High-latitude effusive volcanism and Arctic warming: Insights from the Holuhraun eruption

Tómas Zoëga

et al.:
Kirstin Krüger
Trude Storelvmo

Flagship seminar
12.06.2025

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Terminology

Volcanic eruptions

... are events when magma exits the ground (Siebert et al., 2015)

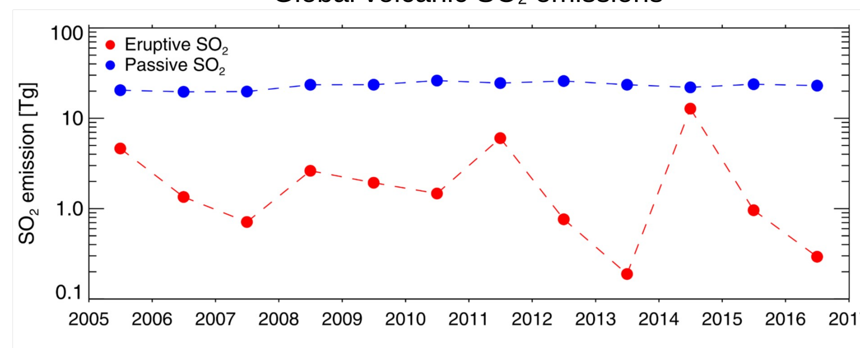
(passive or quiet degassing)

Very diverse

Explosive | **Effusive**

>95% tephra | >95% lava

Global volcanic SO_2 emissions (c)



Tordarson and Larsen (2007)

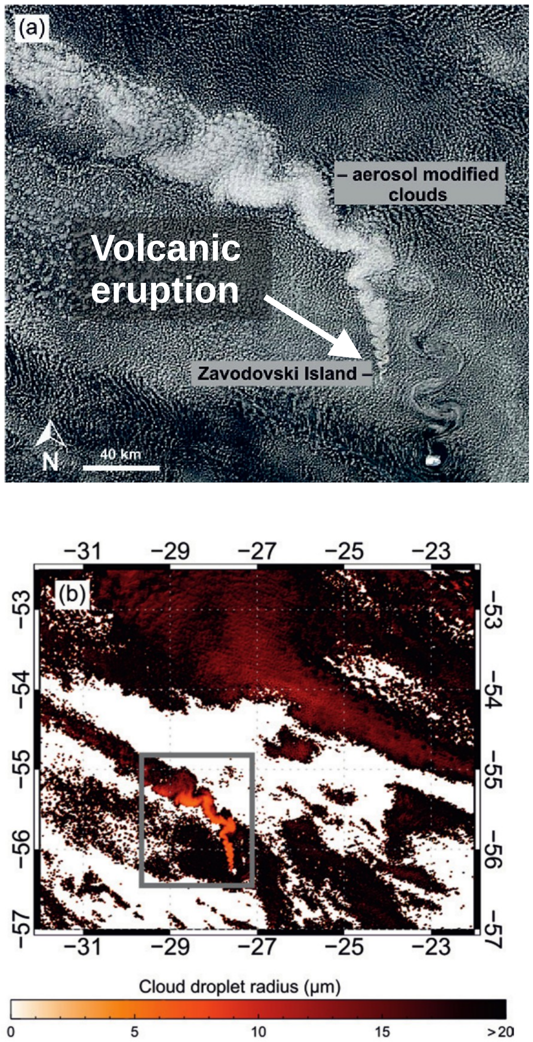
Carn et al. (2017)

Effusive eruptions

- **Non-explosive**
- **Tropospheric emissions**
- Recent eruptions have been found to significantly impact clouds (e.g. Malavelle et al., 2017; Chen et al., 2022)

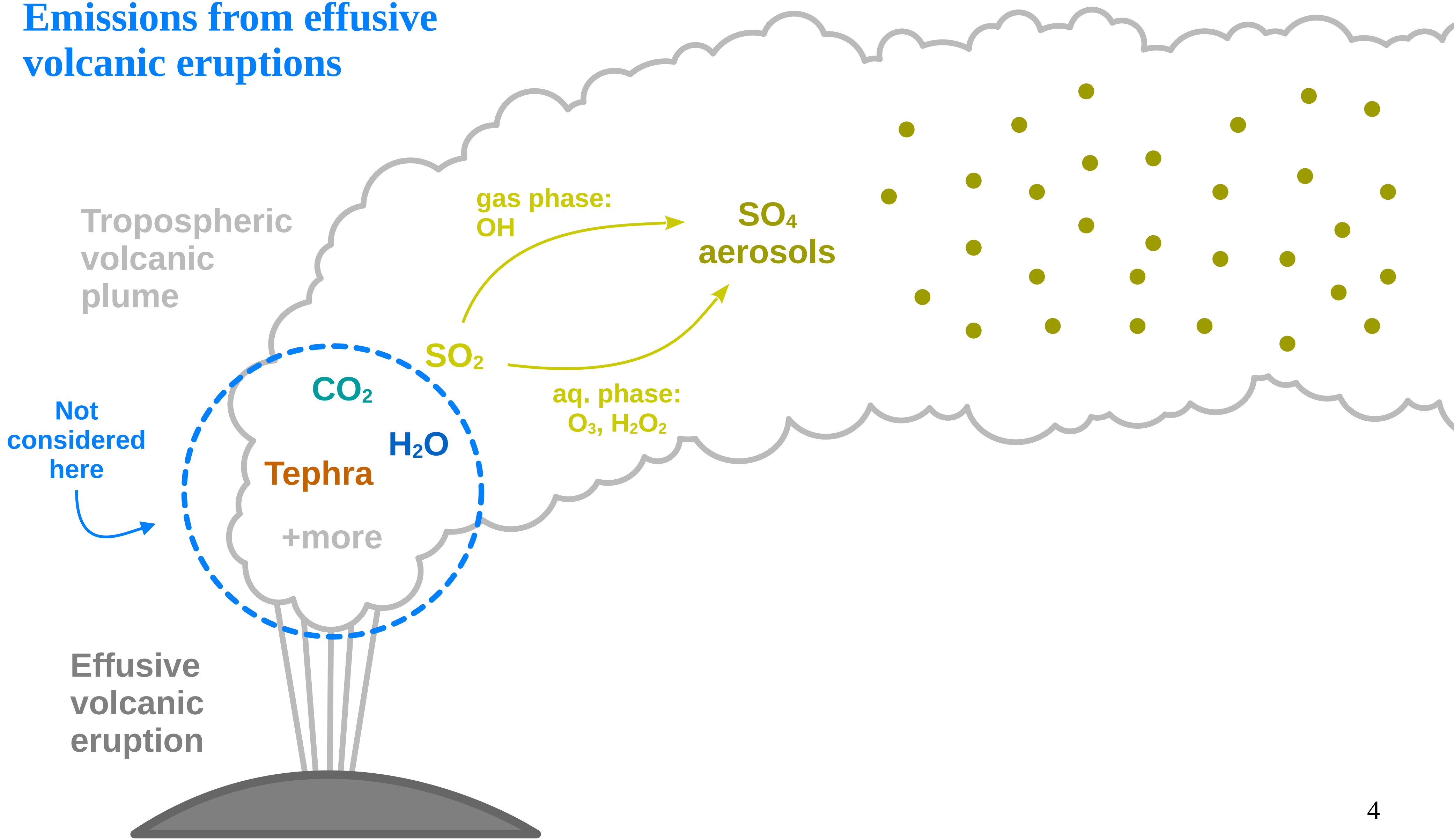
2021 Fagradalsfjall

2010 Fimmvörðuháls



MODIS, Schmidt et al. (2012), South Sandwich Islands

Emissions from effusive volcanic eruptions



Motivation

Thordarson and Larsen (2007):

- 35 of 205 eruptions (ca. 17%) in Iceland over the past 1100 years effusive or mixed
- The rest is explosive

→ **Effusive eruptions are relatively rare**

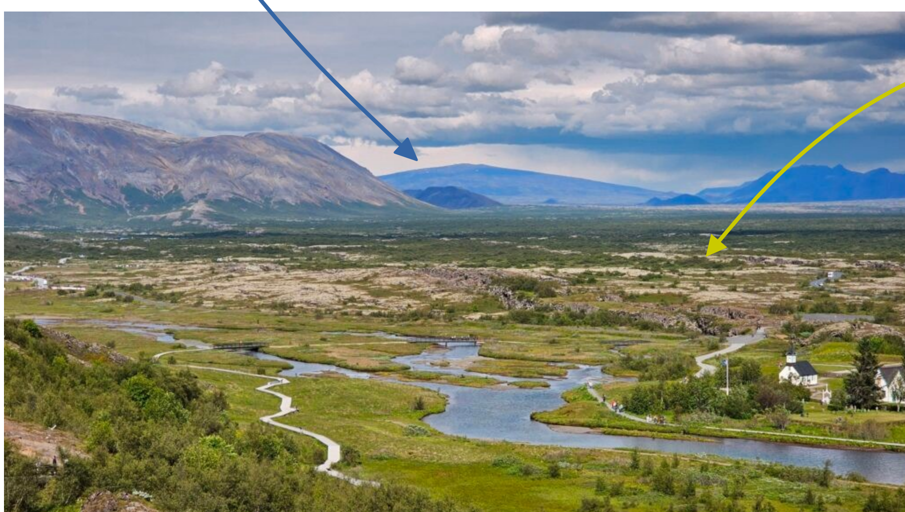
However

- Several **prominent effusive events in recent decades** → e.g. Krafla, Holuhraun, Reykjanes peninsula
- Very large basalt formations formed in **effusive eruptions lasting years**
- Strong **increase in volcanism after the retreat of ice age glaciers** (11 kyr BP)

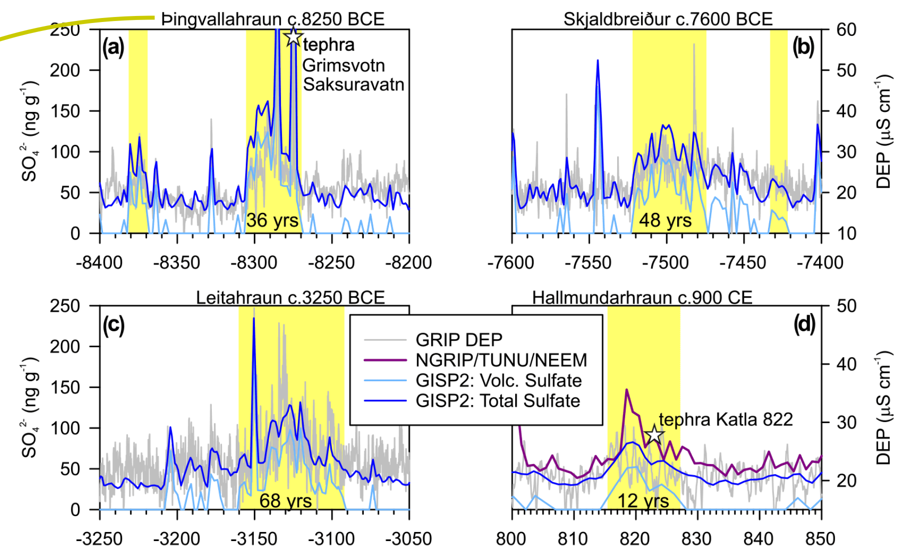
→ e.g. Skjaldbreiður, Þingvallahraun, Þjórsárhraun

Motivation

	Duration	Total SO_2	Mean SO_2 rate	Ref.
ca. 10 kyr BP Skjaldbreiður	>10 yrs (?)	?	25 kt/day (?)	Thordarson and Höskuldsson (2008) + own est.
1783-84 Laki	8 months	122 Tg	~500 kt/day	Thordarson and Self (2003)
2014-15 Holuhraun	**181 days**	**9.6 Tg**	**53 kt/day**	Pfeffer et al. (2018)
2021 Fagradalsfjall	183 days	0.97 Tg	5.3 kt/day	Pfeffer et al. (2024)
2024 Sundhnúksgígar (VI)	14 days	0.4 Tg (?)	30 kt/day (?)	Own est. based on lava volume



https://icelandinfocus.com/mt-skjaldbreidur-the-magnificent-shield-volcano/



Sigl et al. (2022)

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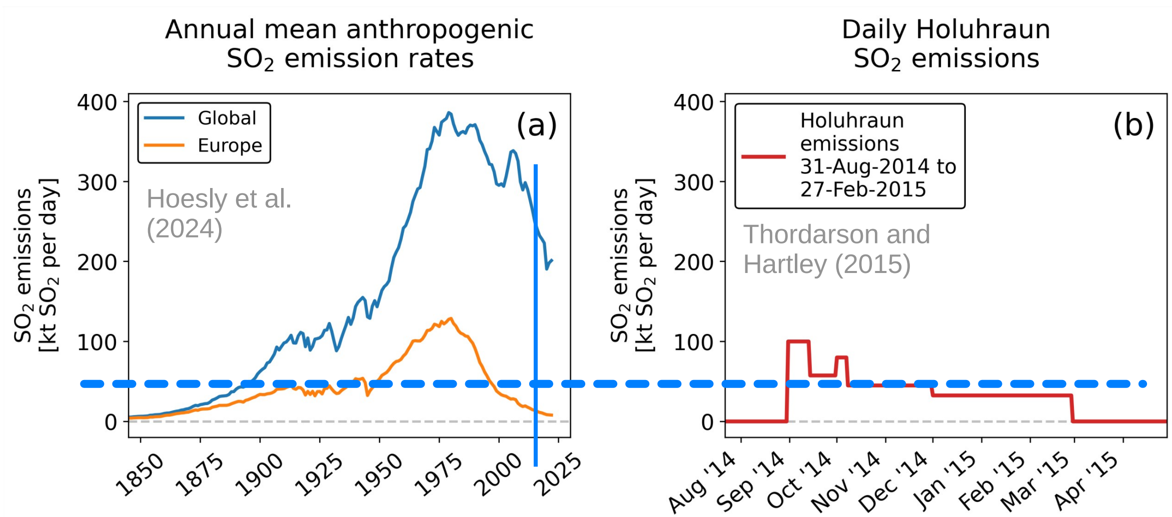

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A lot has happened in the past decade

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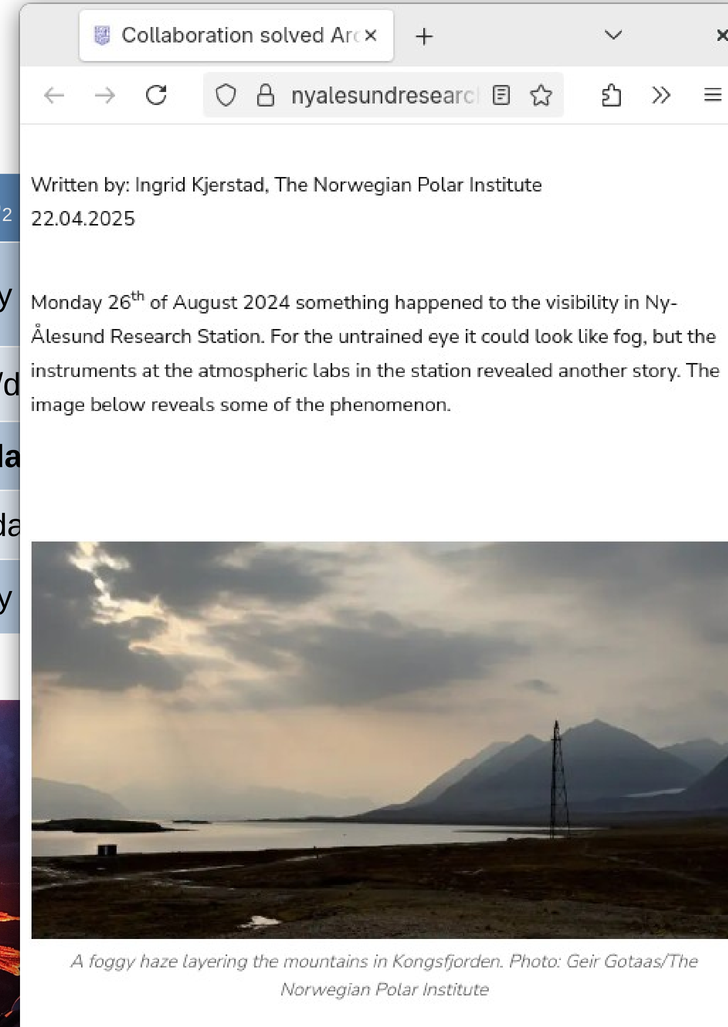


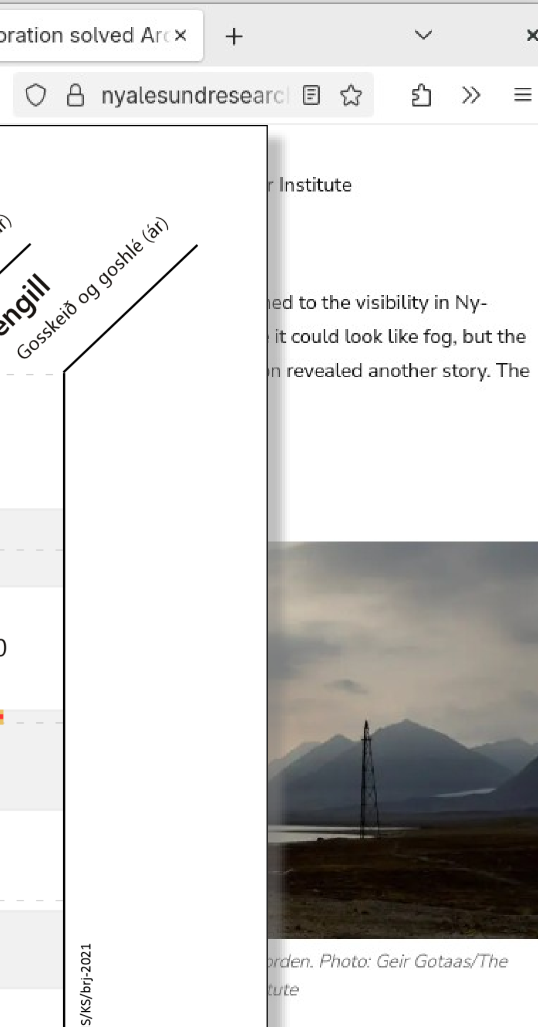
Written by: Ingrid Kjerstad, The Norwegian Polar Institute
22.04.2025

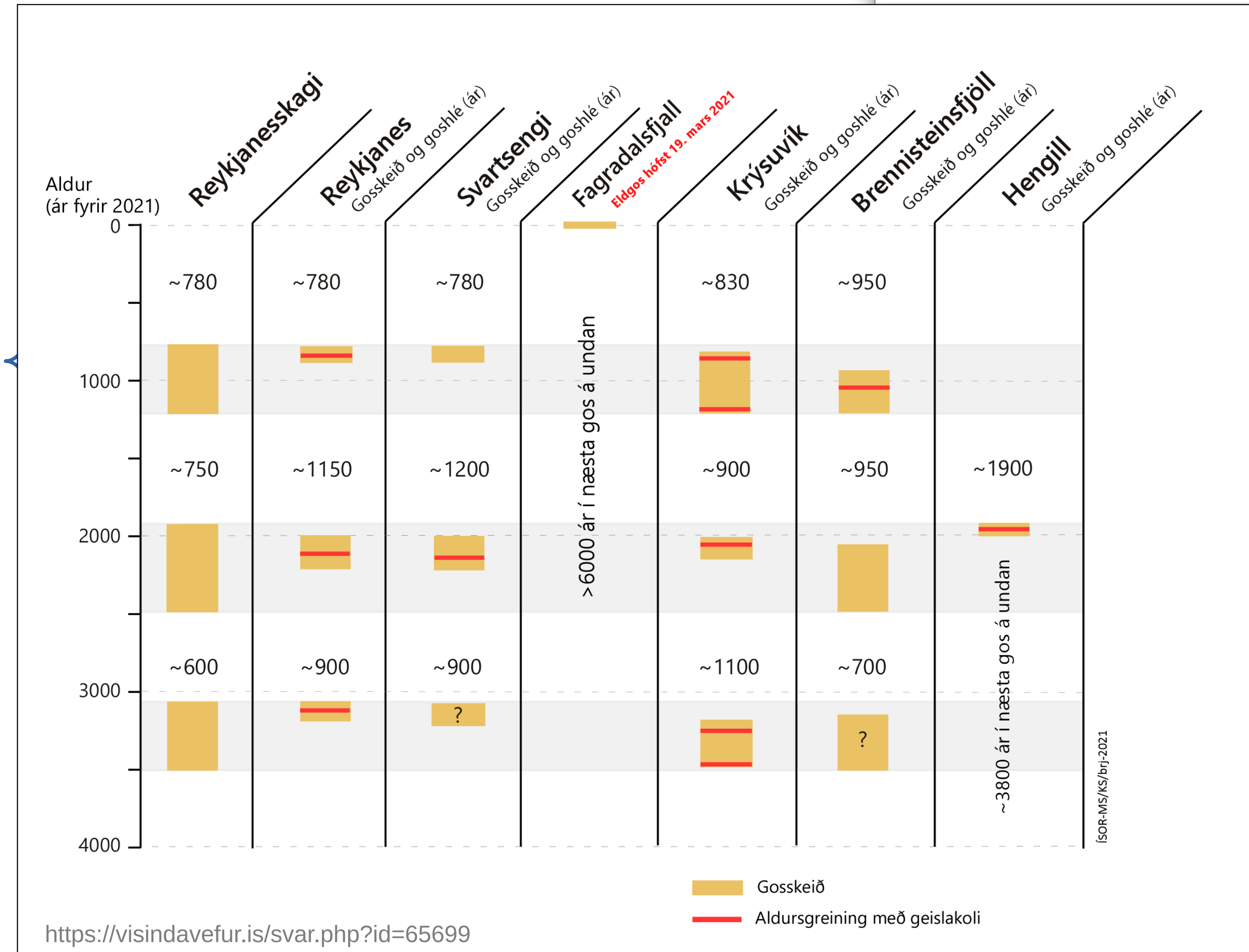
Monday 26th of August 2024 something happened to the visibility in Ny-Ålesund Research Station. For the untrained eye it could look like fog, but the instruments at the atmospheric labs in the station revealed another story. The image below reveals some of the phenomenon.

A foggy haze layering the mountains in Kongsfjorden. Photo: Geir Gotaas/The Norwegian Polar Institute

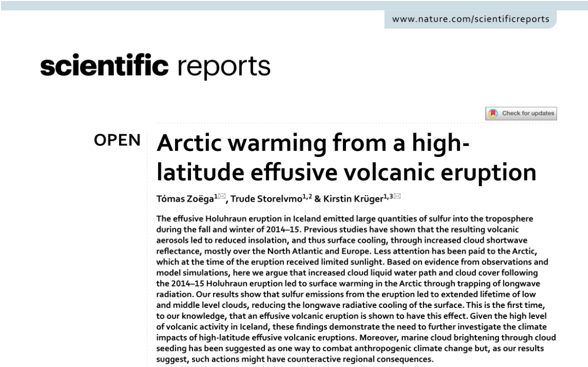
Motivation

A lot has happened in the past decade





A series of papers



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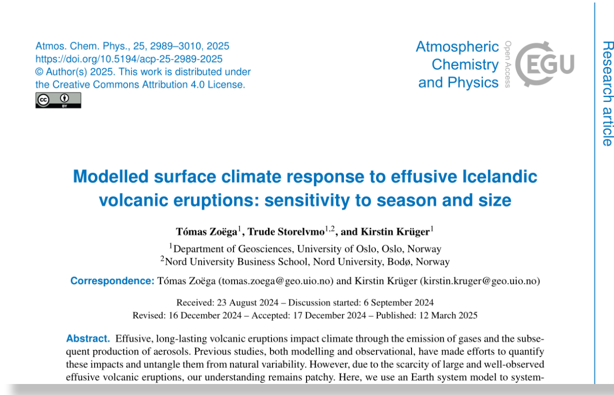
Arctic warming from a high-latitude effusive volcanic eruption

Tómas Zoëga[1], Trude Storelvmo[1,2] & Kirstin Krüger[1,3]

The effusive Holuhraun eruption in Iceland emitted large quantities of sulfur into the troposphere during the fall and winter of 2014–15. Previous studies have shown that the resulting volcanic aerosols led to reduced insolation, and thus surface cooling, through increased cloud shortwave reflectance, mostly over the North Atlantic and Europe. Less attention has been paid to the Arctic, which at the time of the eruption received limited sunlight. Based on evidence from observations and model simulations, here we argue that increased cloud liquid water path and cloud cover following the 2014–15 Holuhraun eruption led to surface warming in the Arctic through trapping of longwave radiation. Our results show that sulfur emissions from the eruption led to extended lifetime of low and middle level clouds, reducing the longwave radiative cooling of the surface. This is the first time, to our knowledge, that an effusive volcanic eruption is shown to have this effect. Given the high level of volcanic activity in Iceland, these findings demonstrate the need to further investigate the climate impacts of high-latitude effusive volcanic eruptions. Moreover, marine cloud brightening through cloud seeding has been suggested as one way to combat anthropogenic climate change but, as our results suggest, such actions might have counteractive regional consequences.



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Atmospheric Chemistry and Physics

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Research article

Modelled surface climate response to effusive Icelandic volcanic eruptions: sensitivity to season and size

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[2]Nord University Business School, Nord University, Bodø, Norway

Correspondence: Tómas Zoëga (tomas.zoega@geo.uio.no) and Kirstin Krüger (kirstin.kruger@geo.uio.no)

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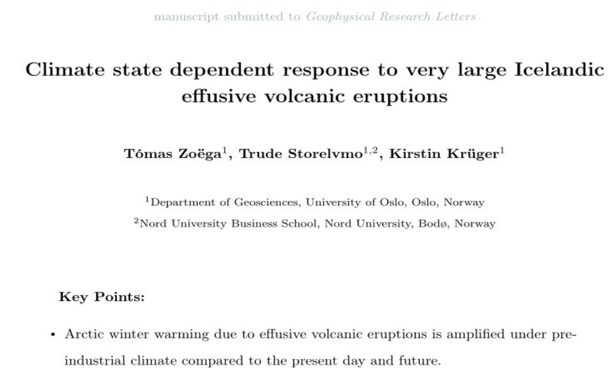
Revised: 16 December 2024 – Accepted: 17 December 2024 – Published: 12 March 2025

Abstract. Effusive, long-lasting volcanic eruptions impact climate through the emission of gases and the subsequent production of aerosols. Previous studies, both modelling and observational, have made efforts to quantify these impacts and untangle them from natural variability. However, due to the scarcity of large and well-observed effusive volcanic eruptions, our understanding remains patchy. Here, we use an Earth system model to system-



manuscript submitted to *Geophysical Research Letters*

Climate state dependent response to very large Icelandic effusive volcanic eruptions

Tómas Zoëga[1], Trude Storelvmo[1,2], Kirstin Krüger[1]

[1]Department of Geosciences, University of Oslo, Oslo, Norway
[2]Nord University Business School, Nord University, Bodø, Norway

Key Points:

- Arctic winter warming due to effusive volcanic eruptions is amplified under pre-industrial climate compared to the present day and future.

A case study of the 2014-15 Holuhraun eruption in Iceland using observational and modelling evidence

Published in
Scientific Reports

https://doi.org/10.1038/s41598-025-98811-5

A modelling study of the climate response to Holuhraun-like eruptions as a function of **eruption season and size**

Published in *Atmospheric Chemistry and Physics*

https://doi.org/10.5194/acp-25-2989-2025

A modelling study of the modulating effects of the **climate state** on the climate response to Holuhraun-like eruptions

In review at *Geophysical Research Letters*

Arctic warming from a high-latitude effusive volcanic eruption

A case study of the 2014-15 Holuhraun eruption

Significant impacts on clouds found in previous studies

E.g. McCoy and Hartmann (2015), Malavelle et al. (2017), Chen et al. (2022)

The focus of this study is on the high latitudes north of Iceland

peterhartree (2014)
https://www.flickr.com/photos/41812768@N07/15145866372/

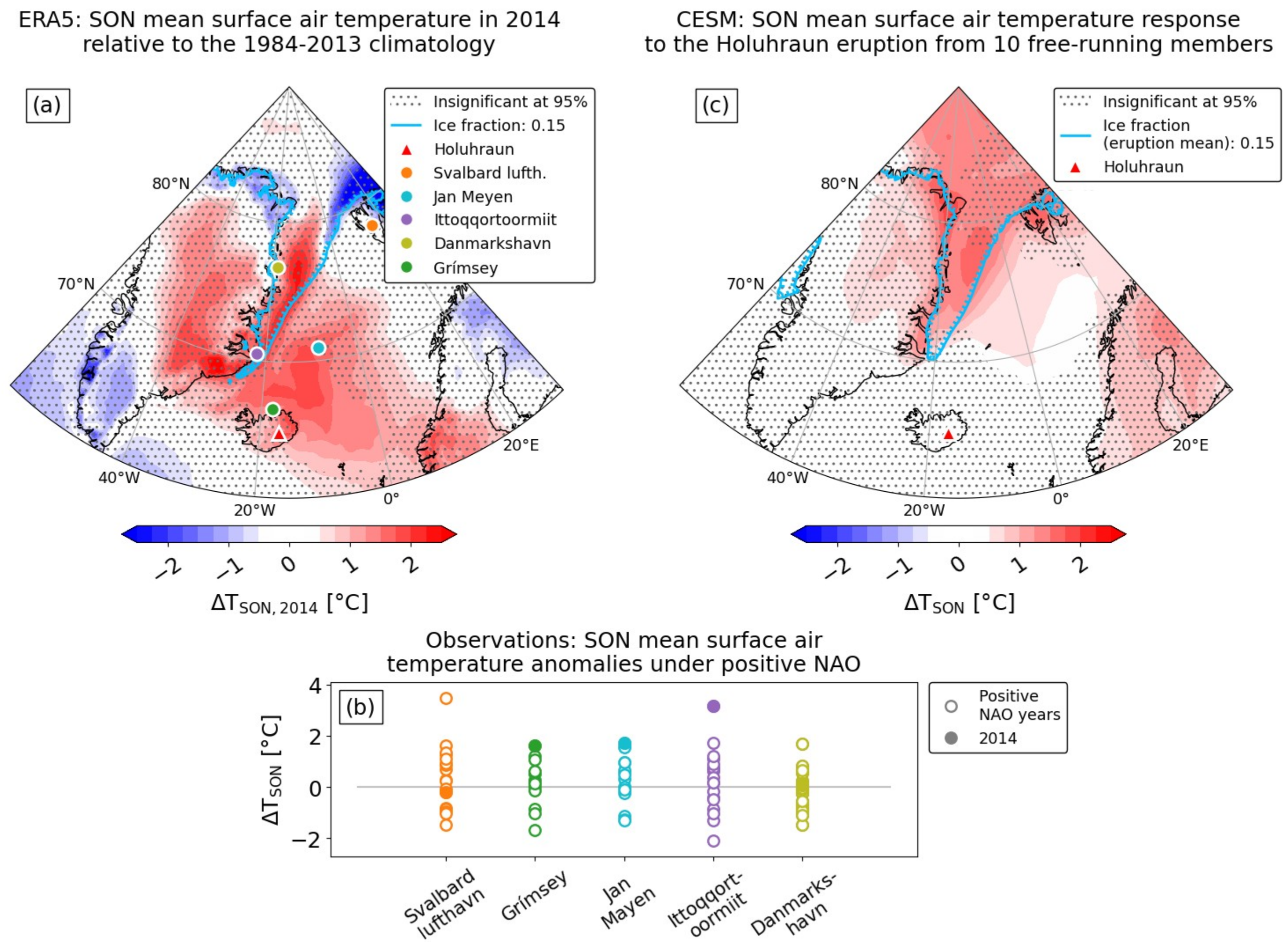
Holuhraun: A case study

Abnormally warm September to November (SON) 2014 over the Nordic Seas, both in **direct observations** (+2 to +3°C) and the **ERA5 reanalysis** (up to +2°C)

Also **positive temperature anomalies** in the free-running **CESM2** simulations (up to +2°C)

⇓

A contribution from the Holuhraun eruption?



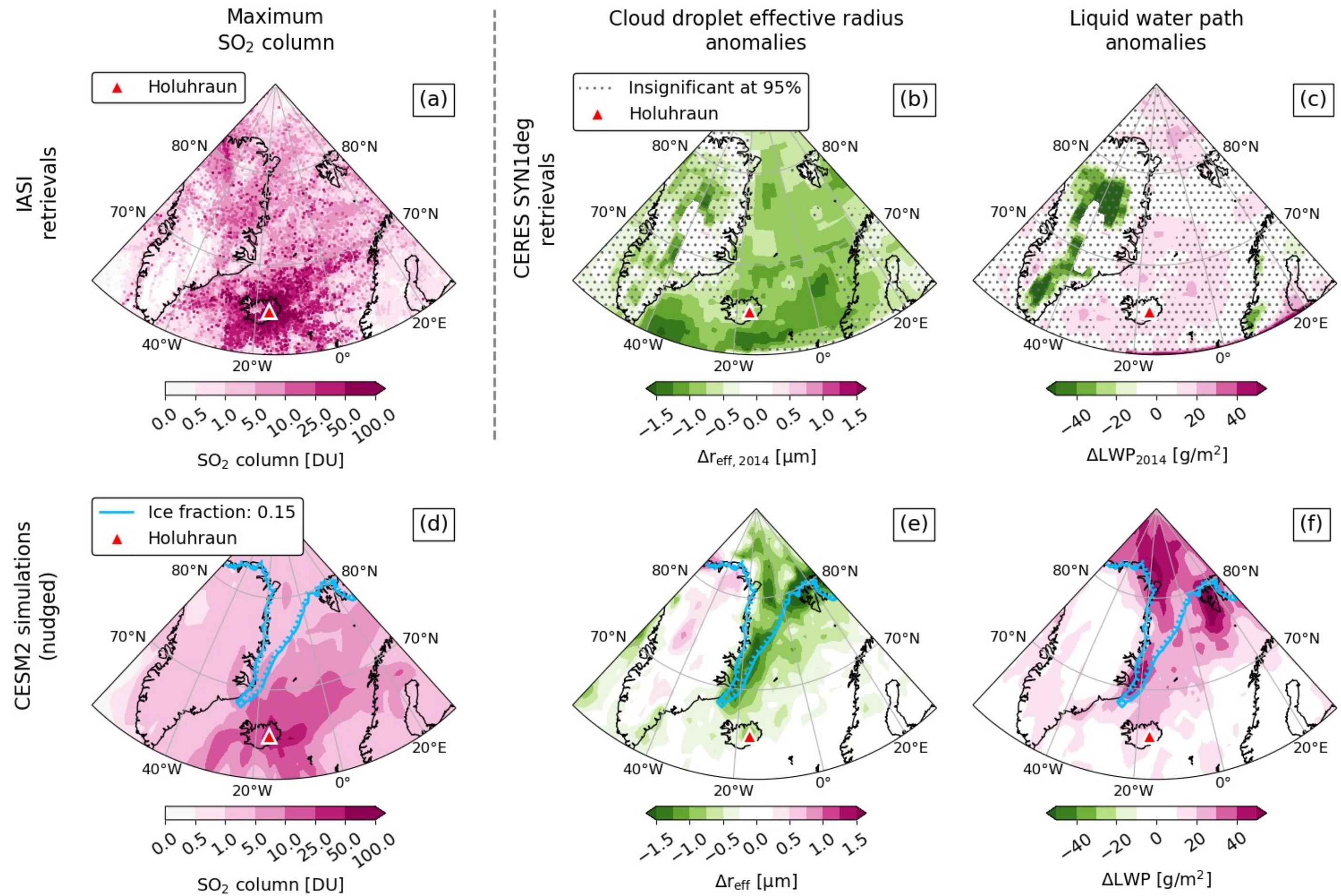
Holuhraun: A case study

Satellite retrievals show

… prominent and widely significant **decrease in cloud droplet size**

… considerable and partially significant **increase in cloud LWP**

Anomalies broadly captured by nudged CESM2 simulations



Holuhraun: A case study

Satellite retrievals show

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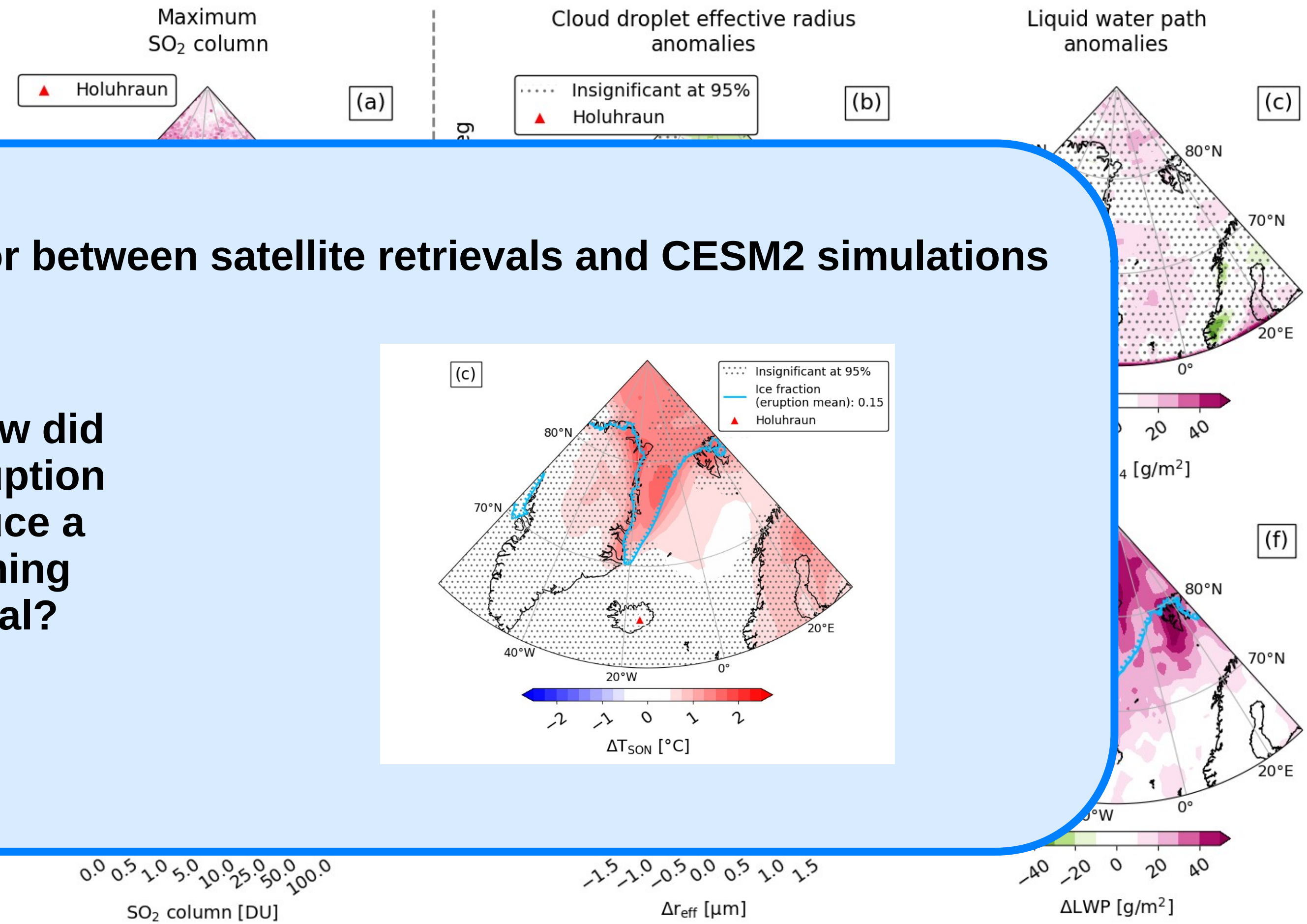
Good agreement for between satellite retrievals and CESM2 simulations

But how did the eruption produce a warming signal?



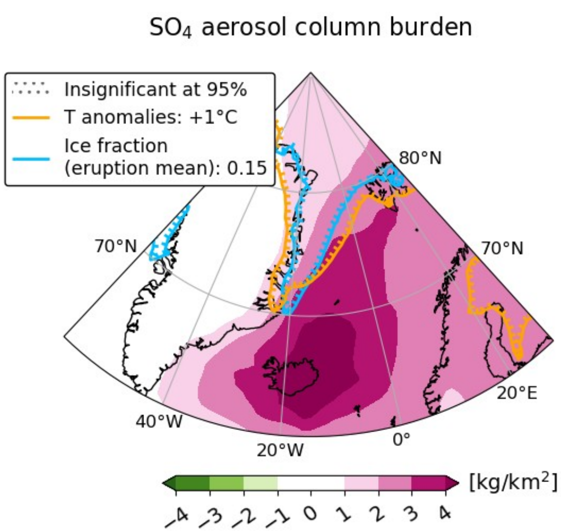
Holuhraun: A case study

Coupled, free-running CESM2 simulations help identify mechanisms

Volcanic emissions of SO_2

SO_4 aerosol mass **increases**

Cloud response



Holuhraun: A case study

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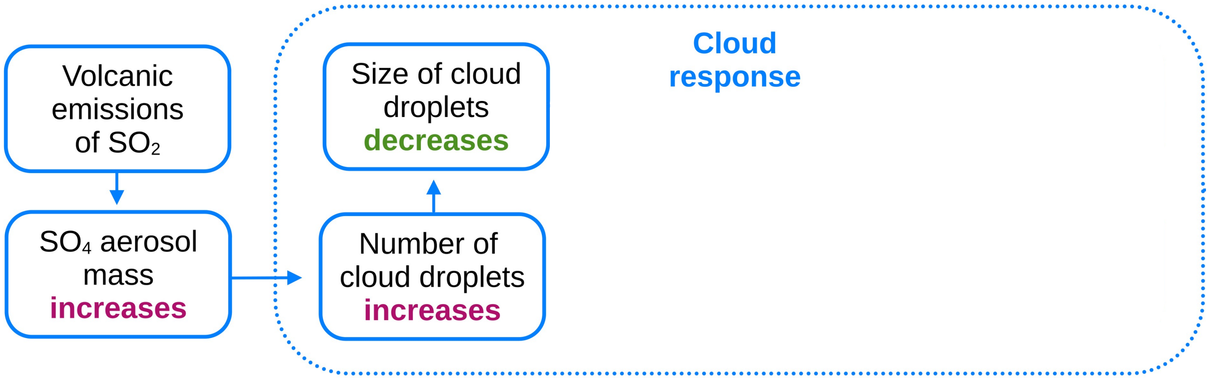

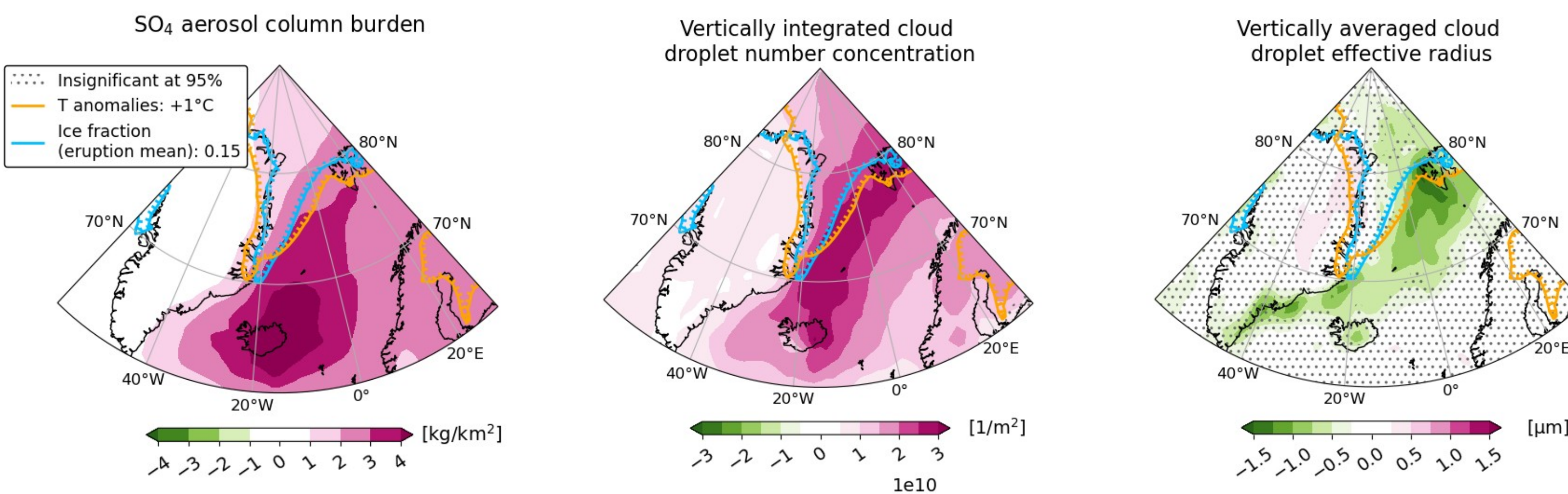

Holuhraun: A case study

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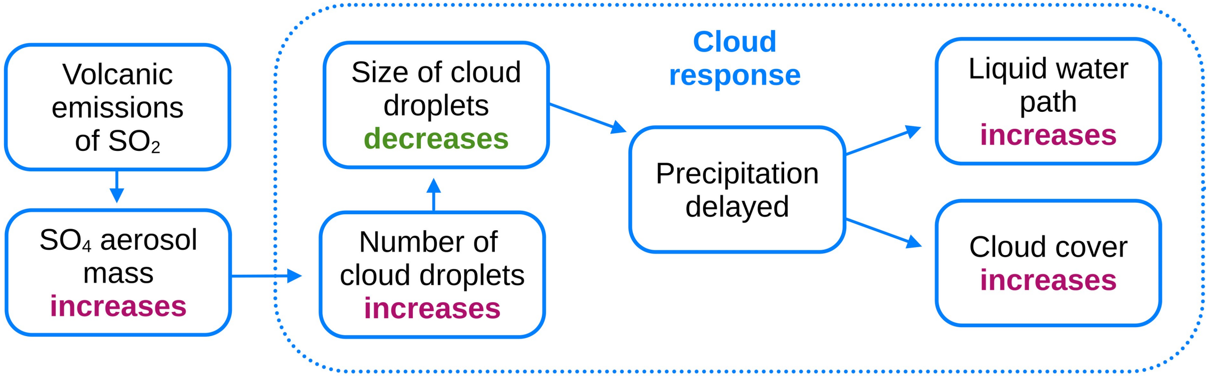

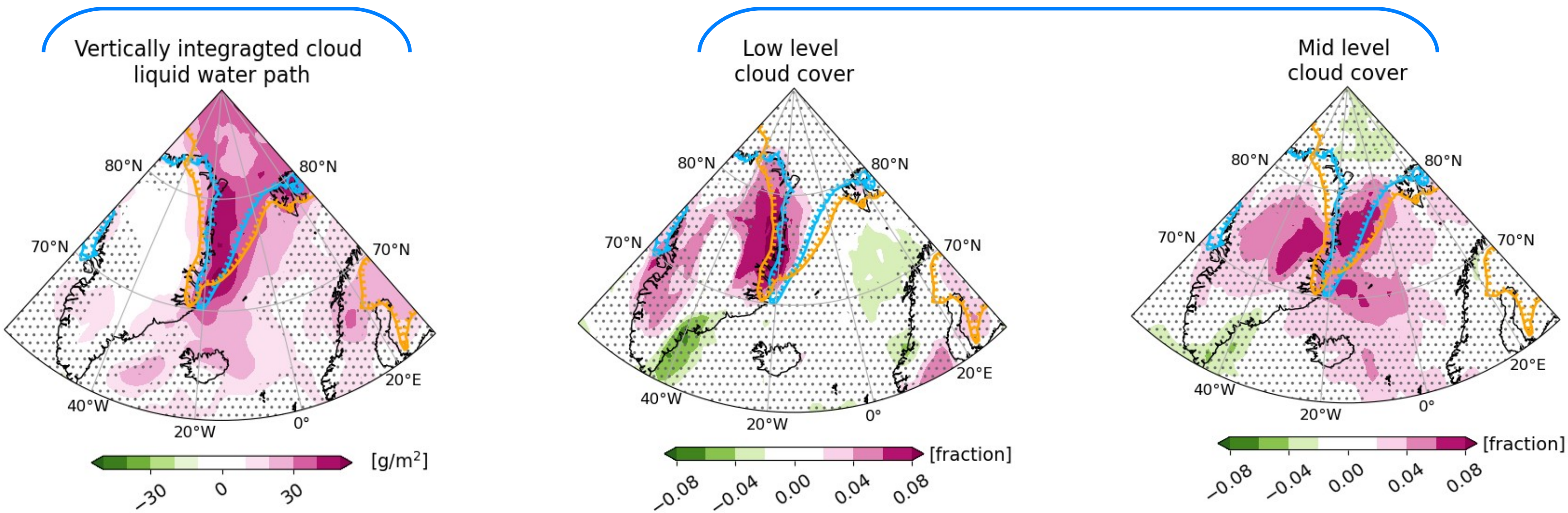

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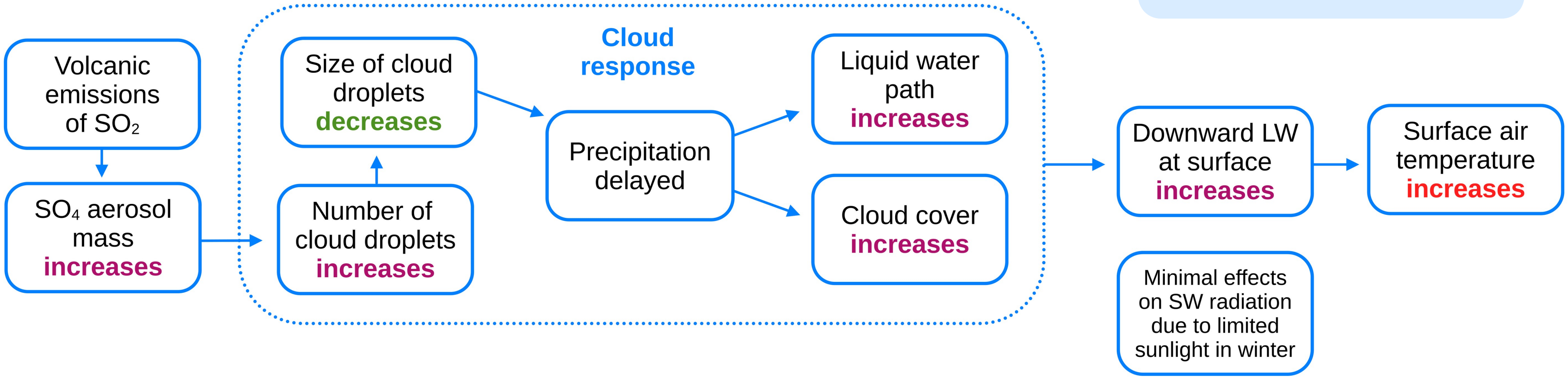
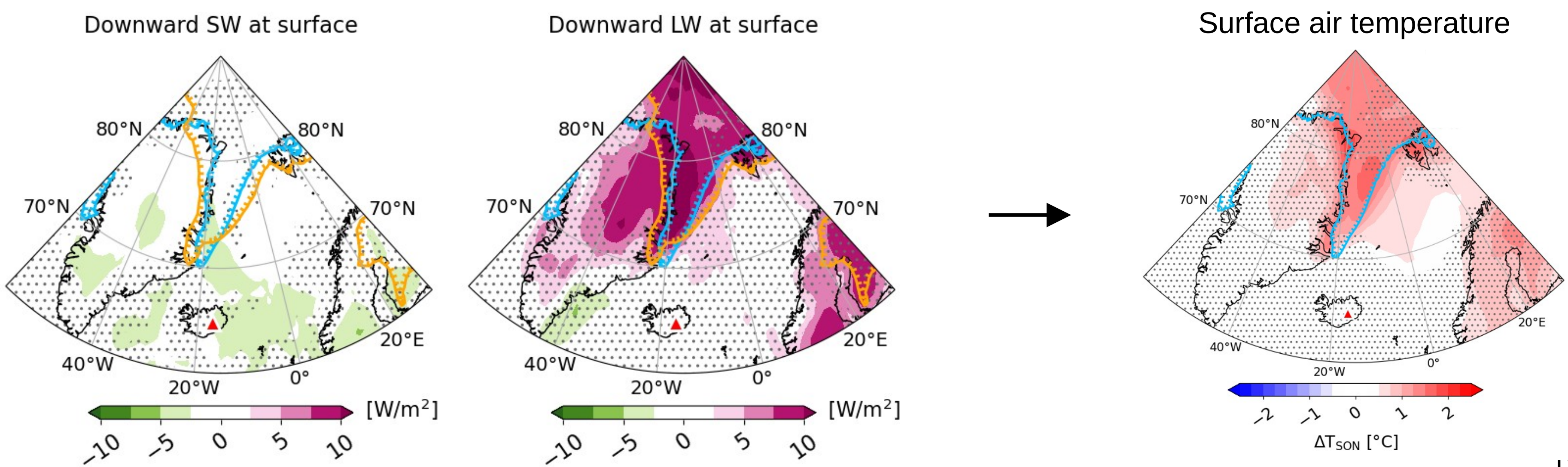
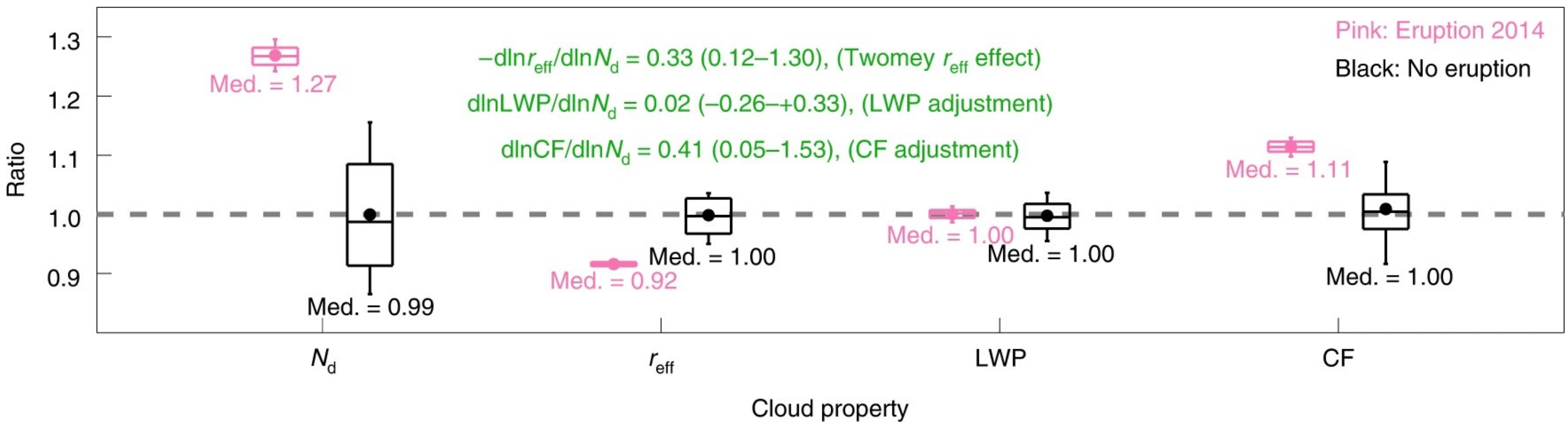




Holuhraun: A case study
Notes on the cloud adjustments

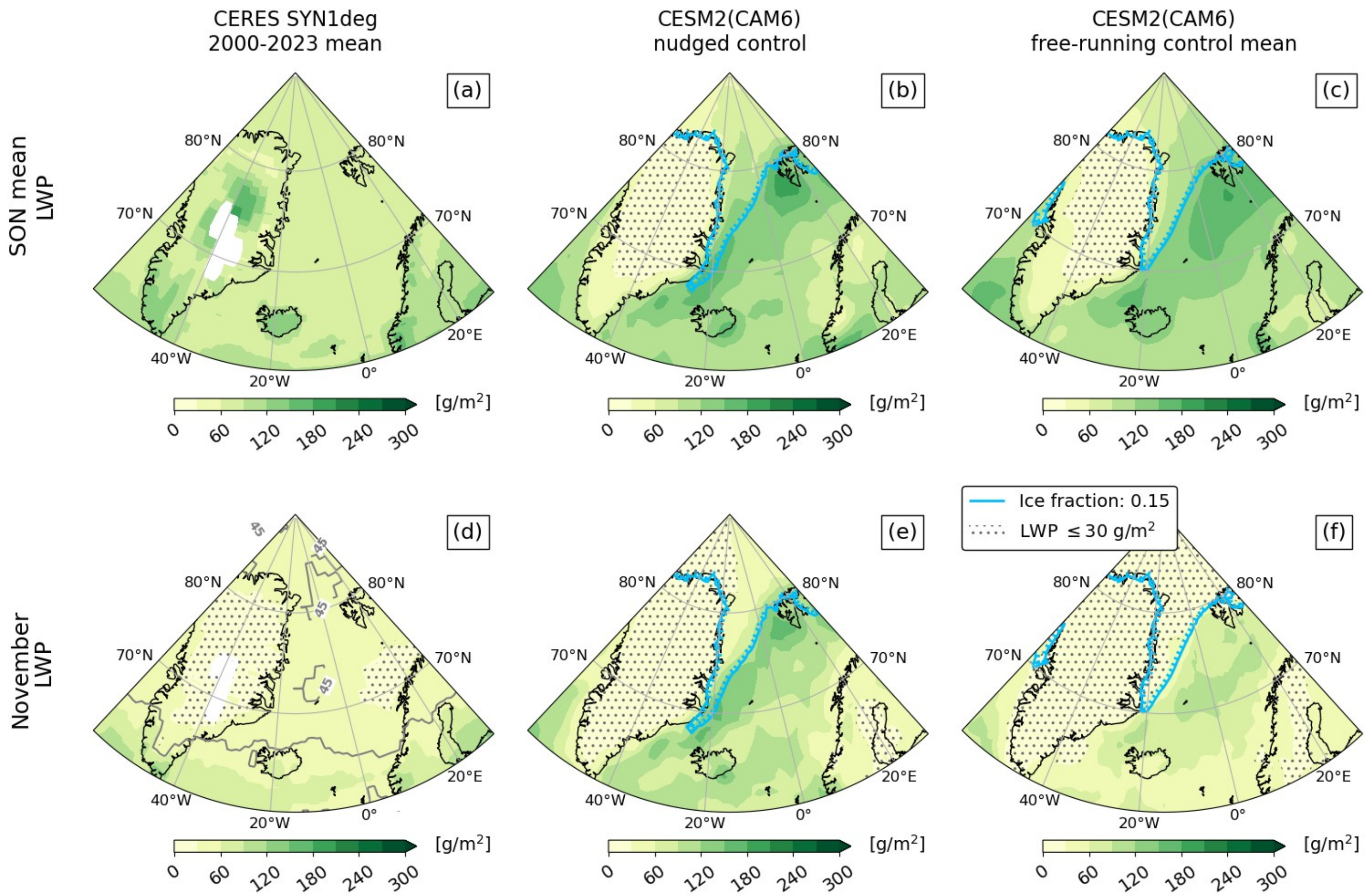


Cloud properties in October 2014 over ocean areas around Iceland **from Chen et al. (2022)** (Fig. 3)

Holuhraun: A case study
Notes on the cloud adjustments

- If LWP > 30 g/m²

⇒ Clouds opaque to LW radiation



Holuhraun: A case study

Summary

- **Observations and reanalysis show warming of up to +2°C over the Greenland Sea in the fall of 2014**
- Using CESM2 simulations and satellite data, this study finds that the **Holuhraun eruption most likely contributed to this warming signal** through increased trapping of LW radiation by low level clouds under limited sunlight
- These results indicate that large, high-latitude effusive volcanic eruptions, similar to the 2014-15 Holuhraun eruption, might have **disproportionally strong climate impacts in the Arctic**

Sensitivity to season and size:
A modelling study

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Research article

Modelled surface climate response to effusive Icelandic volcanic eruptions: sensitivity to season and size

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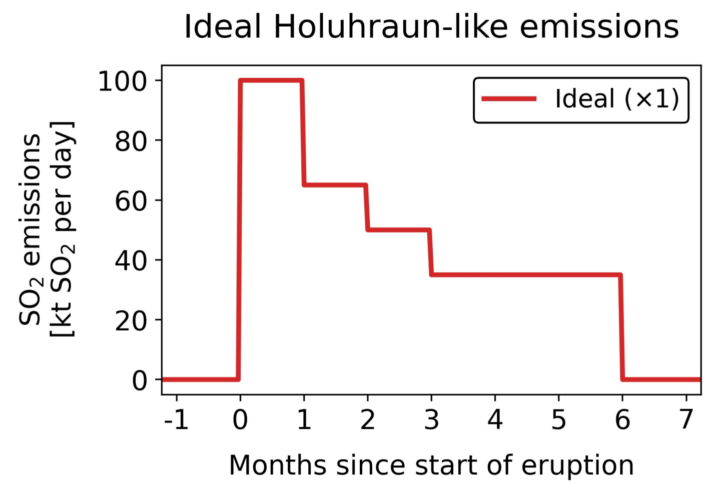
Sensitivity to season and size

A follow up to Paper I, exploring the **climate response to Holuhraun-like eruptions** as a function of **eruption season and size**



Start	Mar	Jun	Sep	Dec
Scaling	×1 ×5 ×25 ×50	×1 ×5 ×25 ×50	×1 ×5 ×25 ×50	×1 ×5 ×25 ×50

×1 Holuhraun

×5 Midway between Holuhraun and Laki

×25 As large or larger than the largest Icelandic eruptions(*)

×50 Rivals the largest known eruptions on Earth(*)

Sensitivity to season and size

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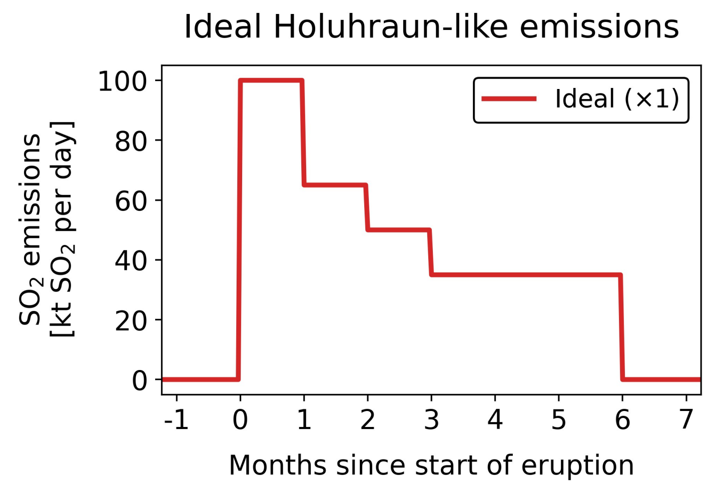
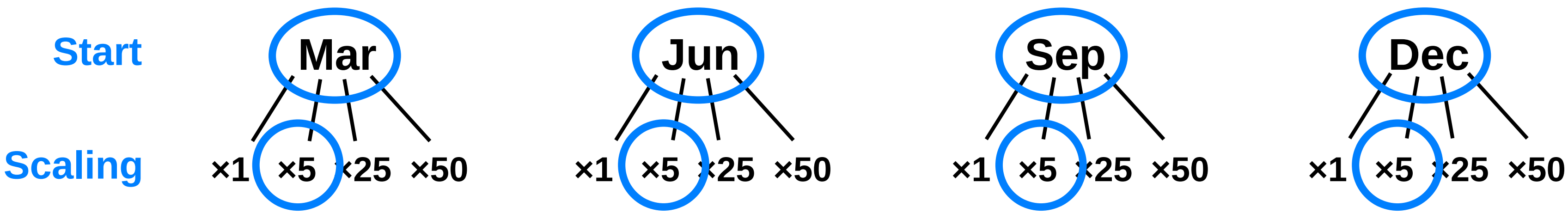
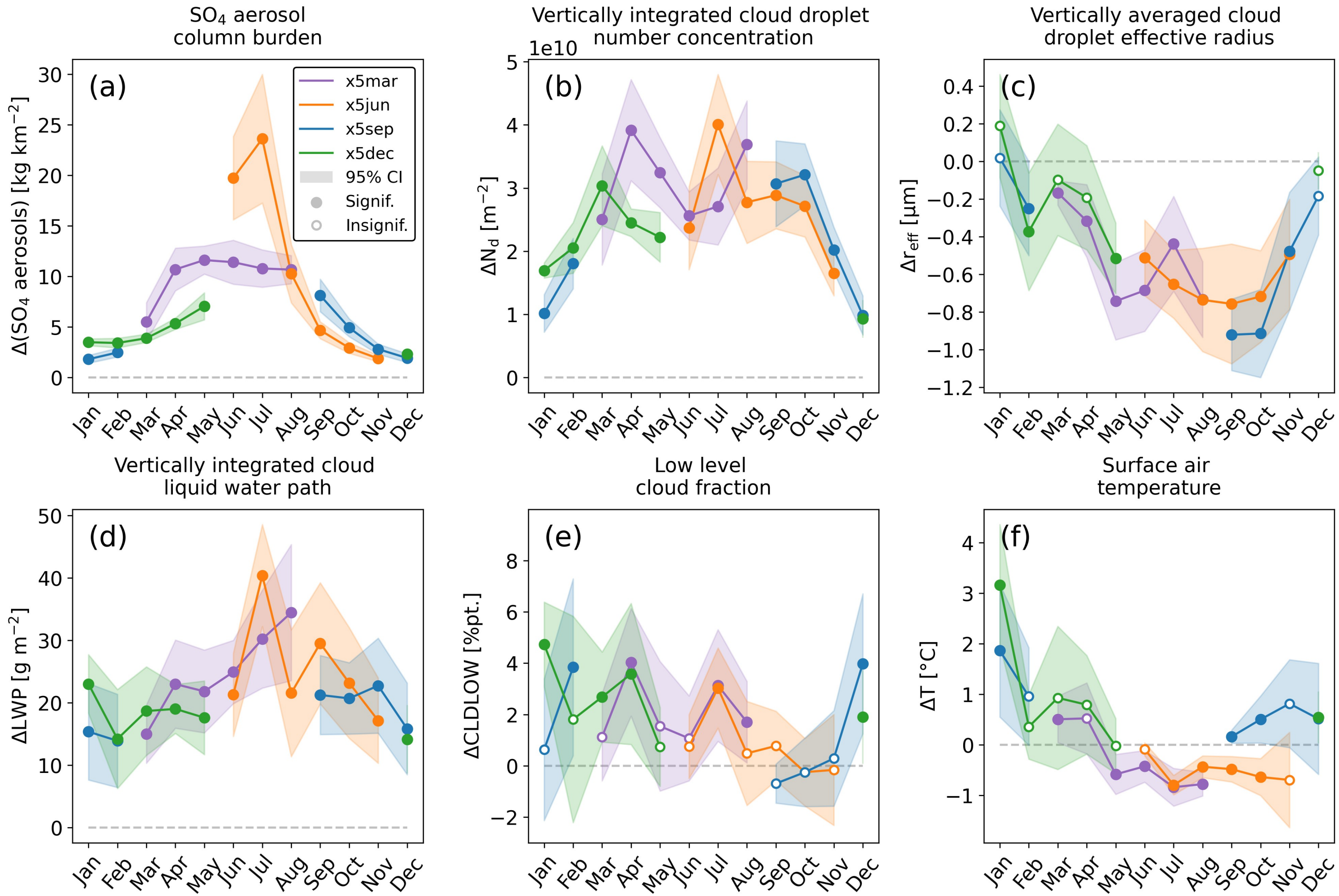




×1	Holuhraun
×5	Midway between Holuhraun and Laki
×25	As large or larger than the largest Icelandic eruptions(*)
×50	Rivals the largest known eruptions on Earth(*)

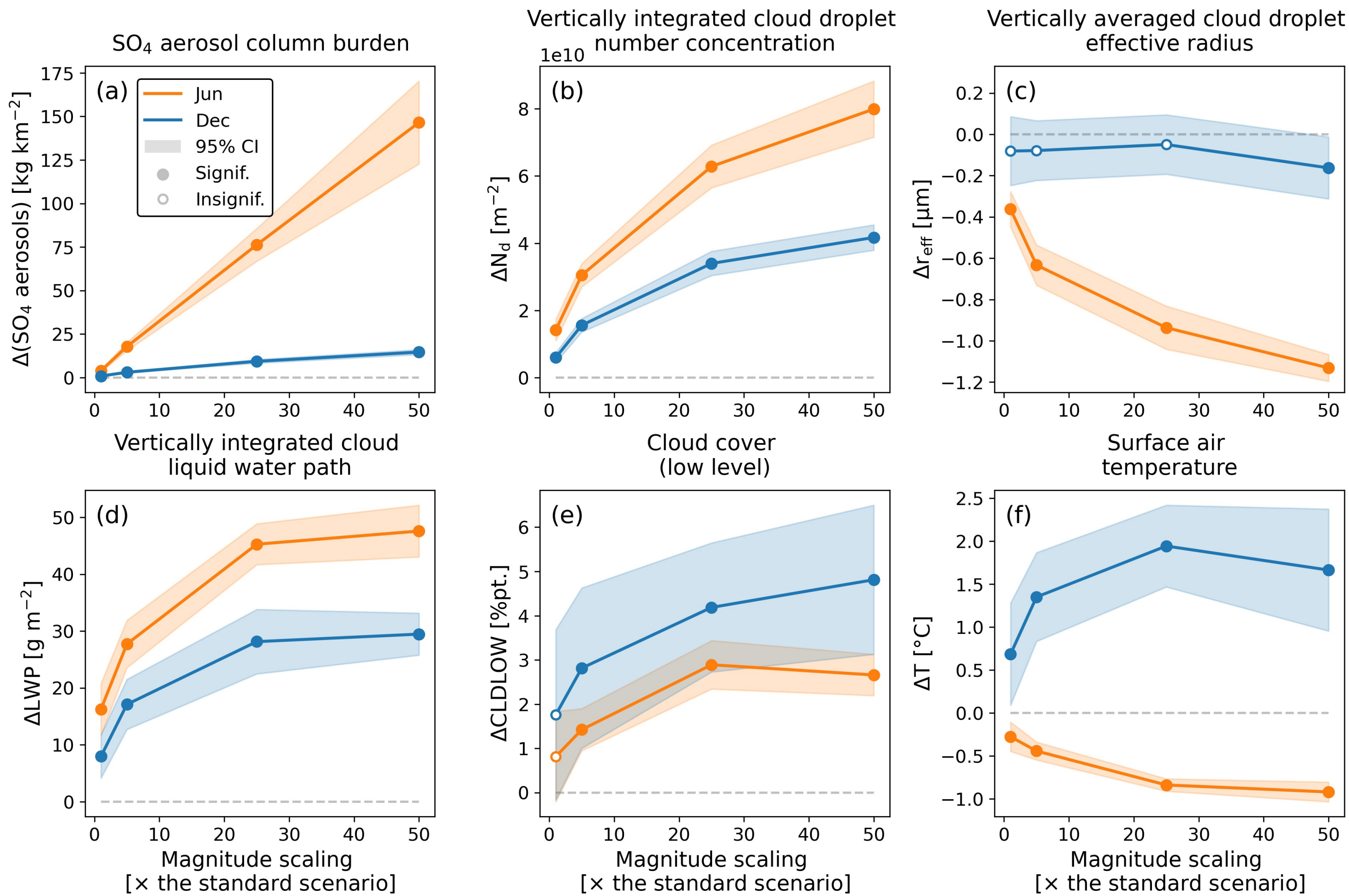
Sensitivity to season and size

Monthly mean responses to the **×5** eruptions in the **Arctic** (north of the Arctic circle)



Sensitivity to season and size

Summer (JJA) and **winter** (DJF) anomalies in the **Arctic** as a function of eruption size



Sensitivity to season and size

Summary

- The climate response to high-latitude effusive volcanic eruptions is **strongly modulated by different seasons**
  - Especially prominent in the Arctic where the forcing is of opposite sign between winter and summer
- The **magnitude of the climate response becomes less sensitive to variations in eruption size as eruptions become larger**
  - Levels out between ×20 and ×30 Holuhraun

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