



# Clouds - their formation and importance for climate

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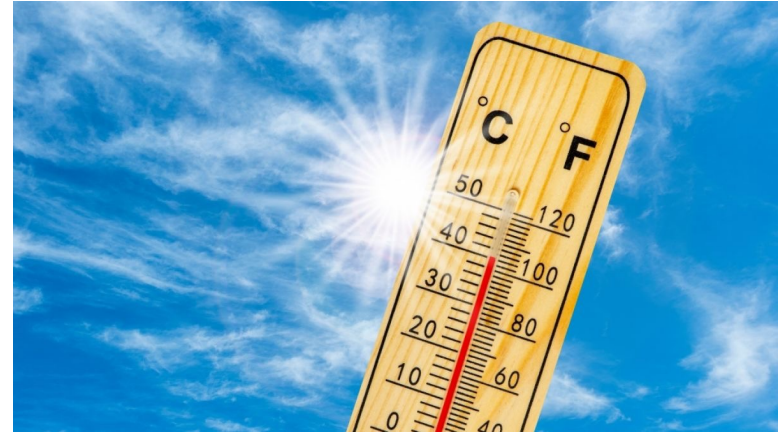
U. Lohmann, Y. Chen, D. Villanueva, Y. Wang

# Variety of clouds



Sources:  
Fabian  
Mahrt  
own photos

# Summer 2022: lack of and too many clouds



China, France:  
drought,  
Pakistan:  
flooding  
Sources:  
Tagesschau;  
media news,  
Handelsblatt



# Outline

How are clouds formed?

How are clouds and aerosols influencing our climate?

What do we expect in future? Can clouds and aerosols be used to (partly) offset global warming?



**How are clouds formed?**

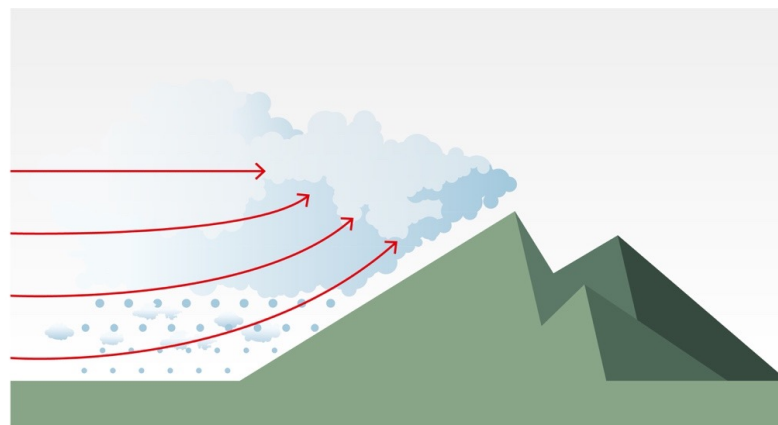
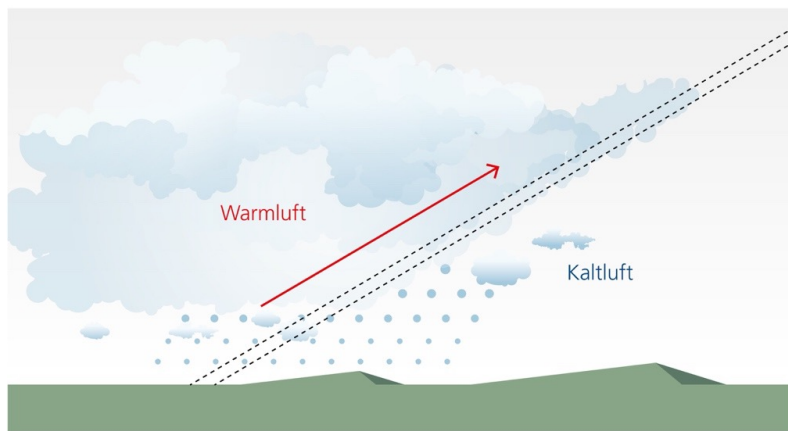
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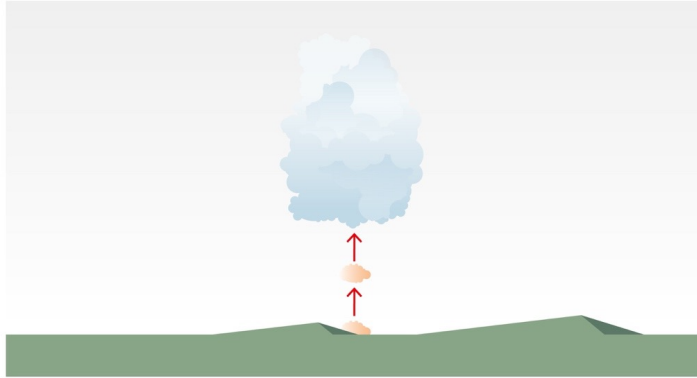
# Cloud formation:

- Sufficient moisture in the atmosphere
- Rising and cooling of air parcels/air masses
- Aerosol particles, on which water vapor can condense/deposit to form cloud droplets/ice crystals

# Cloud formation: Lifting of air at frontal surfaces or orography



# Cloud formation: heating from below

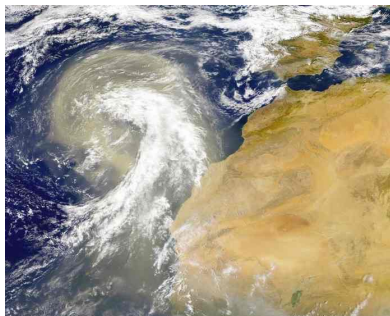


# Downpour over lake Millstätt, Austria



Courtesy: Christoph Schär

# Variety of aerosol sources:



# No particles – no clouds



ASCOS research cruise in summer 2008:

- Temperature: -8 °C,
- Aerosol concentration: < 10 cm<sup>-3</sup> (typical concentration over continents: 1000 cm<sup>-3</sup>)

No particles - no clouds

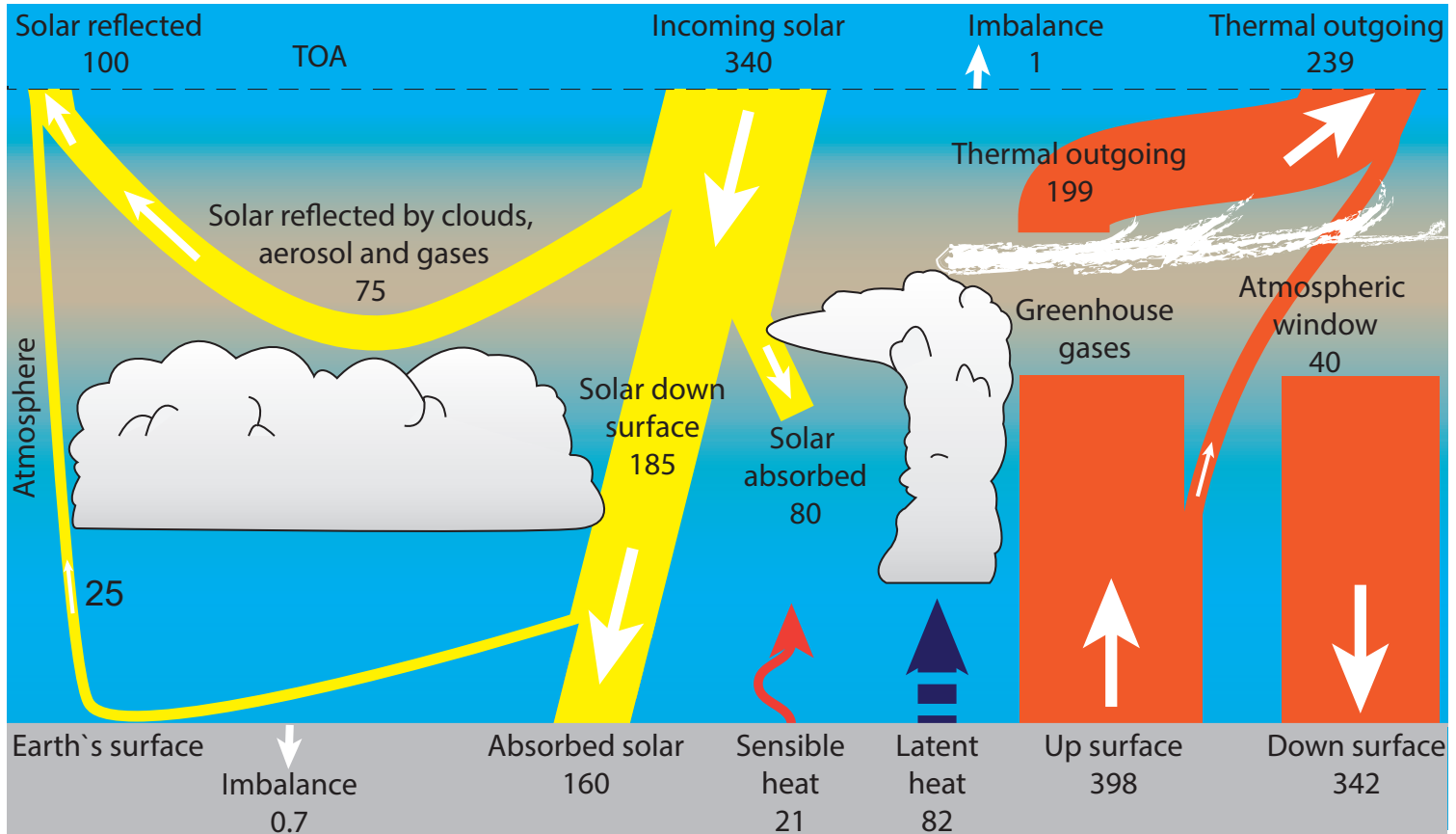


Zoran Ristovski, <http://www.youtube.com/watch?v=EneDwu0HrVg>

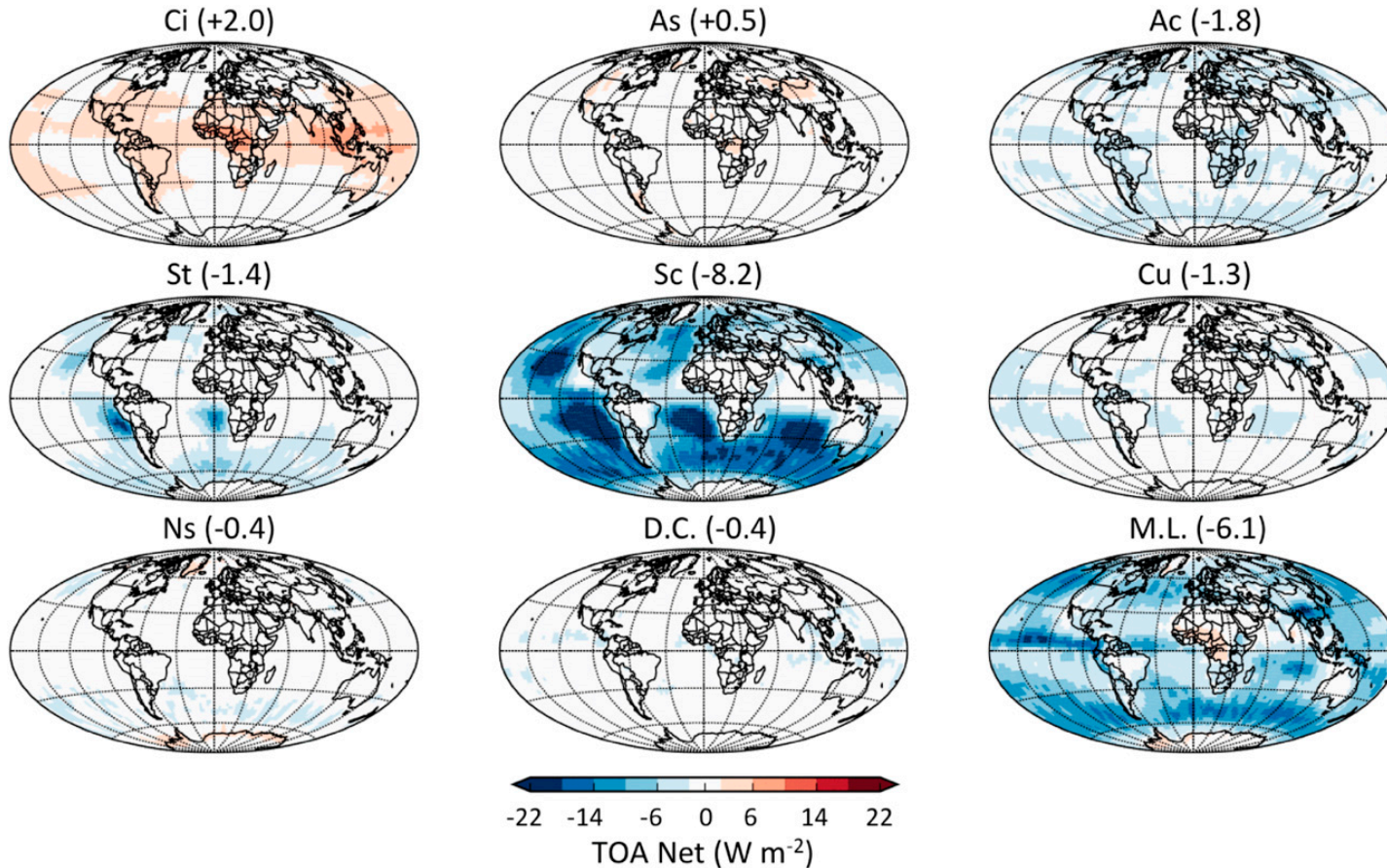


How are clouds and aerosols influencing our climate?

# Global energy budget



# Radiative effect of the different cloud types

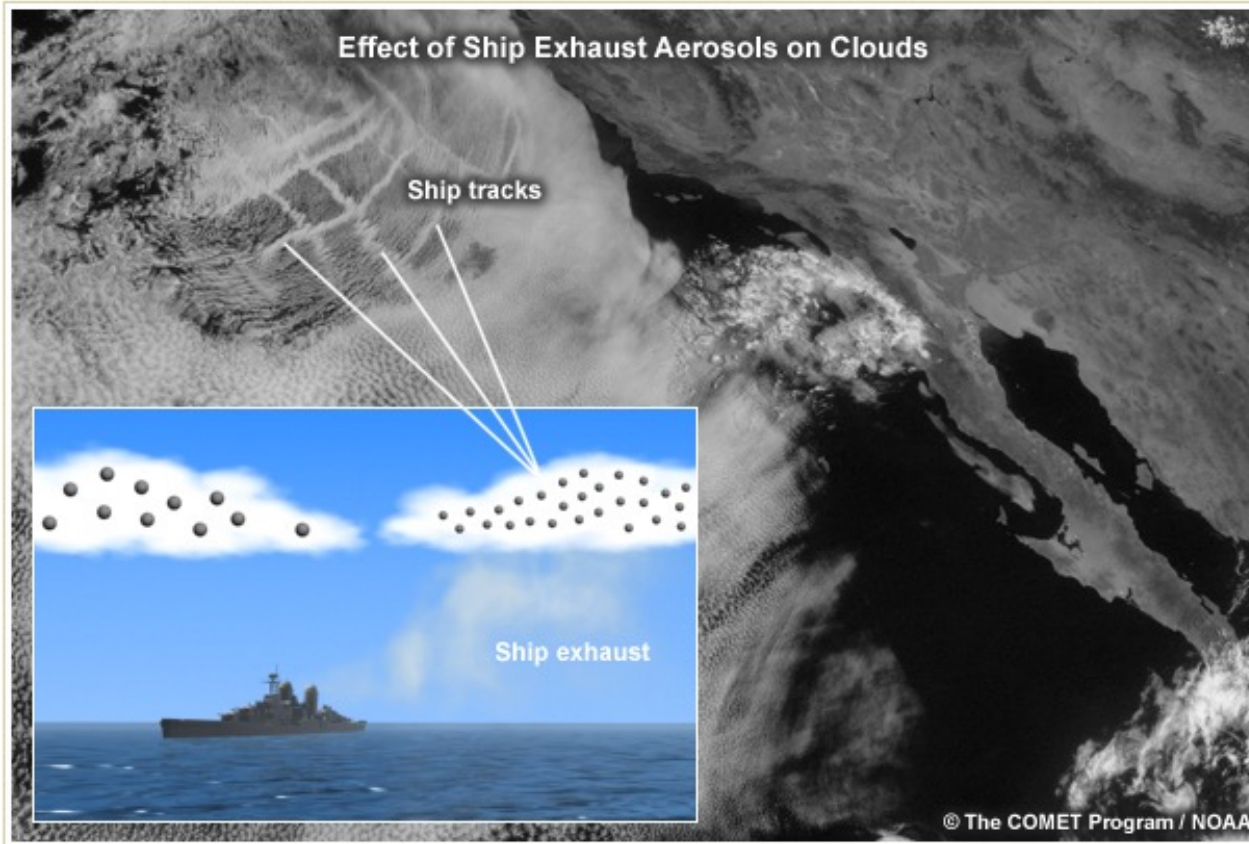


Ci: cirrus  
As: altostratus  
Ac: altocumulus

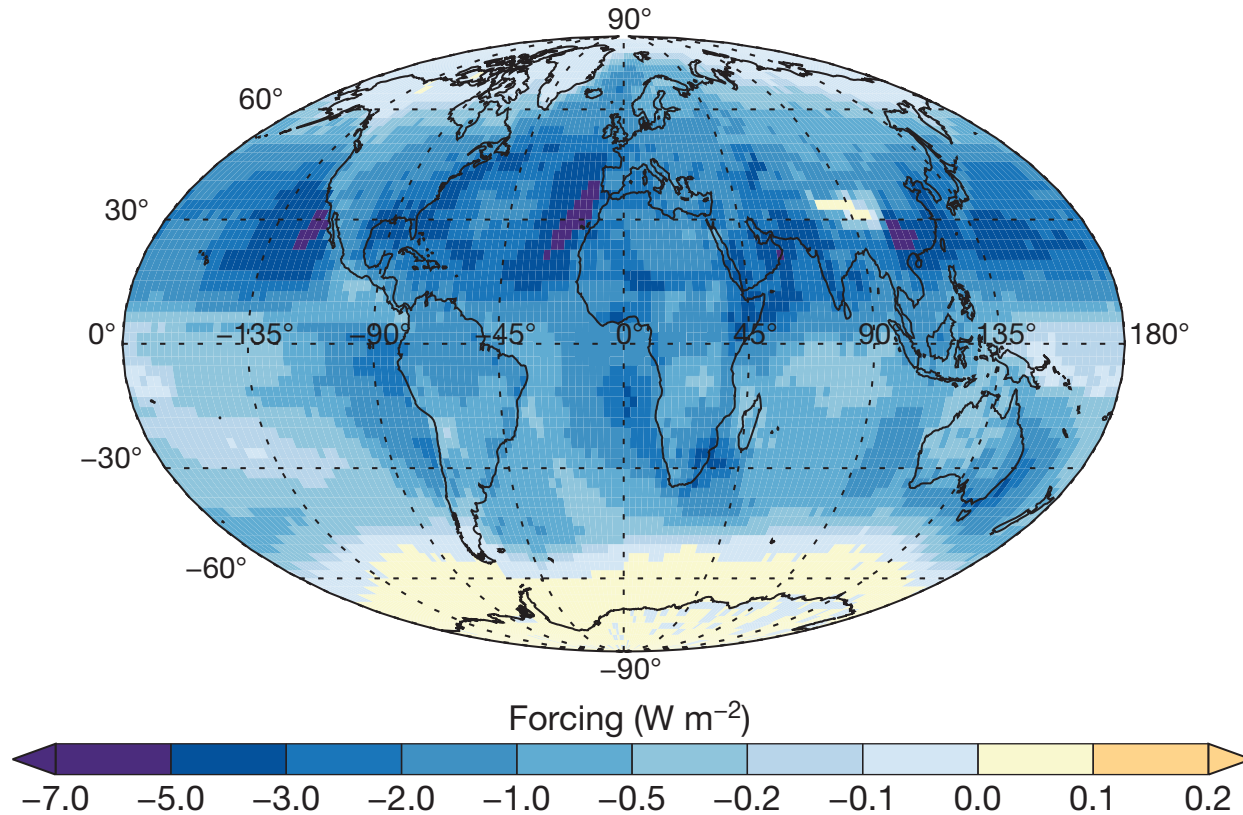
St: stratus  
Sc: stratocumulus  
Cu: cumulus

Ns: nimbostratus  
D.C.: deep conv.  
M.L. multilayer

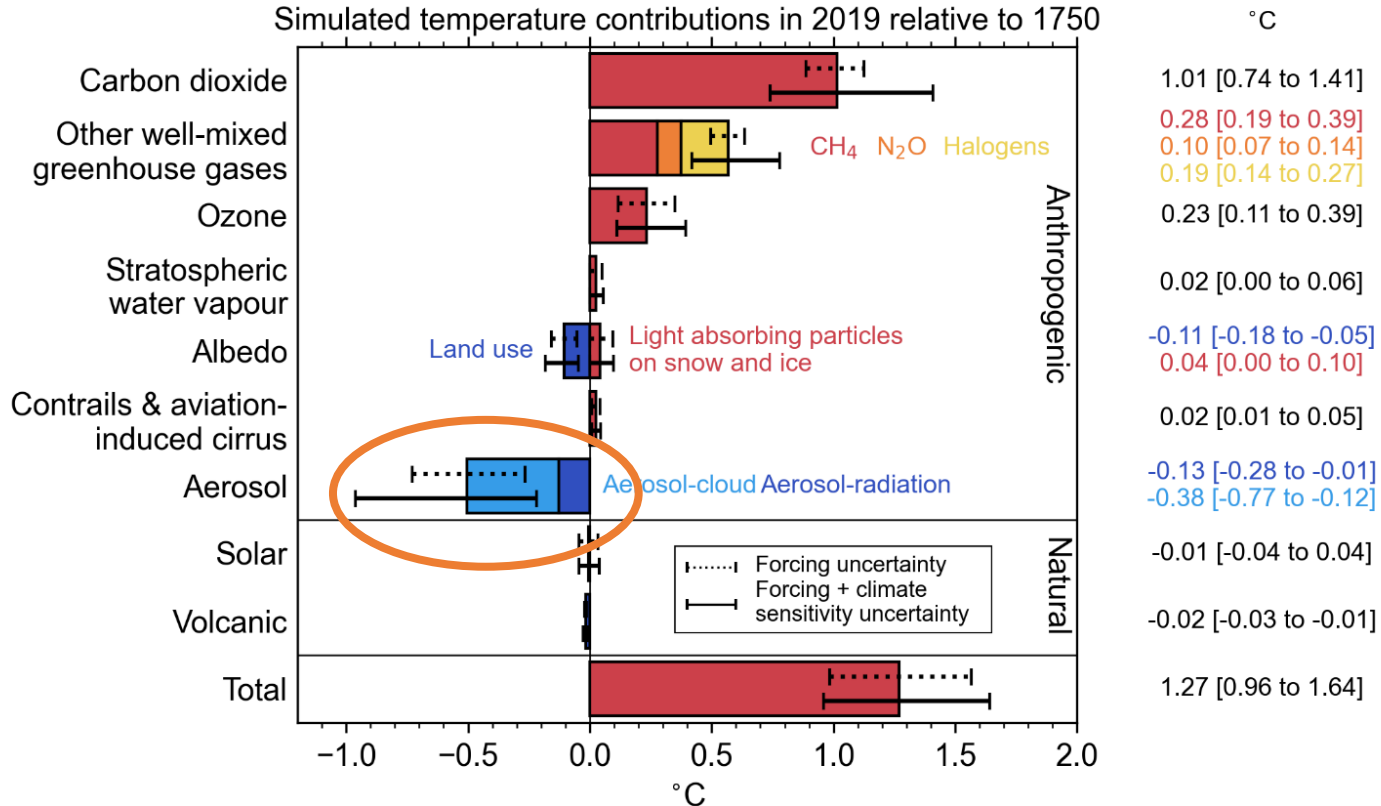
# Aerosol's influence on clouds:



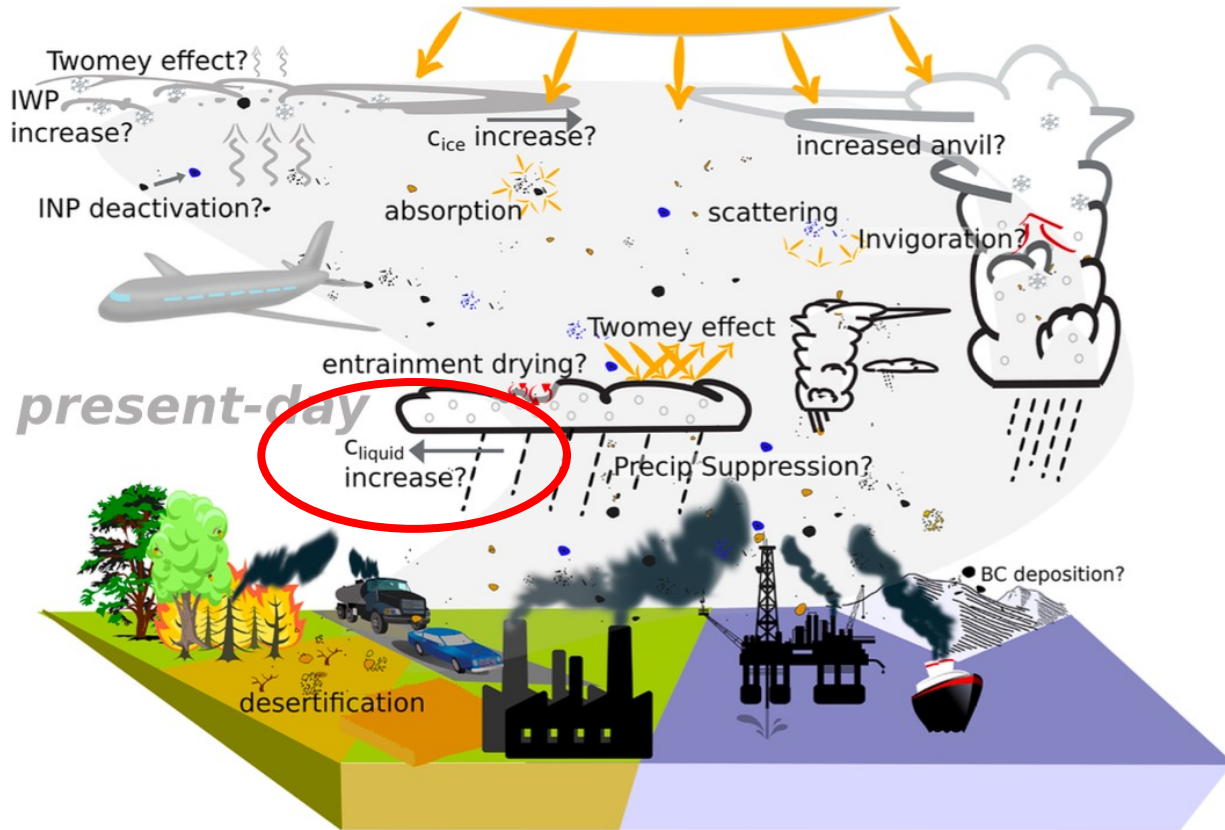
# Radiative forcing due to anthropogenic aerosols



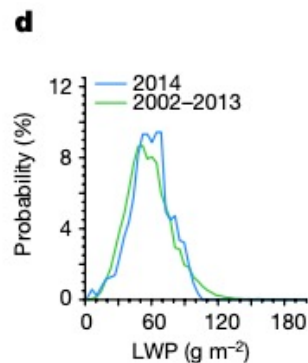
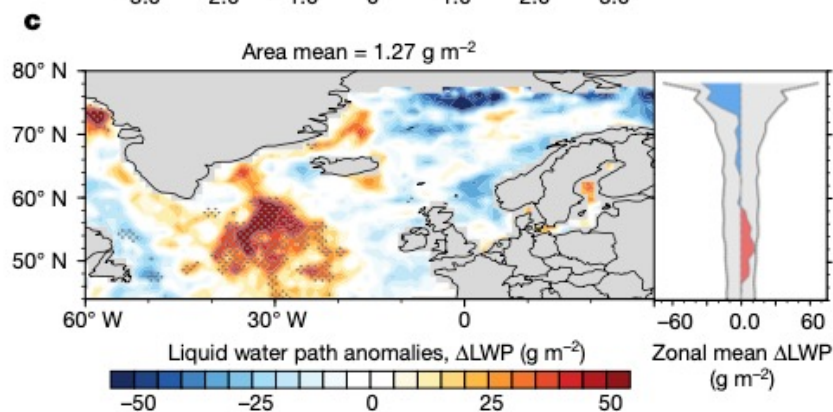
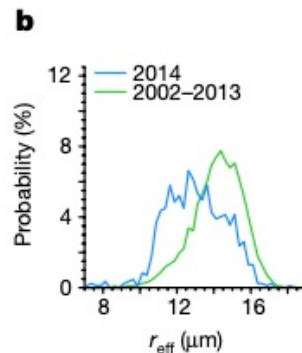
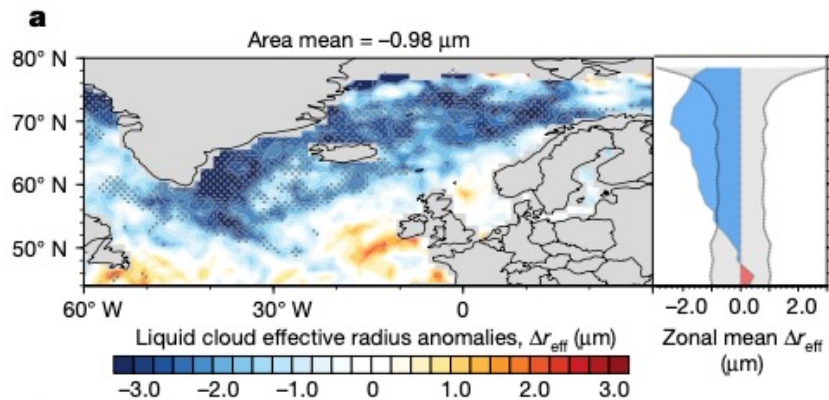
# Contributions to the observed warming since 1750



# Impact of anthropogenic aerosol emissions on climate



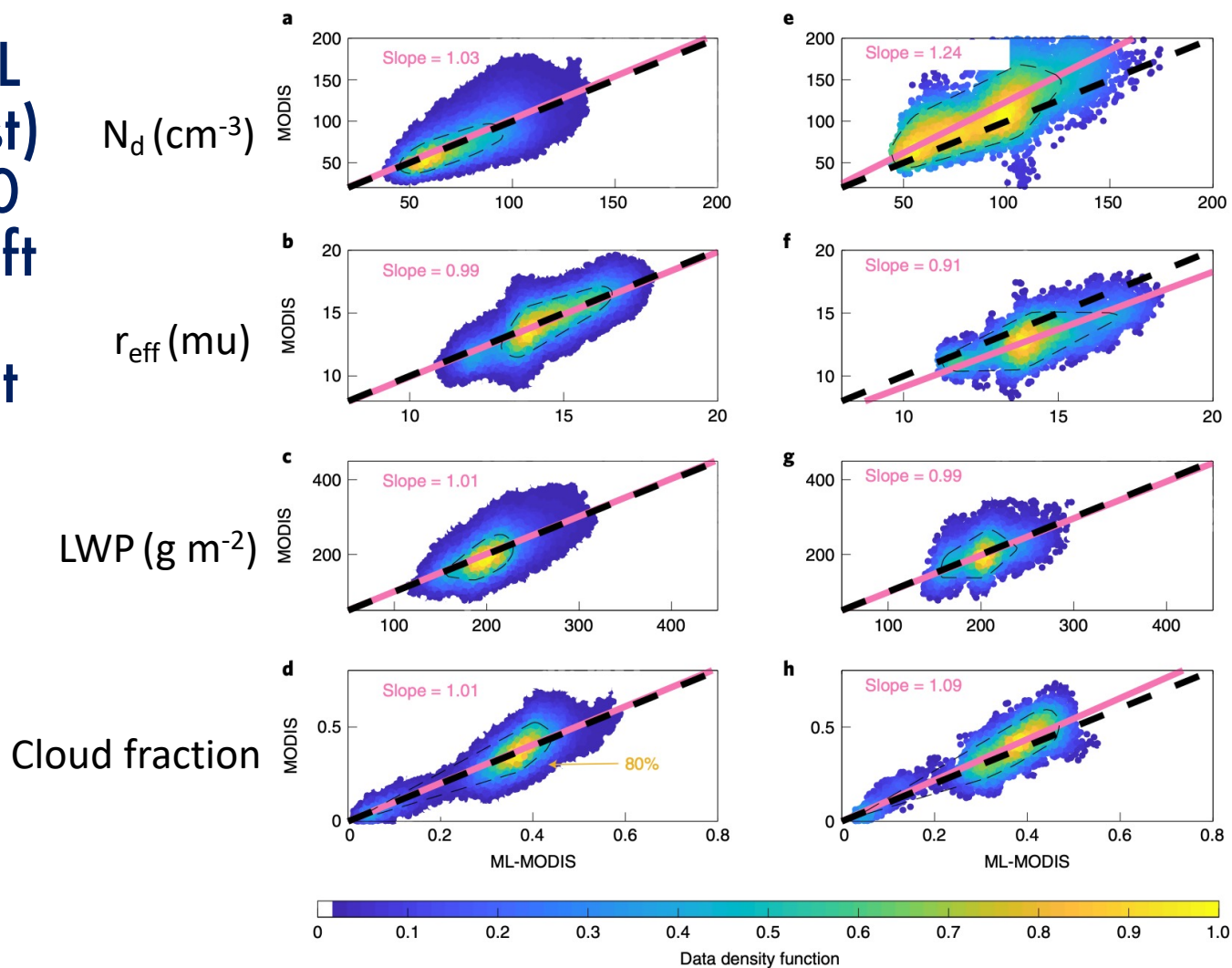
# Cloud response to the Holuhraun eruption for October 2014



**Conclusion:**  
Holuhraun caused a reduced cloud droplet size but had no discernible effect on other cloud properties

# MODIS vs. ML (random forest) for 2001-2020 (w/o 2014) left

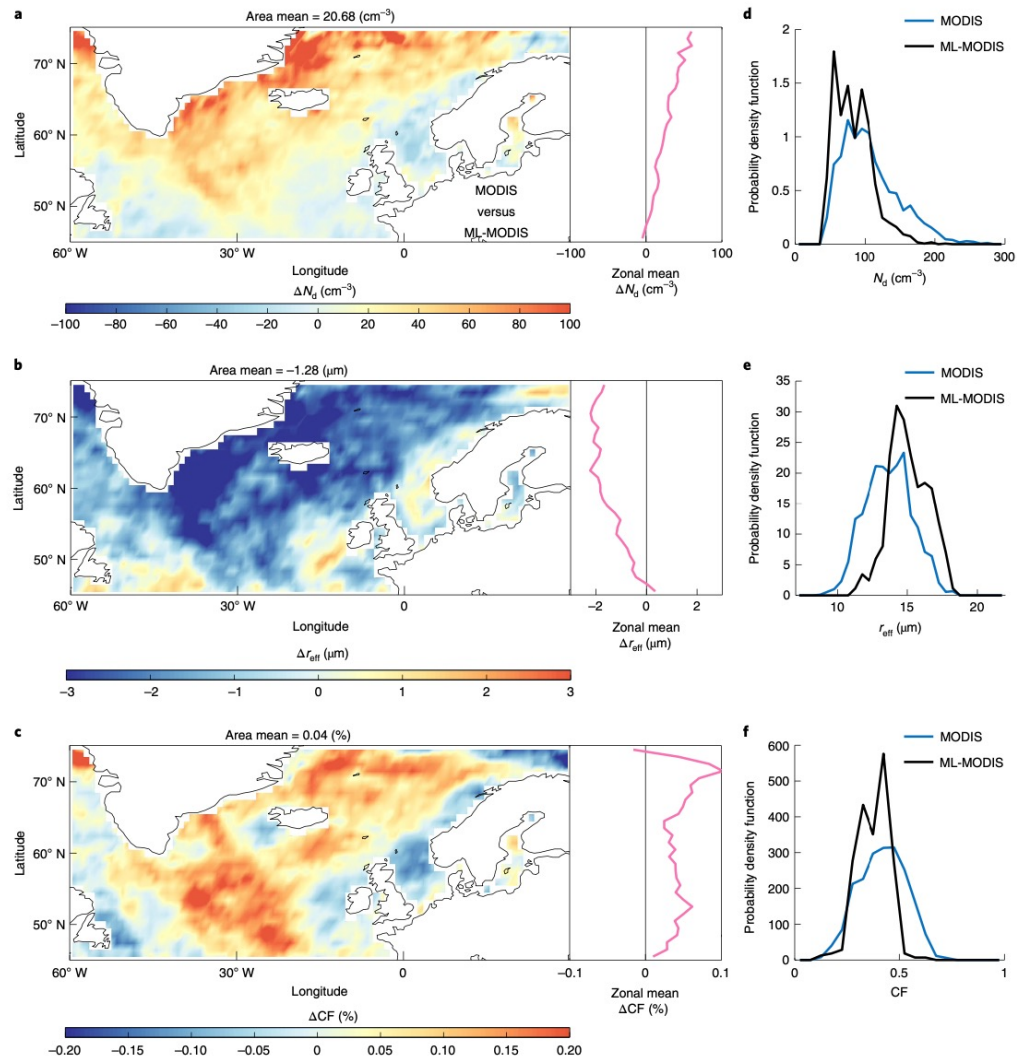
# Oct 2014 right



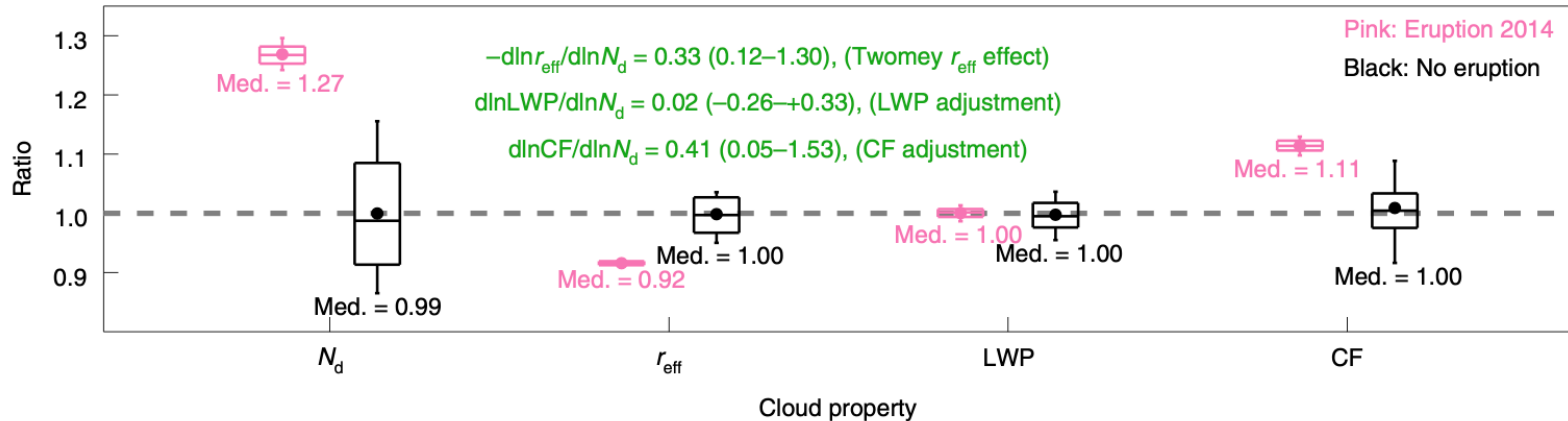
# Cloud responses to the Holuhraun eruption (Oct 2014)

Anomaly: 2014 vs. 2001/2002-2020

Chen et al., NatGeo, 2022



# Conclusions from the Holuhraun study:



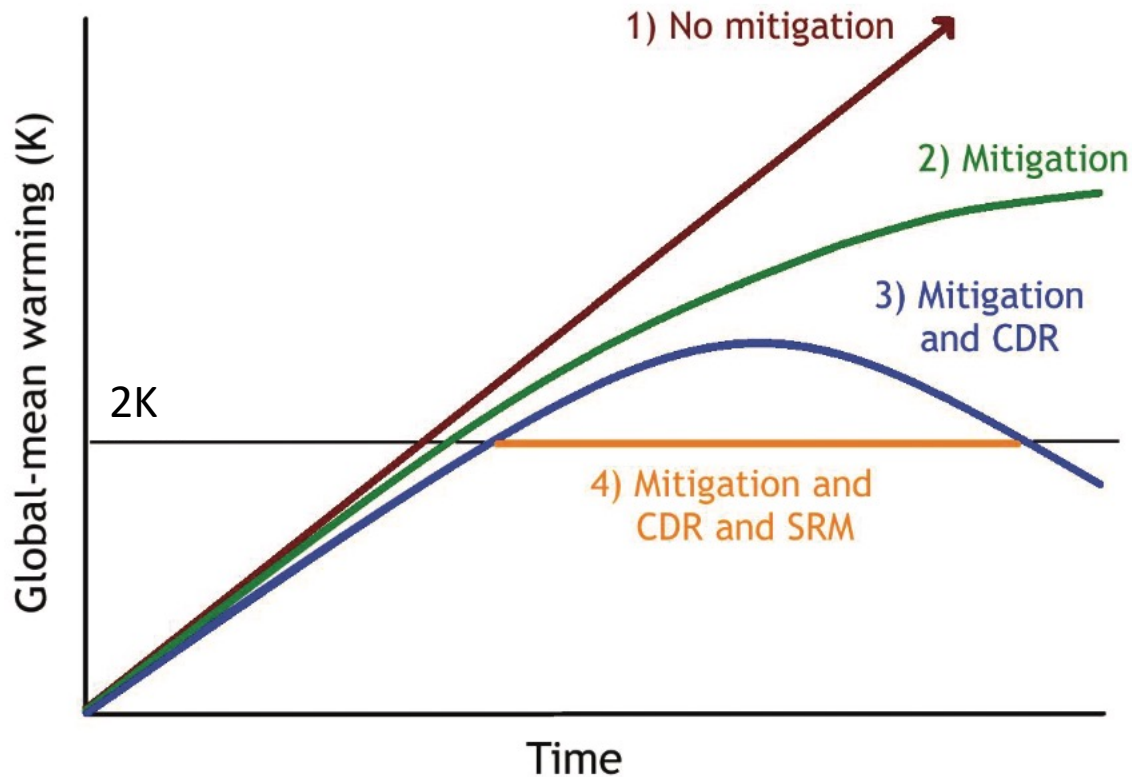
- The Holuhraun eruption led to an increase in cloud cover by approximately 10% with no change in liquid water path
- This effect is larger than the albedo increase from the reduced cloud droplet size



**Can clouds and aerosols be used to (partially) offset global warming?**

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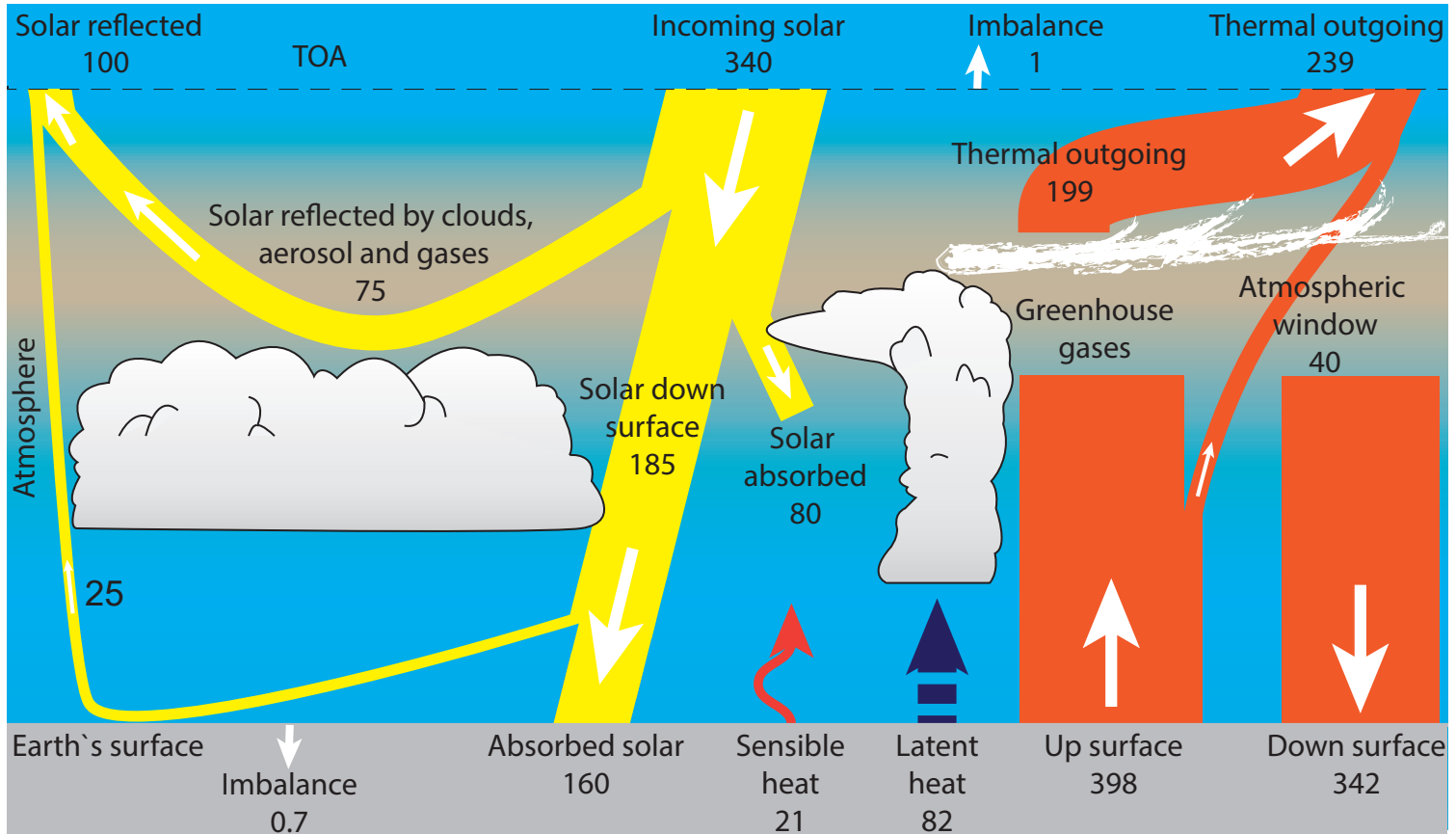
# We decide if and how we reach the 2 °C climate goal



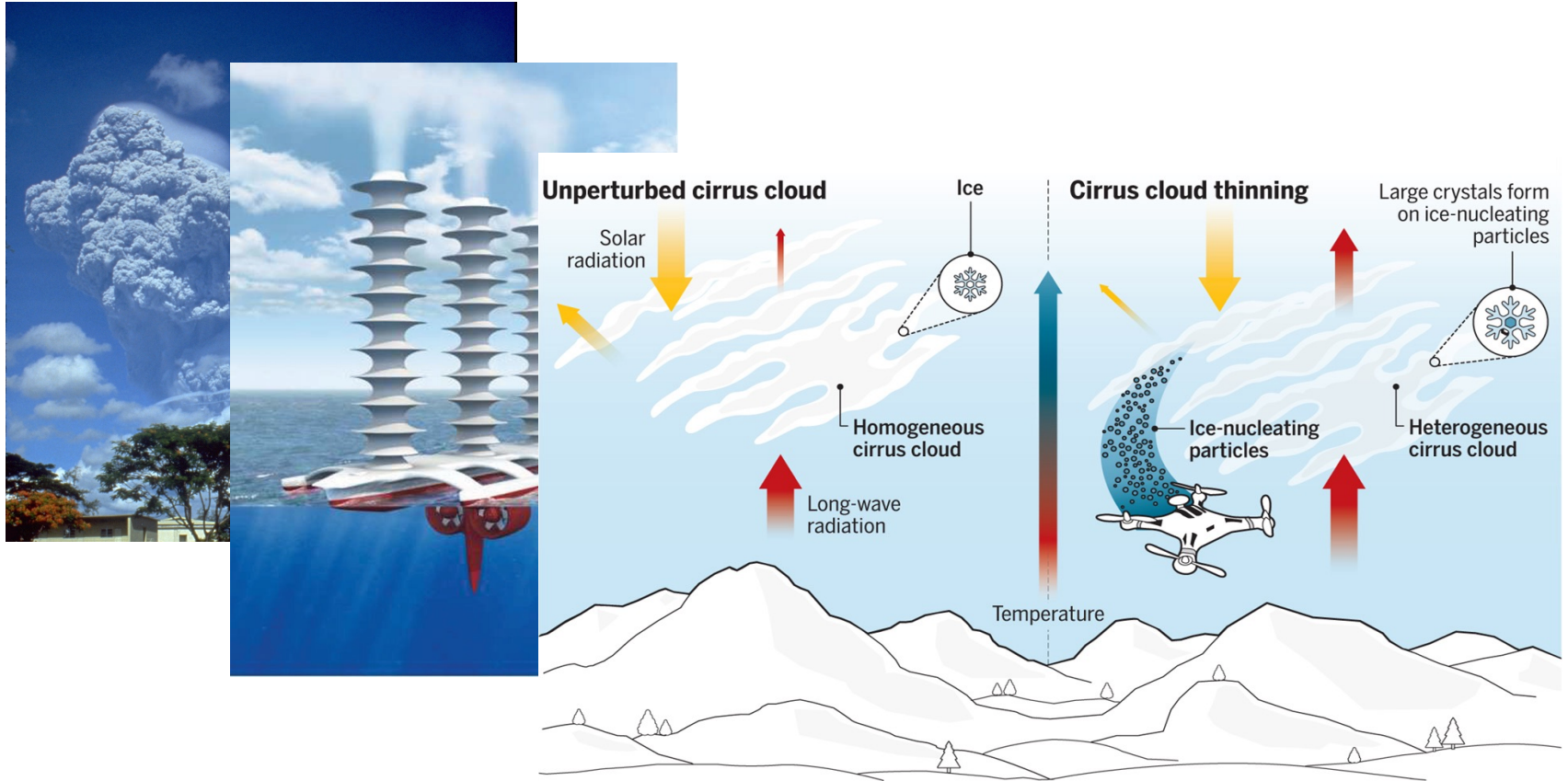
CDR: carbon dioxide removal

SRM: solar radiation management

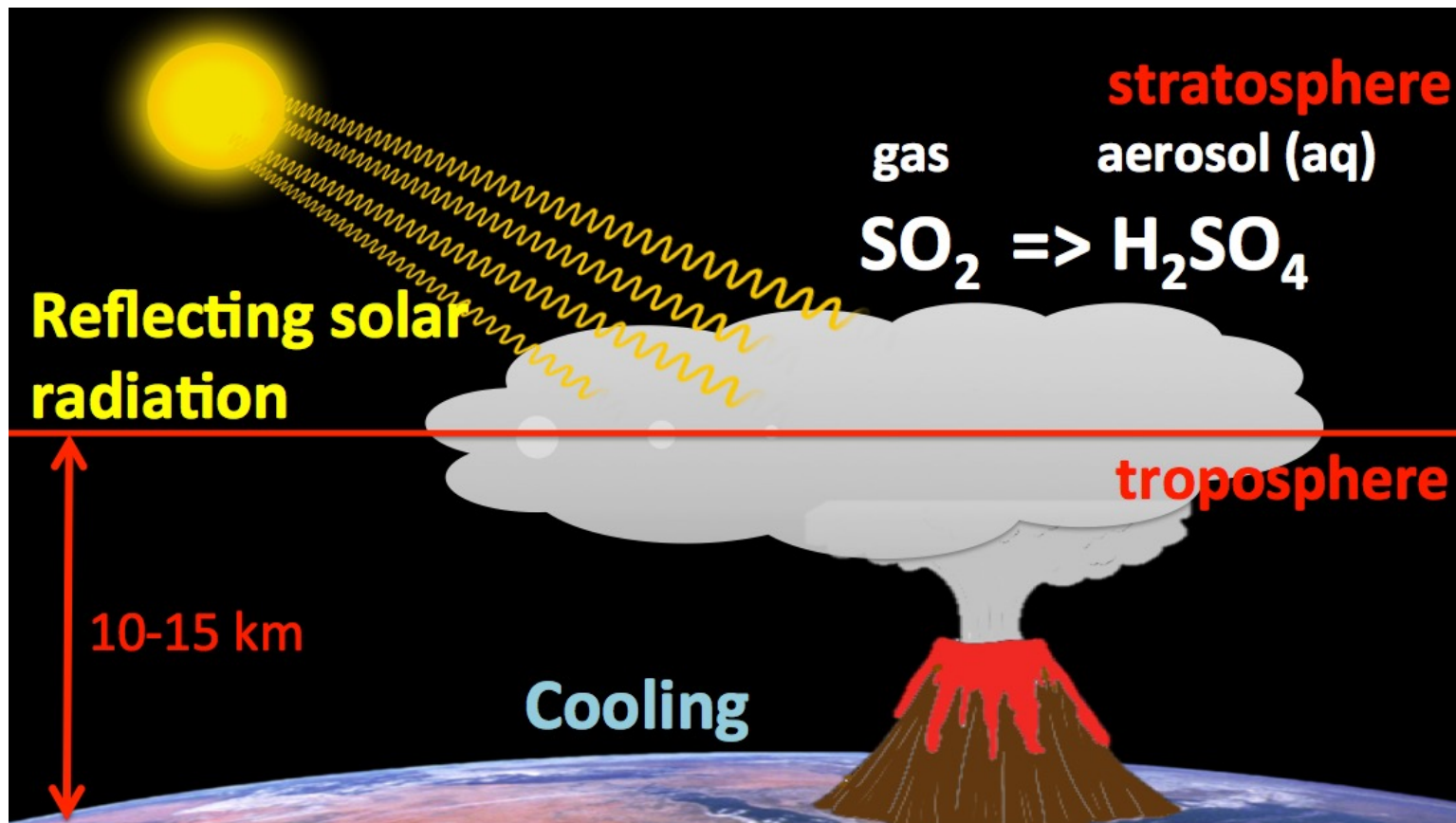
# Global energy budget



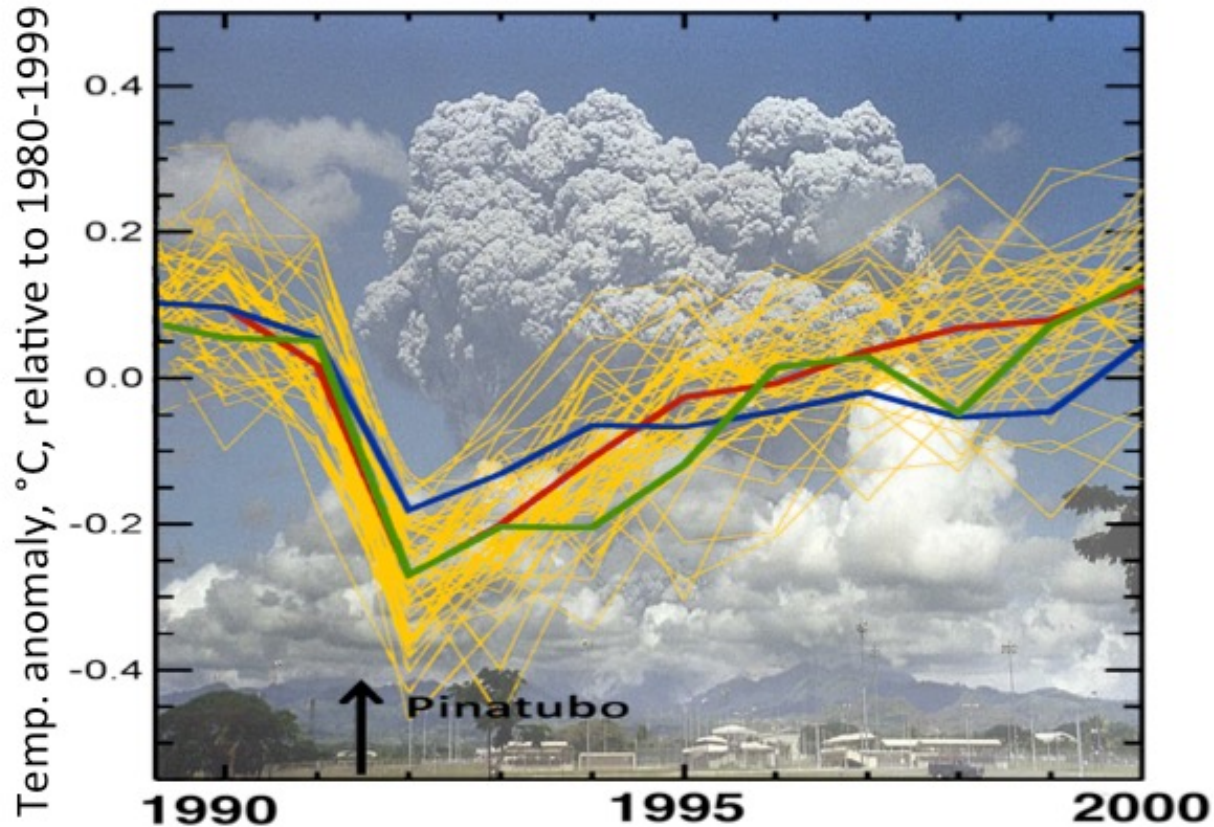
# Radiation management methods



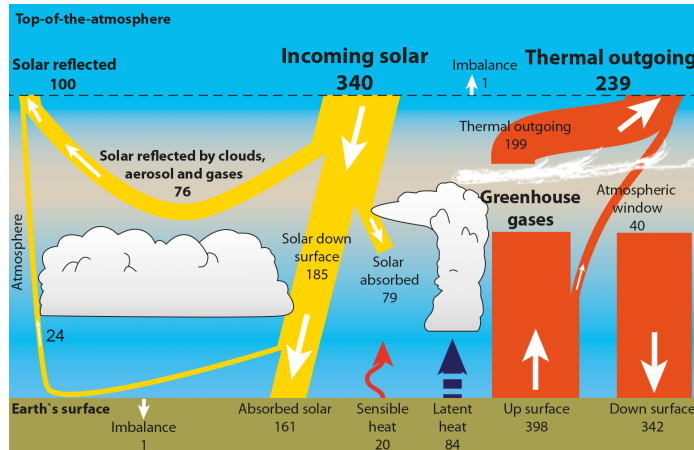
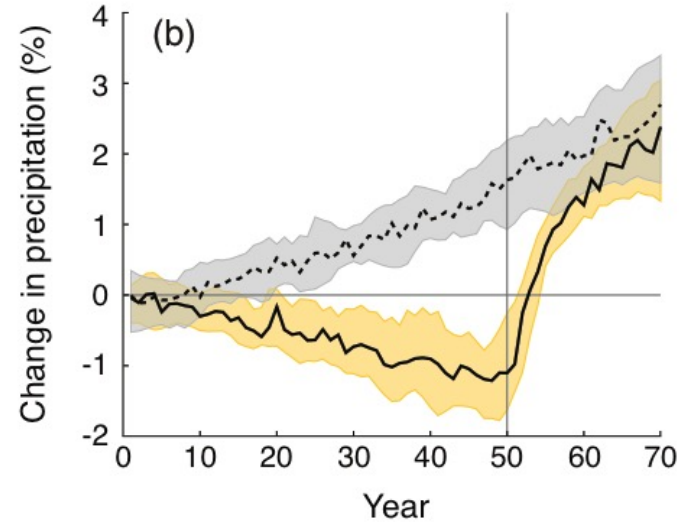
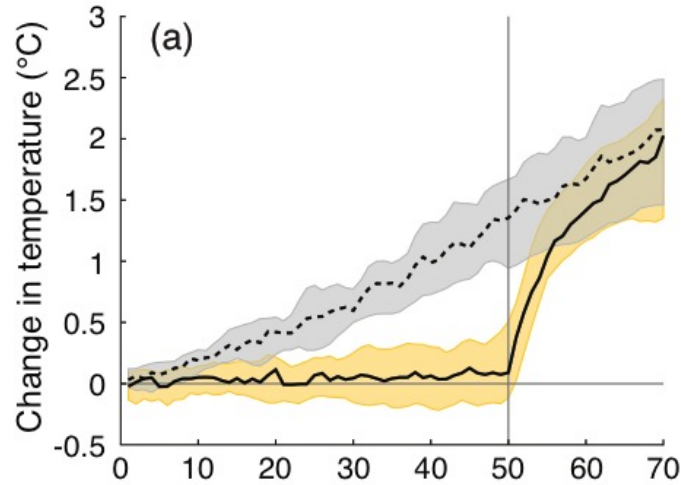
# Natural analogon: volcanic eruptions



# Observed temperature response after Mt. Pinatubo

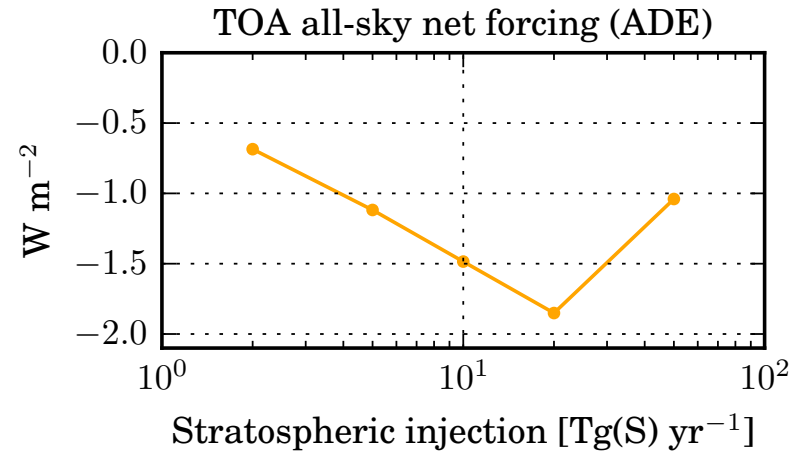
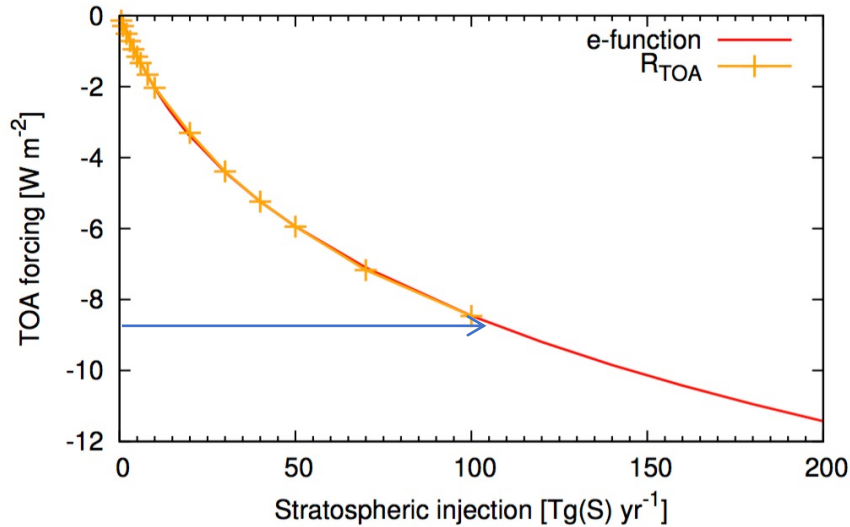


# Effect of stratospheric aerosol injections on temperature & precip



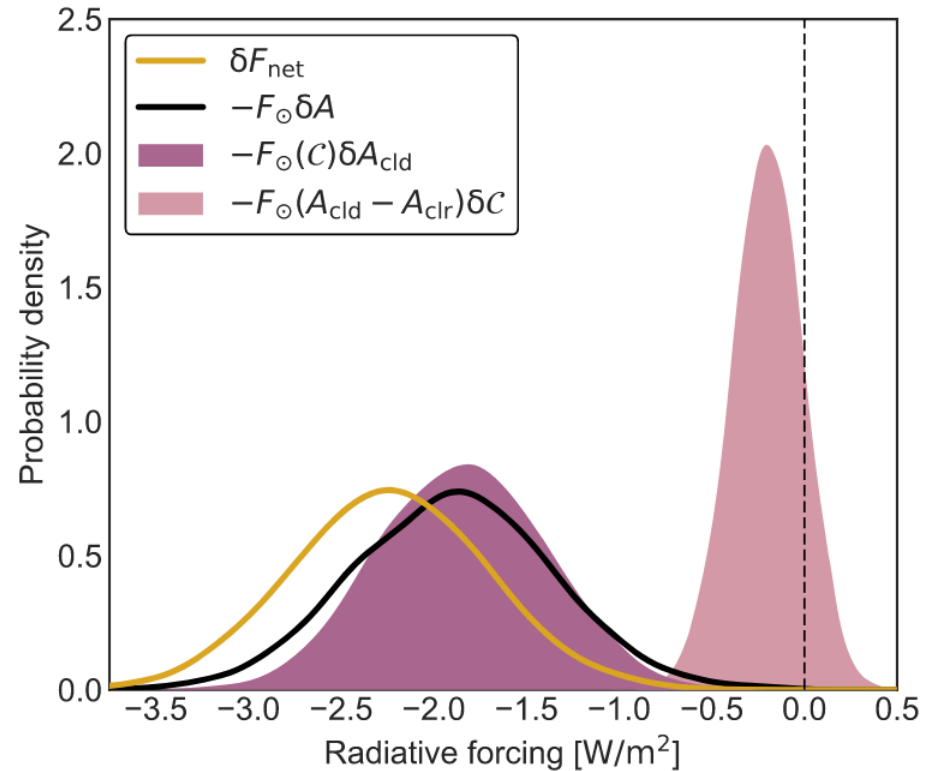
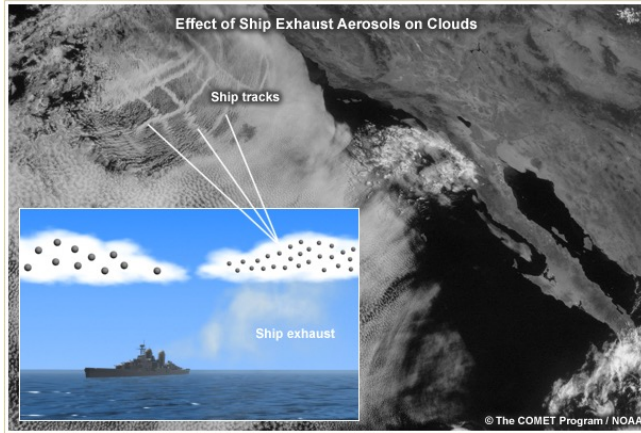
→ Temperature and precipitation cannot be simultaneously restored with solar radiation management

# Limits of stratospheric aerosol injections



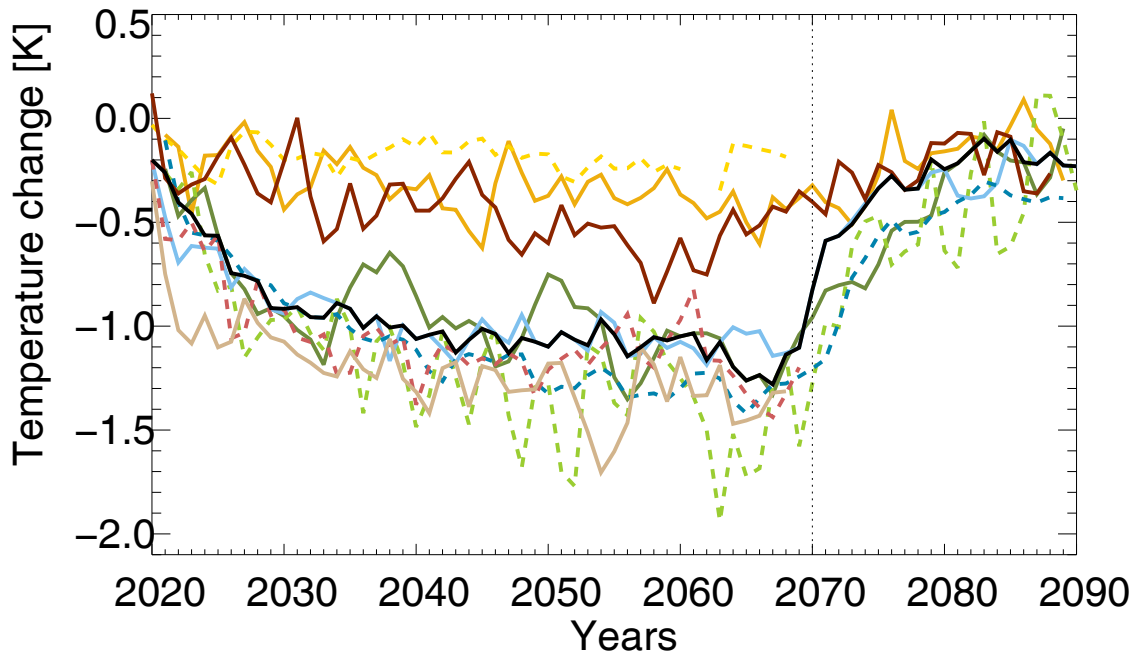
2/3 of the year 2000 sulfur emissions of 145 Tg S are needed to counteract the radiative forcing of the RCP8.5 scenario in 2100  
Higher aerosol injection rates result in faster coagulation and sedimentation

# Cooling due to brighter clouds over the oceans



Ship traffic in the Southern Atlantic causes a radiative forcing of  $\approx -2 \text{ W m}^{-2}$

# Temperature evolution with vs. without marine cloud brightening



Ensemble mean temperature change: climate engineering - RCP4.5:  $-1^{\circ}\text{C}$

# Can artificially altered clouds save the Great Barrier Reef?

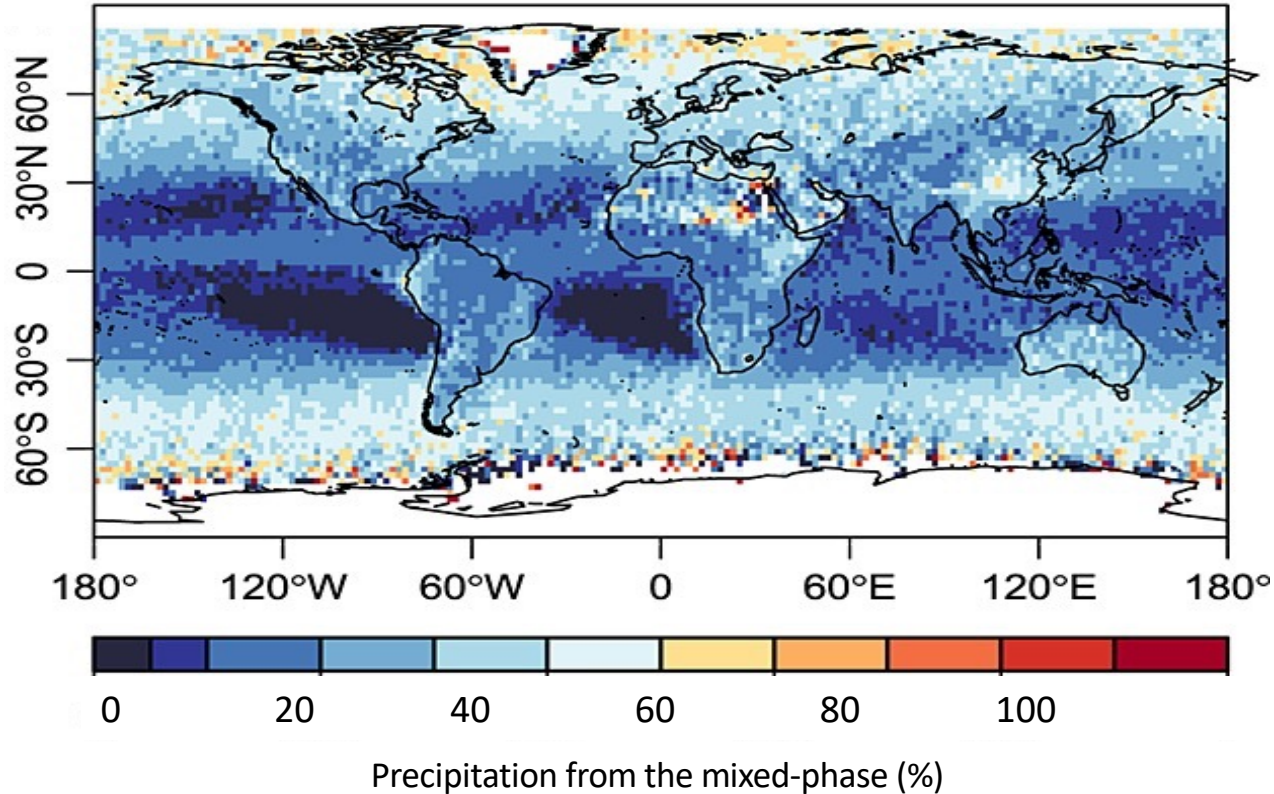
Australian scientists are rushing to develop new technologies – such as ways to block sunlight – to help preserve corals in the face of climate change.

[Jeff Tollefson](#)

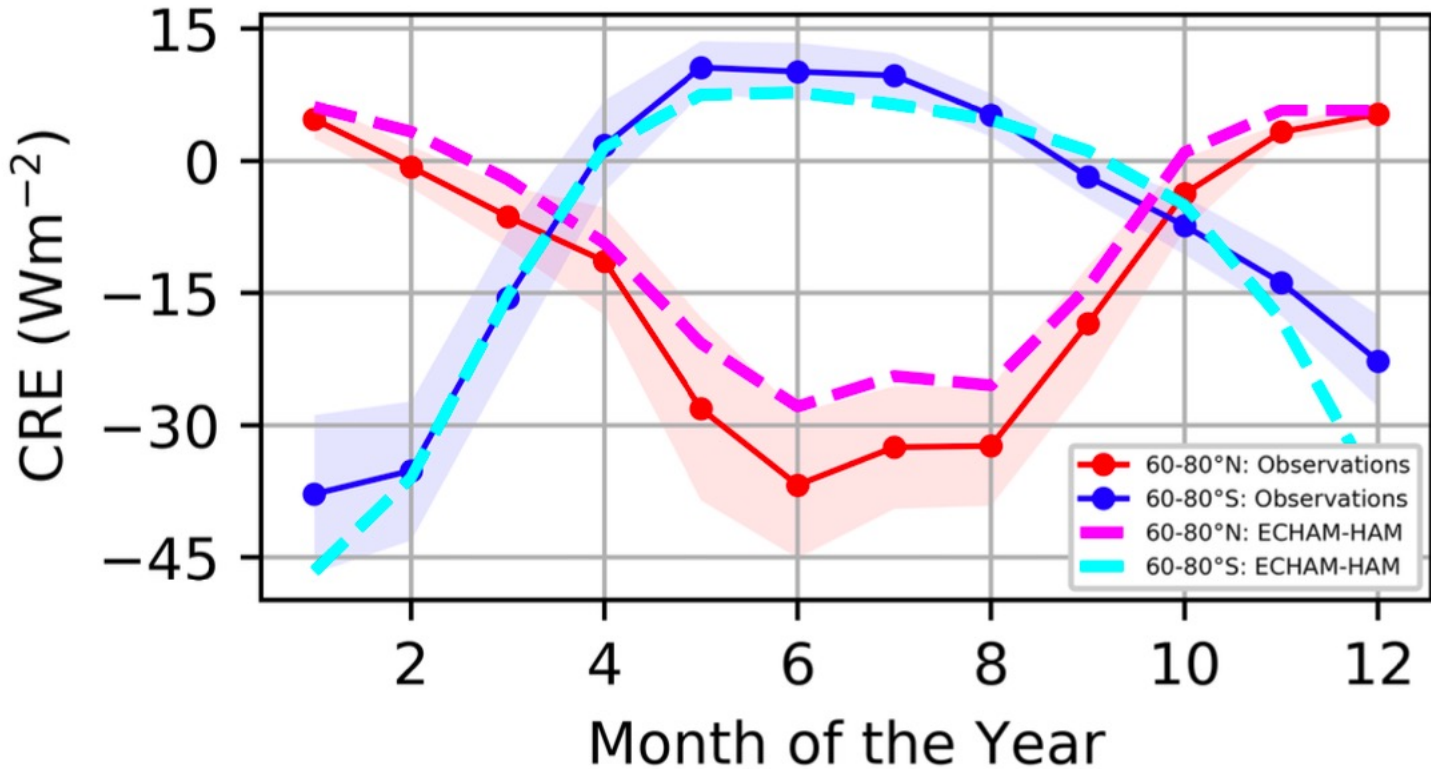


During a field trial, a turbine generates plumes of seawater droplets that rise into the sky. Credit: Brendan Kelaher/SCU

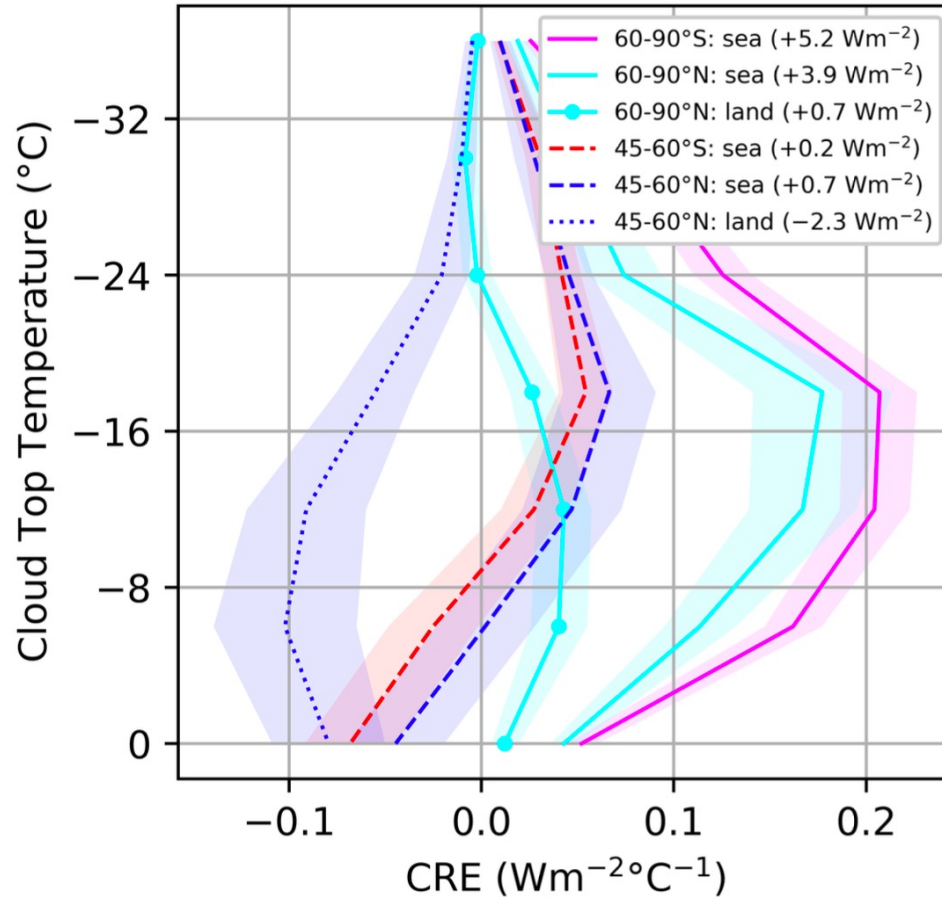
# Importance of mixed-phase clouds



# Cloud radiative effect of high latitude MPCs



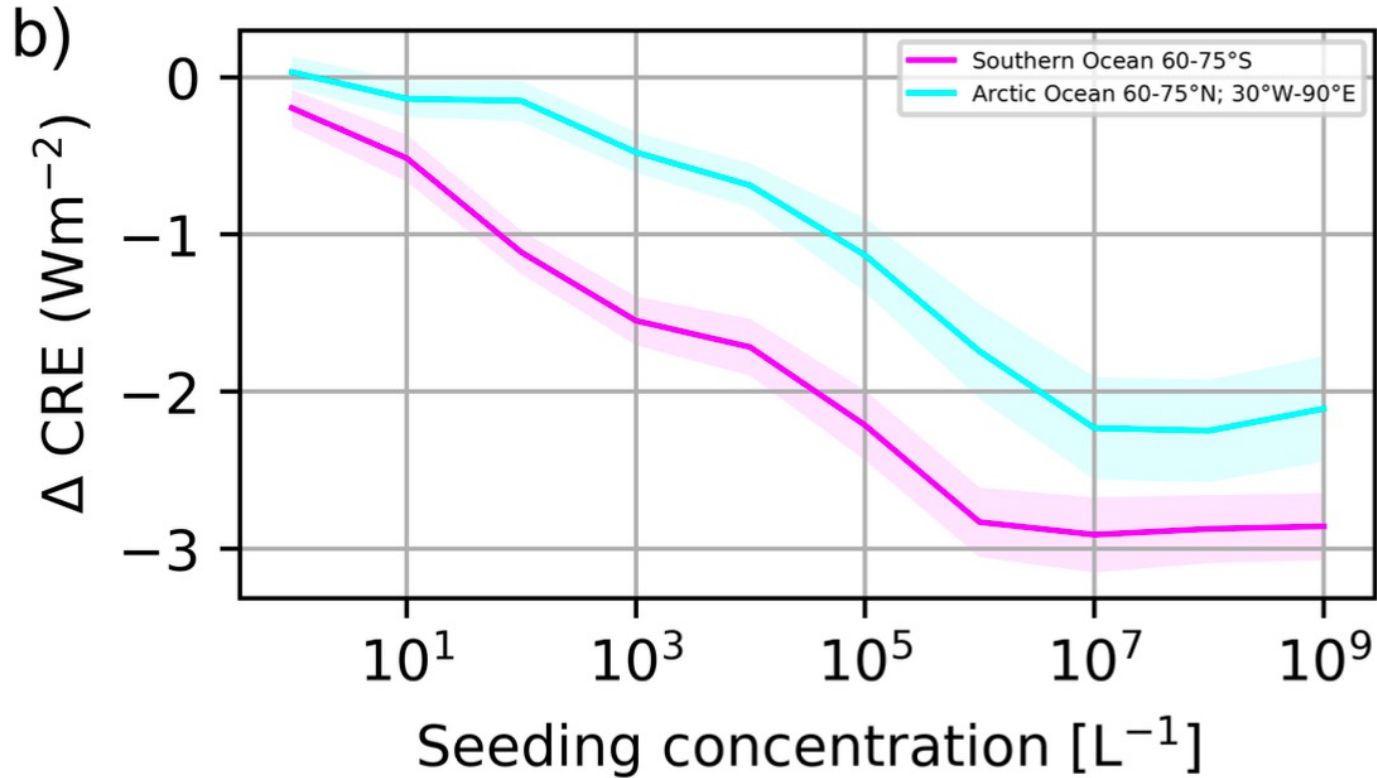
# Cloud radiative effect of wintertime MPCs



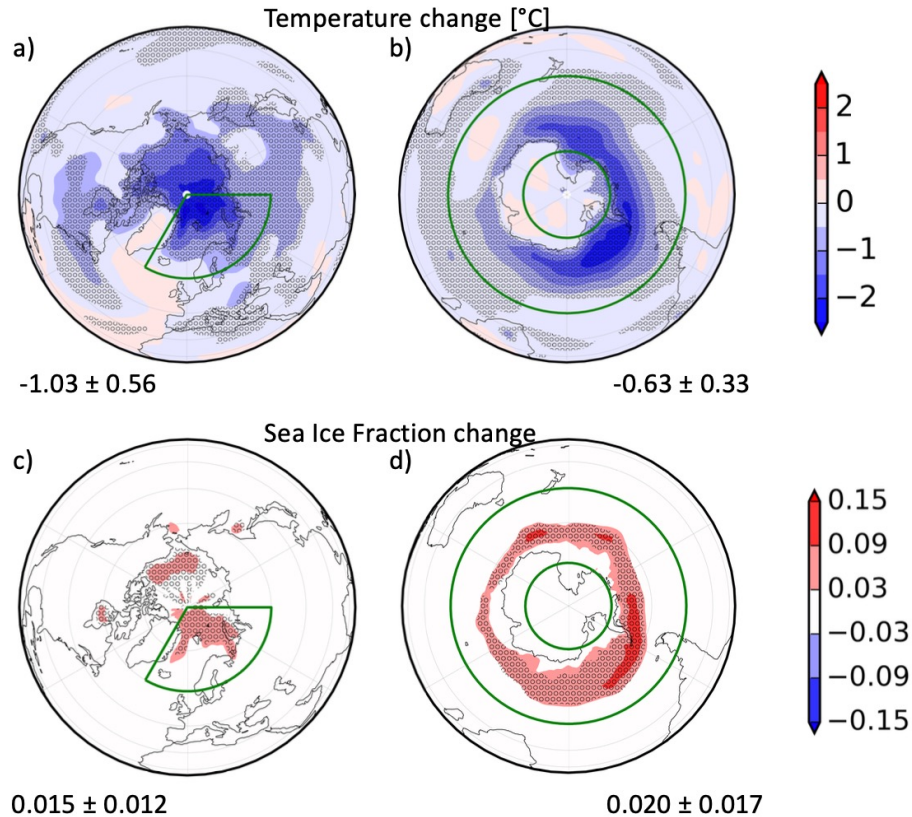
# Hole-punch cloud



# Cloud radiative effect of seeded high-latitude oceanic MPCs



# Climate implications of MPC seeding



# Take-home messages: mixed-phase cloud seeding

Mixed-phase cloud seeding could offset about 25% of the expected increase in polar sea-surface temperature due to the doubling of CO<sub>2</sub>.

This is accompanied by an annual increase in sea-ice surface area of 8% around the Arctic, and 14% around Antarctica.

Mixed-phase cloud seeding, however, cannot prevent sea-ice loss during summer and as every climate intervention method only cures the symptoms.



**Thanks a lot for your attention!**

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**Questions?**

# Formation of a hole-punch cloud

