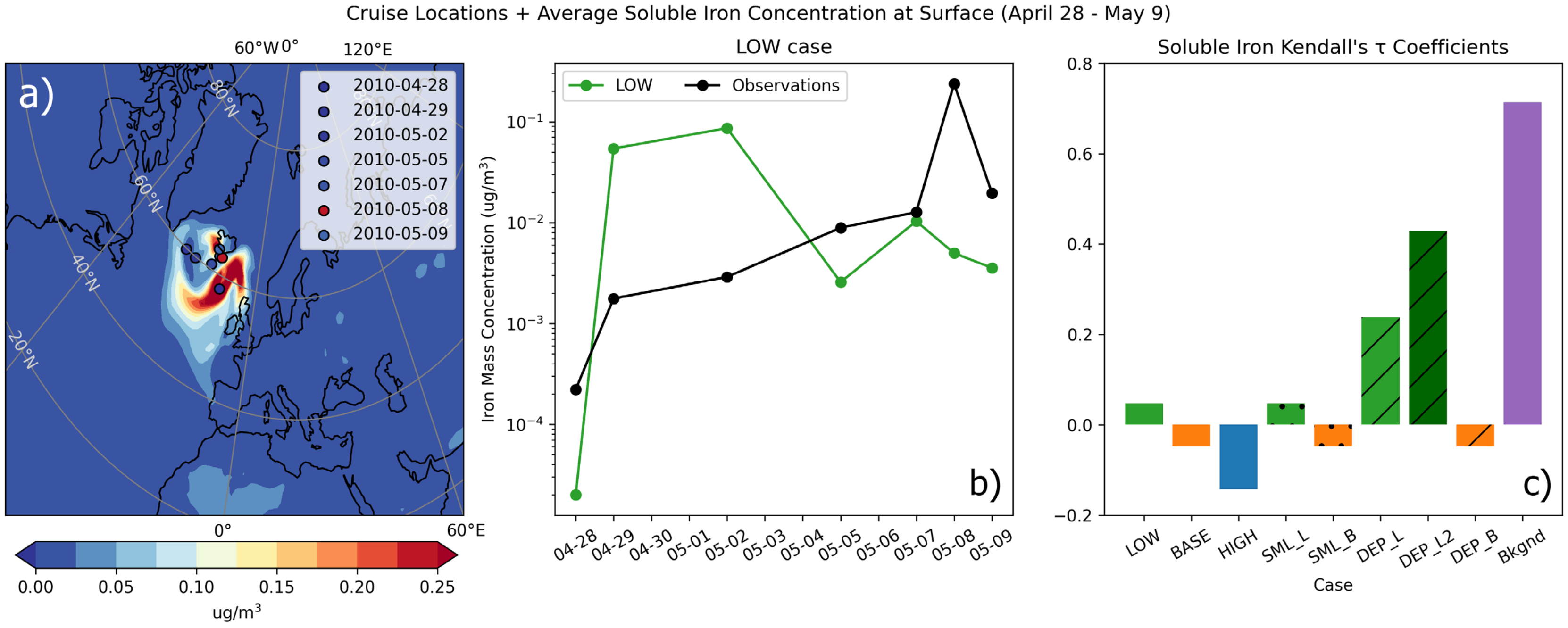
Volcanic ash can contain soluble iron, which is an important limiting nutrient for phytoplankton and is particularly important in high-nutrient low-chlorophyll (HNLC) regions. There is significant overlap between these iron-limited ocean regions and those with a high likelihood of ash deposition downwind, suggesting that volcanic ash could act as a significant intermittent source of iron. An increase in volcanic ash following an eruption can therefore fertilize the ocean and cause phytoplankton blooms, which can also potentially impact the carbon cycle.

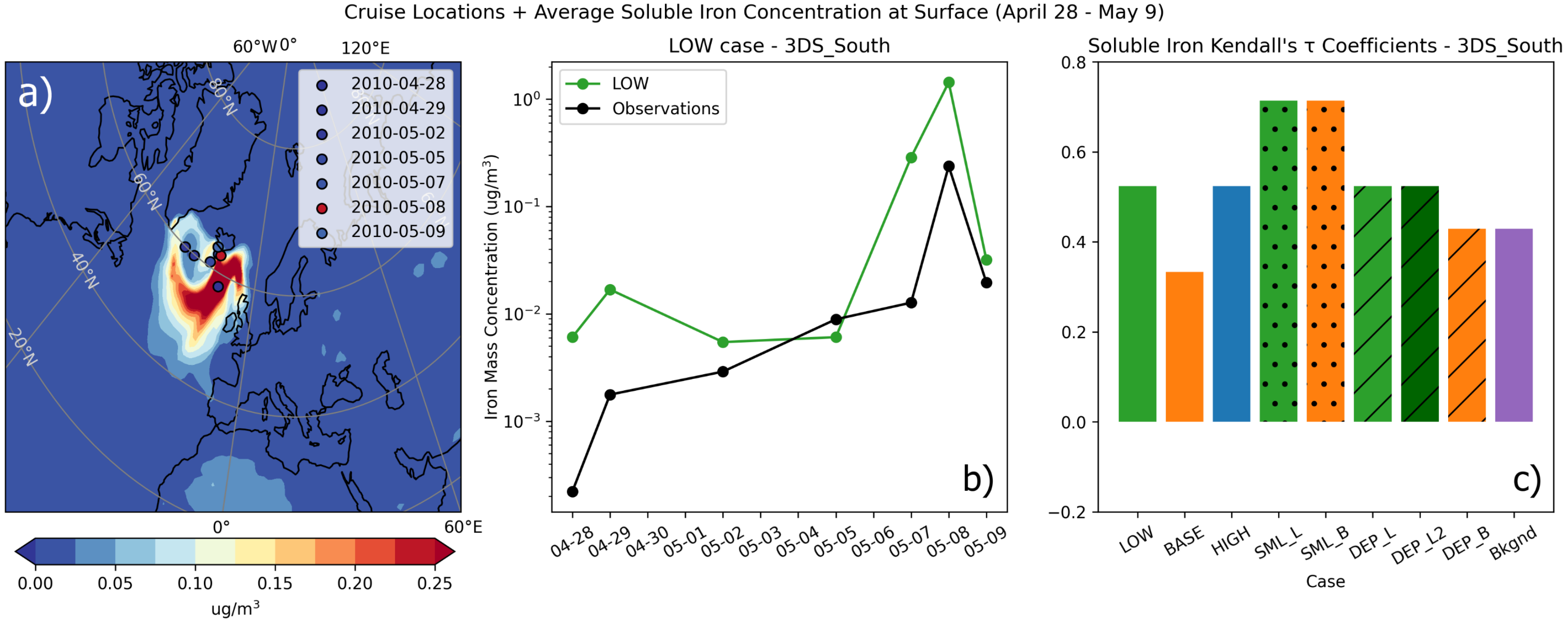
Bisson et al., 2023; Duggen et al., 2010; Langmann, 2014; Olgun et al., 2011

Conclusions + Next Steps

- Our model can simulate some facets of volcanic ash from Eyja
- **Ash plume height > particle size distribution, deposition velocity**
- The radiative forcing of the volcanic ash is net positive, but is also dependent on the particle size distribution
- **The volcanic ash added 24X to 45X more soluble iron to the ocean ecosystem over the North Atlantic than the background**
- Overall, the **LOW** case seems to best match the available observations, but we need more measurements to better verify
- **Next steps: more sensitivity experiments, volcanic eruptions**
    - LARGE – incorporate particle sizes beyond 10 μm
    - "Climatology" of volcanic ash eruptions since the 1980s

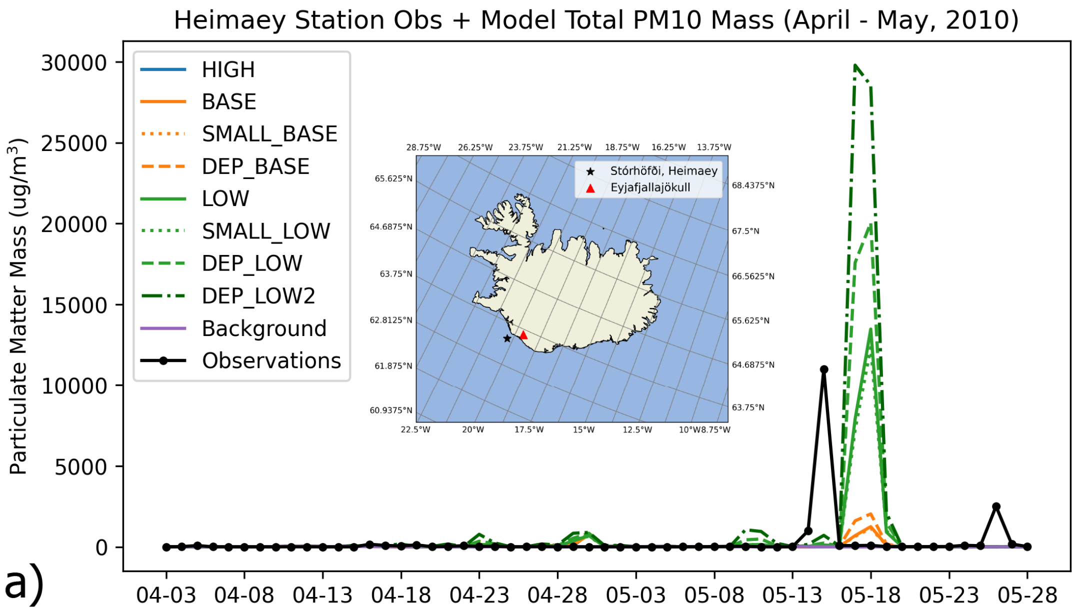
Extra Slides

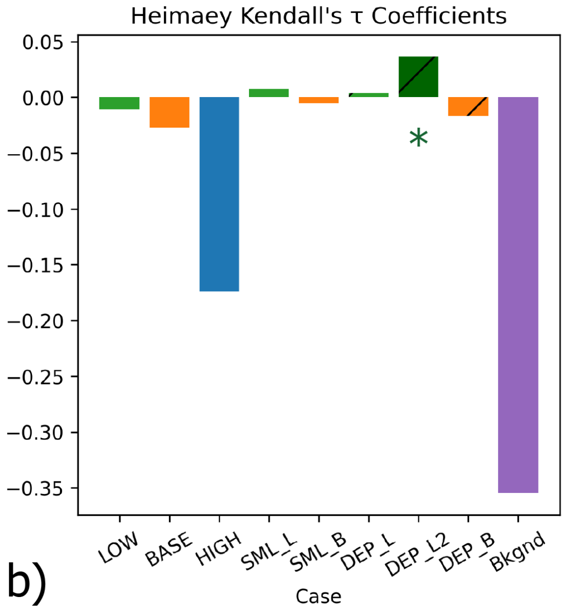




Soluble Iron at the Surface

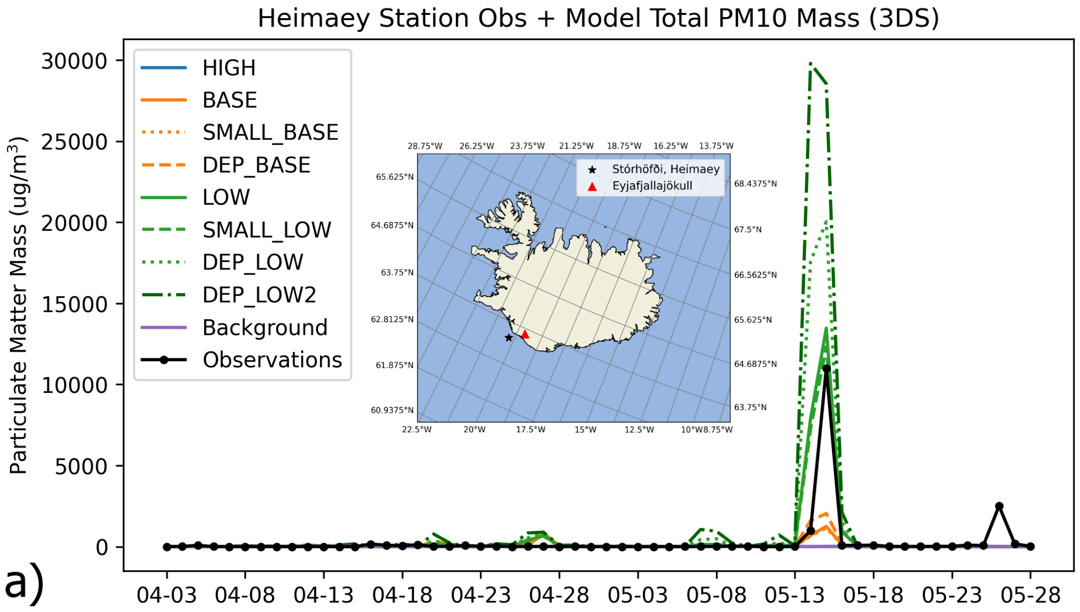
- Observations from the RRS *Discovery* (Achterberg et al., 2013)
- Local iron deposition from ash
  - Here, the 3-day timing shift captures the observed peak on 5/8/2010 better
  - Model performs relatively better compared to the “Background” case without ash

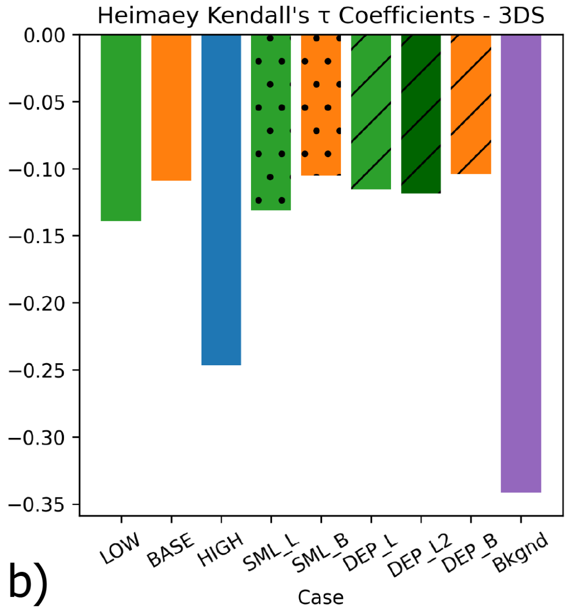




PM10 at the Eruptive Site

- Observations from a lighthouse at Stórhöfði on Heimaey Island (Prospero et al., 2012)
- Local PM10 measurements
  - Model performs relatively poorly compared to the "Background" case without ash
  - There is a 3-day timing delay, which captures the observed peak on 5/15/2010 better?



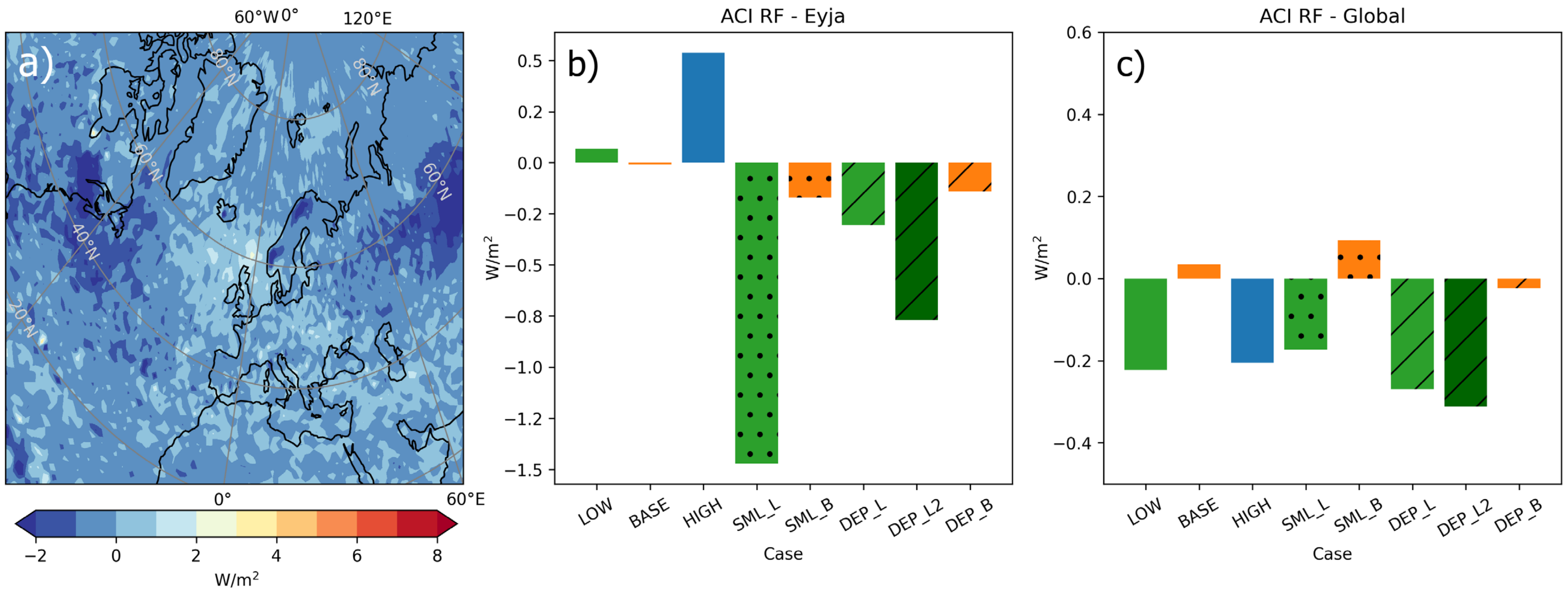


PM10 at the Eruptive Site

- Kendall's tau does not look any better?
  - Pearson r correlations are better (not shown)
  - LOW cases seem to best match observations after shift?

<u> Top of atmosphere (TOA) RF</u>**

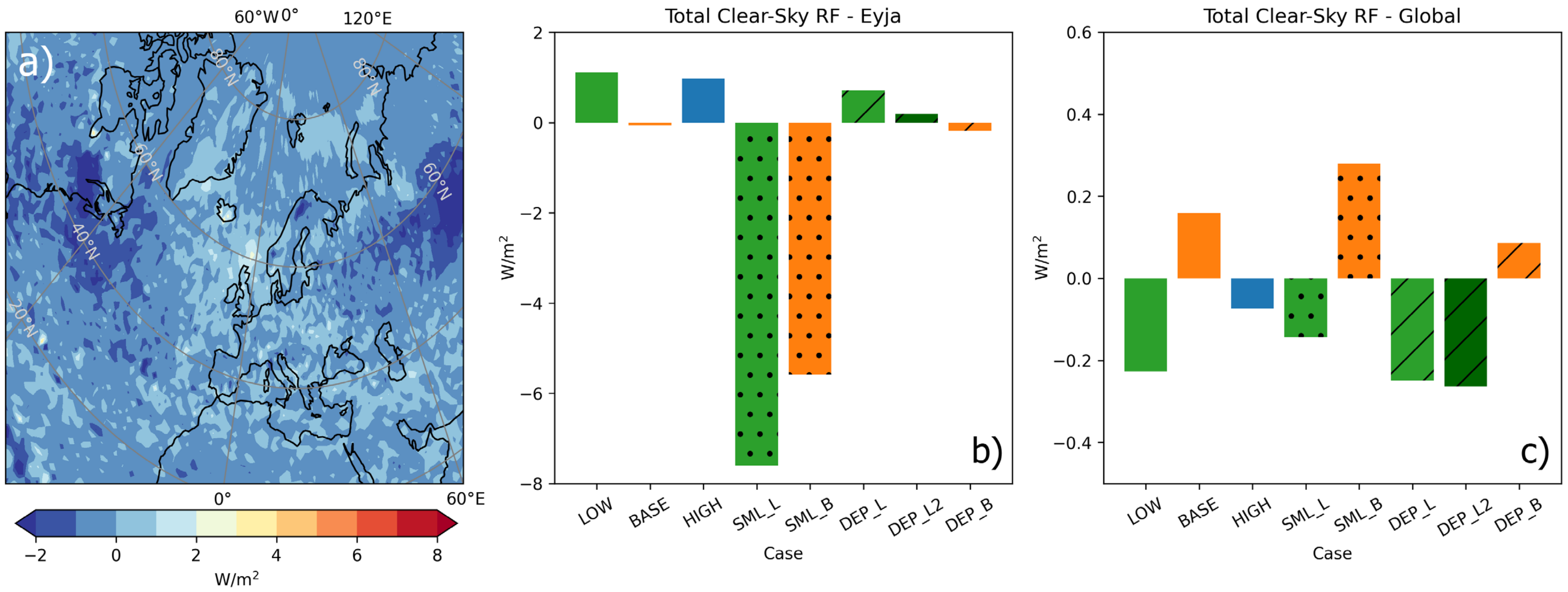
Average Indirect (Aerosol-Cloud Interactions; ACI) Radiative Forcing (April 14 - May 17)



<u>ACI RF</u>

- Very strong negative local RF
  - cooling (b)
- Minimal global RF (c)
- <u>SMALL_LOW: ACI contributes to cooling in the Clear-Sky</u>

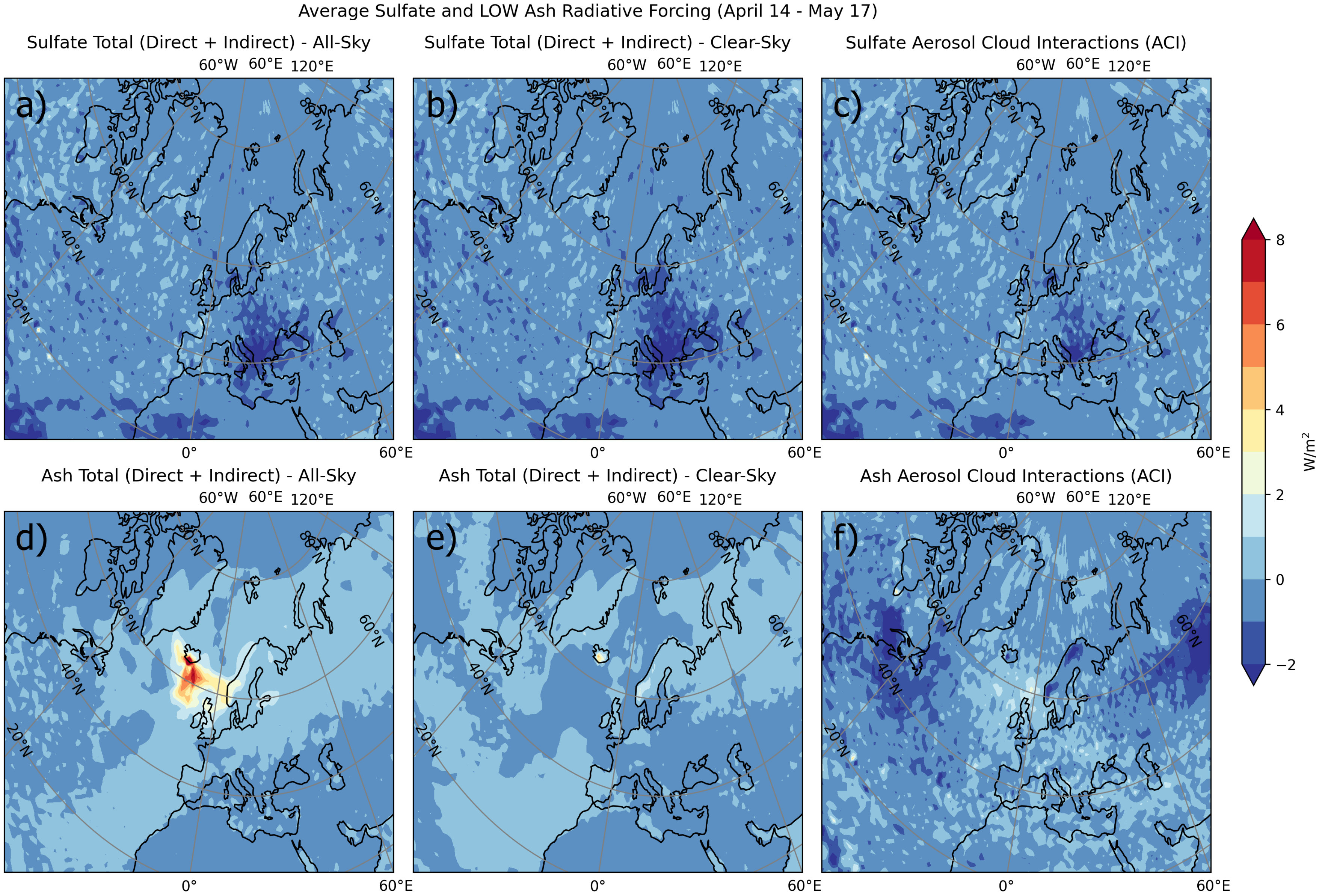
Average Total (Direct + Indirect) Radiative Forcing (Clear-Sky) (April 14 - May 17)



<u>Clear-Sky (without clouds)</u>

- Less strong local RF than All-Sky
  - Very strong <u>NEGATIVE</u> RF for the “SMALL” cases with more mass in the smaller aerosol size bins (b)
- Minimal global RF (c)
- **<u>Senstive to particle size!</u>**

**** Top of atmosphere (TOA) RF**

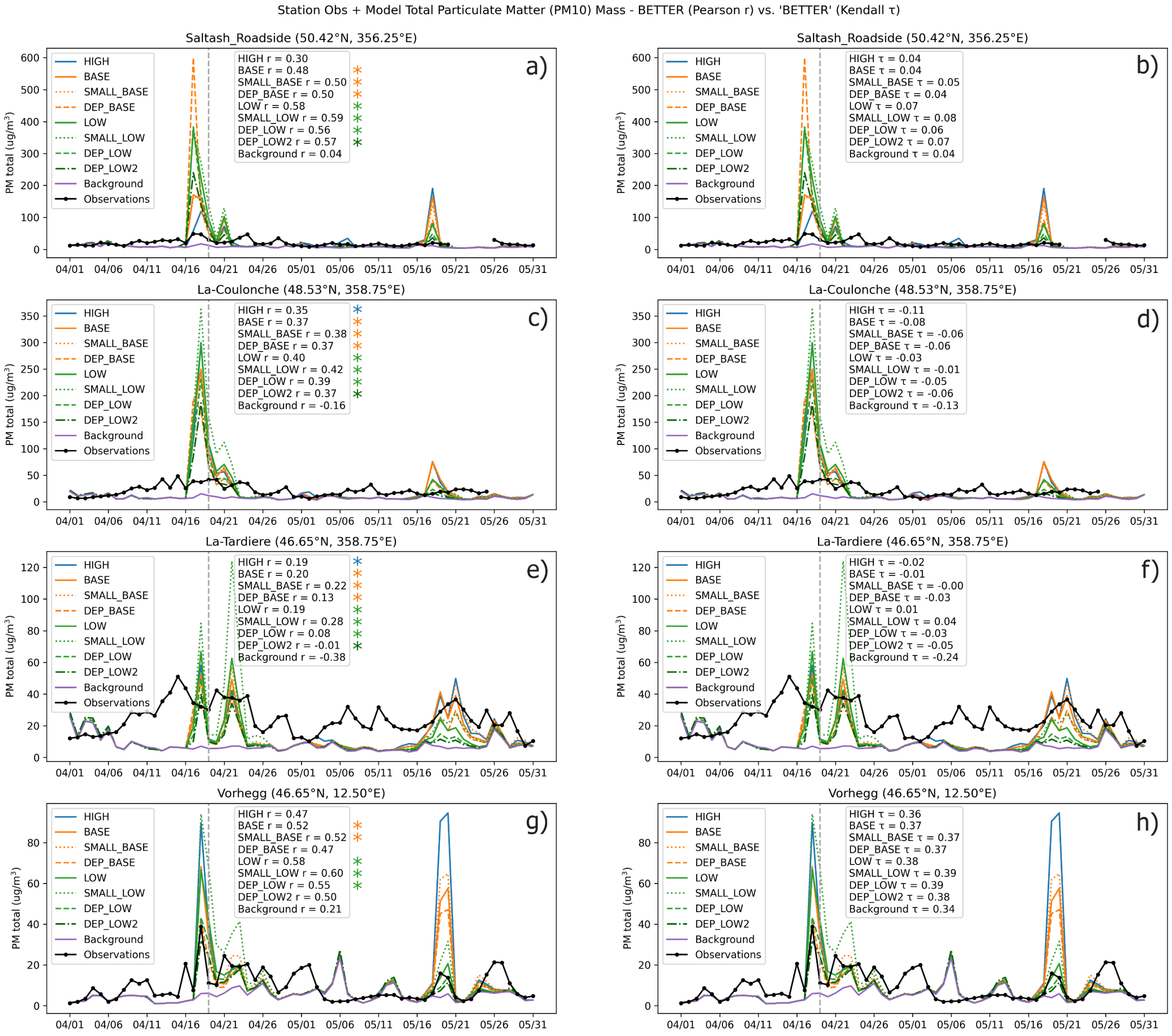


Sulfate RF

- Less strong RF compared to ash
- Sulfates unimportant because they did not reach the Stratosphere
- Could have possible chemistry interactions on ash surface (Zhu et al., 2020)?
  - Not in this model

Ash RF

- Stronger All-Sky RF compared to sulfates
- **Locally, has a larger impact on the RF**



Particulate Matter (PM10)

- Station observations from the AERO-MAP dataset (Mahowald et al., 2025)
- Pearson r correlations "statistically significantly" than the Background case without volcanic ash
- **Overestimating** ash in the beginning

2/186 stations where all cases were statistically significantly better than the Background case → including volcanic ash doesn't improve the model....

Case	Vertical plume profile	Particle size distribution (%)	Deposition velocity	Total emissions mass (Tg)	Lifetime (days)
LOW	Constant mass mixing ratio	Aitken: 0.1 Accumulation: 1 Coarse: 98.9	Dust	34.9	2.4
BASE	90% mass in the top km, 10% evenly in the bottom	Aitken: 0.1 Accumulation: 1 Coarse: 98.9	Dust	34.9	5.5
HIGH	100% mass at the maximum plume height	Aitken: 0.1 Accumulation: 1 Coarse: 98.9	Dust	34.9	6.8
SMALL_LOW	Constant mass mixing ratio	Aitken: 0.1 Accumulation: 8 Coarse: 91.9	Dust	34.9	3.2
SMALL_BASE	90% mass in the top km, 10% evenly in the bottom	Aitken: 0.1 Accumulation: 8 Coarse: 91.9	Dust	34.9	6.8
DEP_LOW	Constant mass mixing ratio	Aitken: 0.1 Accumulation: 1 Coarse: 98.9	1.5X dust	34.9	1.7
DEP_LOW2	Constant mass mixing ratio	Aitken: 0.1 Accumulation: 1 Coarse: 98.9	2X dust	34.9	1.4
DEP_BASE	90% mass in the top km, 10% evenly in the bottom	Aitken: 0.1 Accumulation: 1 Coarse: 98.9	1.5X dust	34.9	3.9

%	SOU	LP3	LP11	LP14	Ash Average	Dust
Aitken	1.991e-4	1.691e-3	1.222e-3	5.056-4	9.149e-4	1.65e-3
Accumulation	0.9482	8.055	5.821	2.408	4.31	1.1
Coarse	99.05	91.94	94.18	97.59	95.69	98.9

For reference:
Aitken: 0 – 0.1 µm
Accum: 0.1 – 1 µm
Coarse: 1 – 10 µm

"SMALL"
Aitken: 0.1%
Accum: 8 %
Coarse: 91.9 %

Current Ash:
Aitken: 0.1%
Accum: 1%
Coarse: 98.9 %

Current Dust:
Aitken: 0.1%
Accum: 1%
Coarse: 98.9 %

Ash and dust particle size distribution as a percentage of the mass in the three aerosol size modes: Aitken (0-0.1 µm), accumulation (0.1-1 µm), and coarse mode (1-10 µm). The first four columns show the mass percentage from different volcanic ash measurement collections: SOU (La Soufrière from April 2021) and LP (La Palma/Cumbre Vieja from October 2021), based on deposition particle sizes as reported in Elliott et al. (2025). The average of the four ash observations (column 5) very closely resembles the current dust size distribution in the model (column 6), providing support for the use of dust tracers as ash tracers. Thus, we currently assume 0.1% ash mass in the Aitken mode, 1% in the accumulation mode, and 98.9% in the coarse mode. Note that LP3 (second column) represents an extreme case out of the four samples. We use this to constrain our "SMALL" cases, assuming 0.1% ash mass in the Aitken mode, 8% in the accumulation mode, and 91.9% in the coarse mode.

Elliott et al., 2025