Department of Meteorology

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BOUNDING GLOBAL AEROSOL RADIATIVE FORCING OF CLIMATE CHANGE

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EGU2020 Online, 4 May 2020

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A new assessment approach

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- Base the assessment on multiple, traceable and arguable lines of evidence.
  - In-situ observations, remote sensing from the ground, aircraft or satellite.
  - Cloud resolving models, large eddy simulation.
  - Climate models, including multi-model and perturbed parameter ensembles.
  - Inferences based on observed changes (top-down approaches).
- Clearly identify the questions that are settled and those that remain open.
  - Which aerosol radiative forcing mechanisms are based on more speculative, untested hypotheses?
- Keep the task manageable.
  - Radiative forcing between "average present-day" 2005-2015 and 1850.
  - Global averages only.
  - 68% confidence intervals (IPCC "*likely*").

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Conceptual model

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Split the aerosol radiative forcing problem into three sets of questions:

1. What are the large-scale changes in aerosol optical depth (ari) and cloud droplet number (aci) over the industrial era?

2. What is the sensitivity of top-of-atmosphere radiation to those changes? What are the sensitivities of absorption and clouds to those changes? What is the sensitivity of top-of-atmosphere radiation to those rapid adjustments?

3. Over what fractions of the globe are the different radiative forcing mechanisms exerted?

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Bounding aerosol ERF

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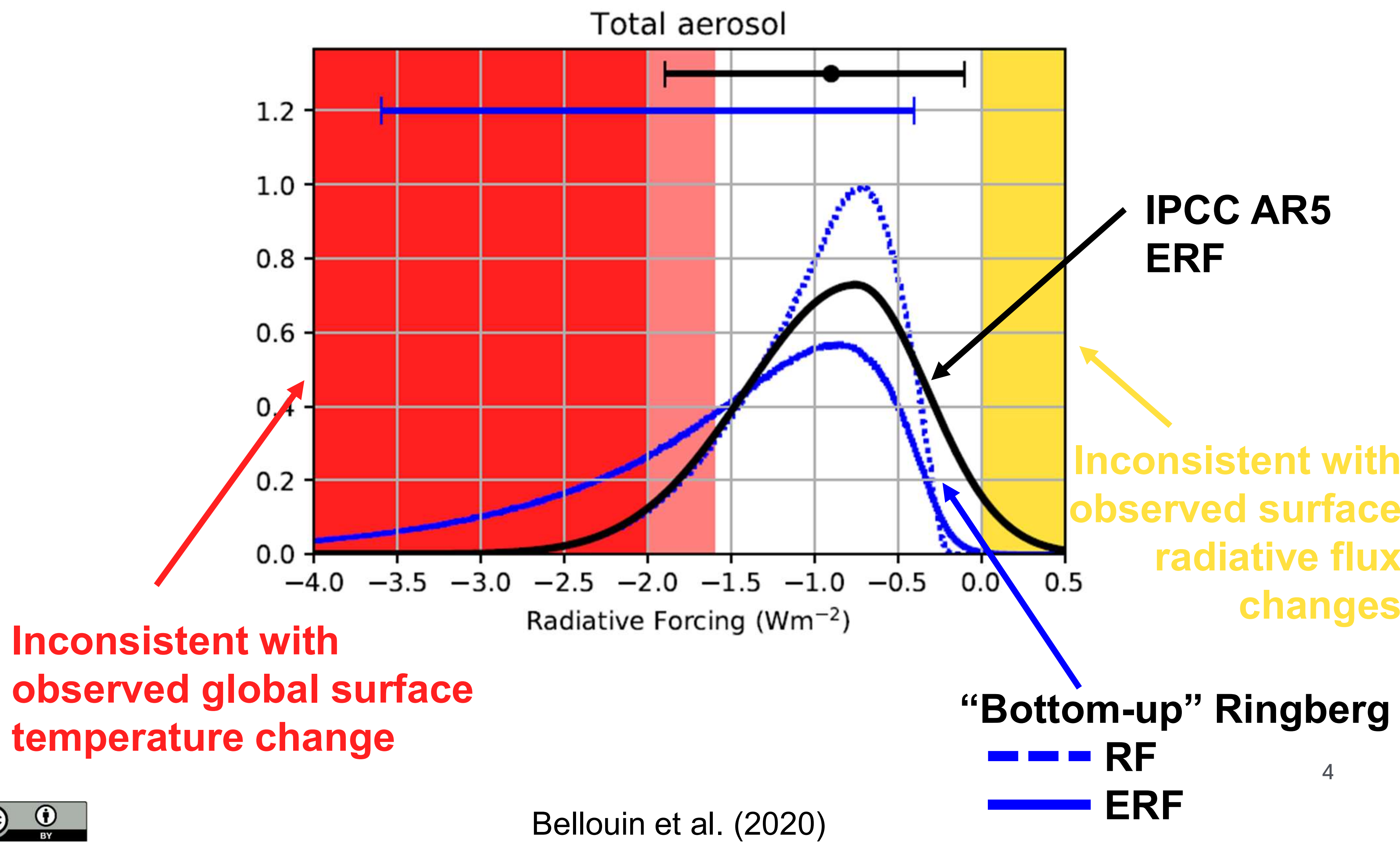

Bellouin et al. (2020)

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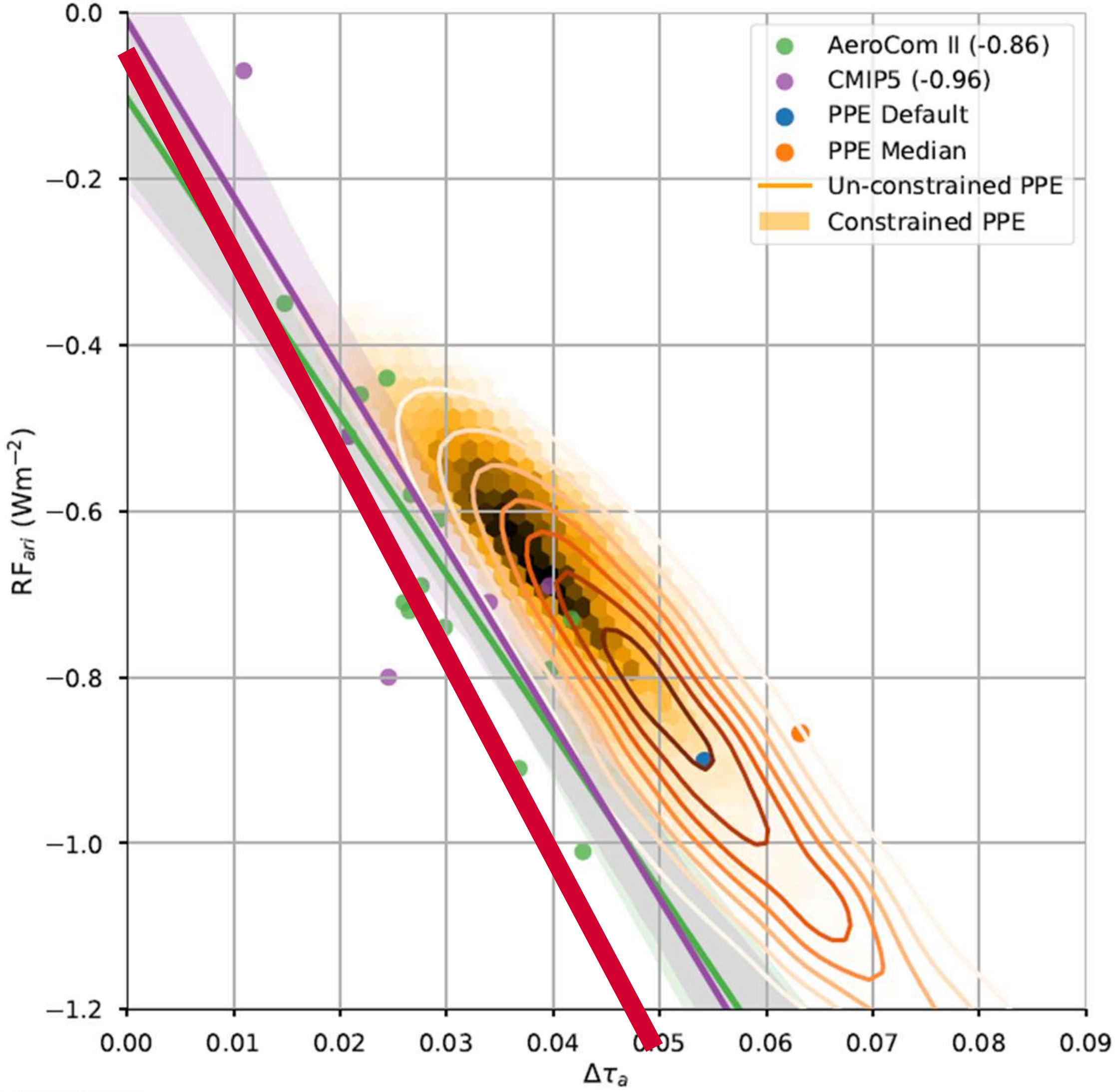
The role of absorption



High level of agreement among large-scale models about sensitivities of top-of-atmosphere to changes in aerosol optical depth.

Assuming purely scattering aerosols (thick red line) is only slightly wrong on the global scale.

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The role of adjustments to ari

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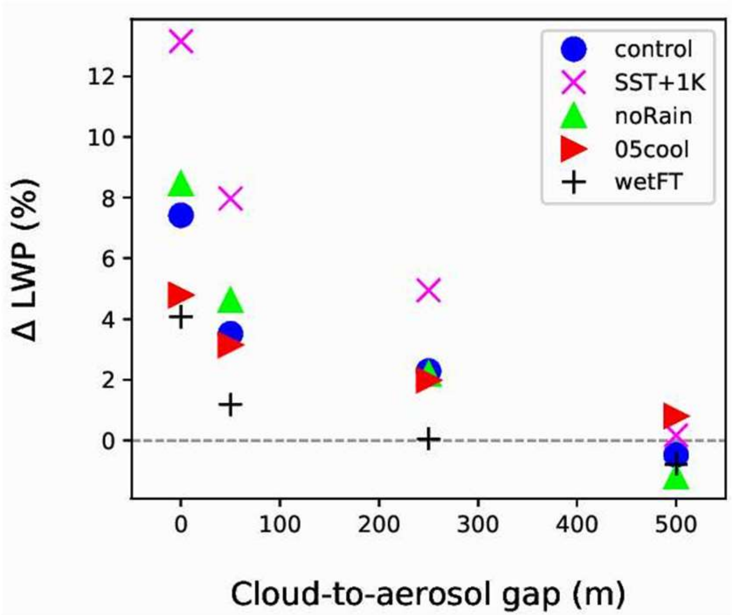
- For black carbon, PDRMIP models estimate a negative rapid adjustment to ari (semi-direct effects): the forcing and adjustment for BC may oppose each other.

Radiative forcing (W m^{-2})	BCx10	SO_2x5
Instantaneous	+2.42	−3.21
Rapid adjustments	−1.25	−0.32
Effective	+1.17	−3.52

Myhre et al. (2018)

- In addition, it is probably more difficult than previously thought for an overlying absorbing aerosol layer to affect stratocumulus cloud water content.



based on Herbert et al. (2019)

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The role of the Twomey effect

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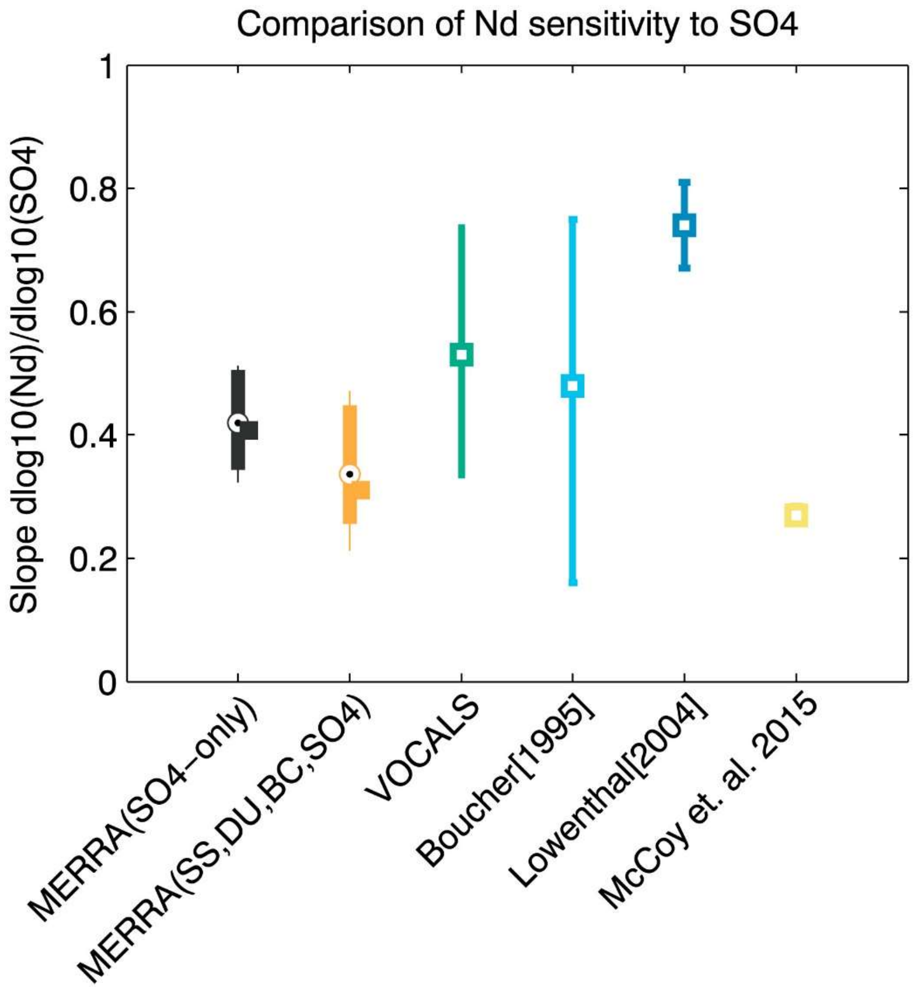
- The theory behind the Twomey effect is supported by many observations.

- But quantifying sensitivities is more challenging, as they depend on cloud regime.
  - Cloud droplet number concentrations are generally much more sensitive to changes in aerosol optical depth in aircraft observations than in satellite studies.



McCoy et al. (2017)

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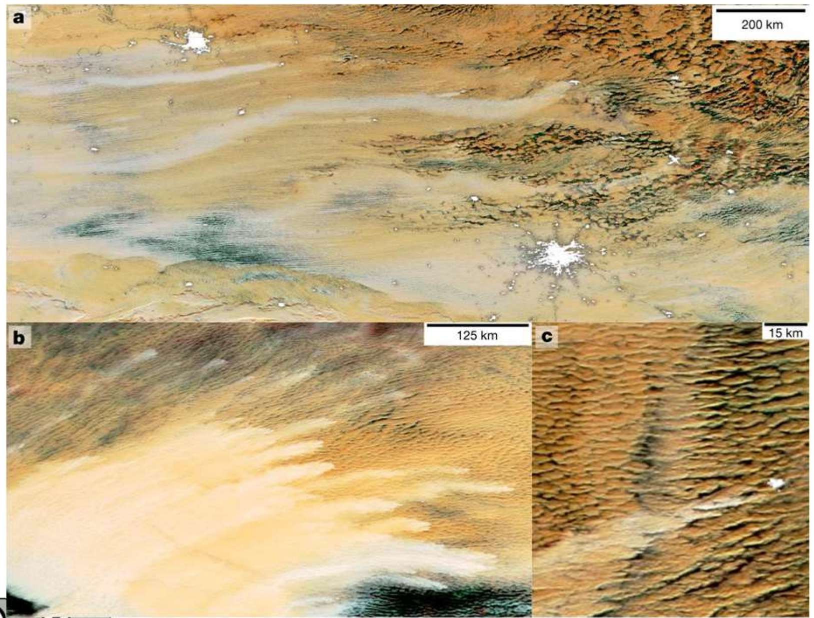
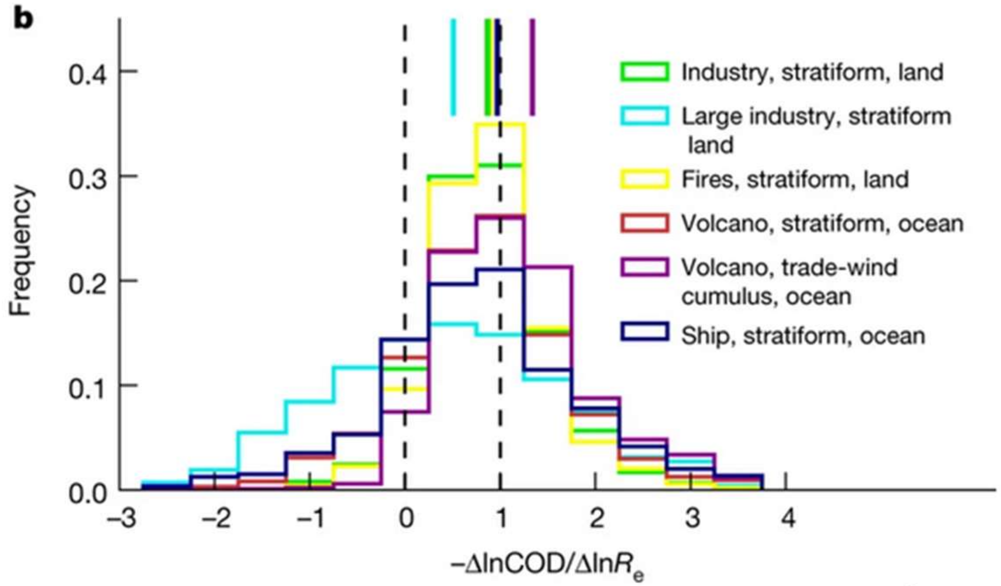
The role of adjustments to aci (1/2)

- The challenge is to separate the impact of aerosols from natural variability in cloud properties.
- A **large-scale response in cloud liquid water content** is probably weak, based on satellite analyses
  - Chen et al. (2014), Malavelle et al. (2017), Toll et al. (2017, 2019), Rosenfeld et al. (erratum, 2019), Gryspeerdt et al. (2019)





Toll et al. (2019)

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The role of adjustments to aci (2/2)

- A **large scale response in cloud fraction** is still possible, and could double or triple RFaci
  - Gryspeerdt et al. (2016), Christensen et al. (2017), Andersen et al. (2017)
  - But the time dependence of that response is unclear.

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What about ice clouds?

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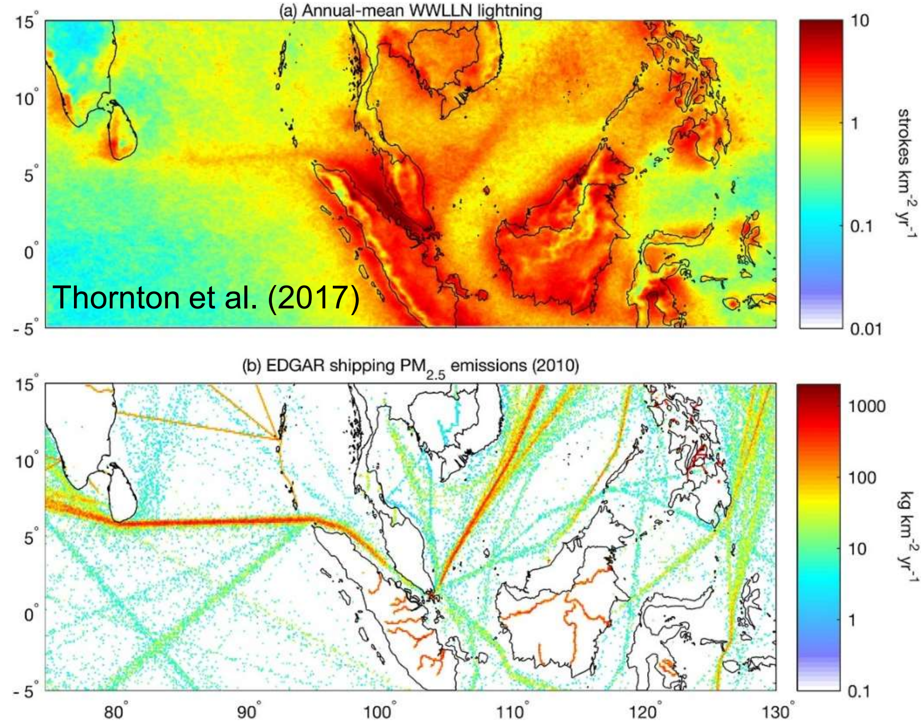
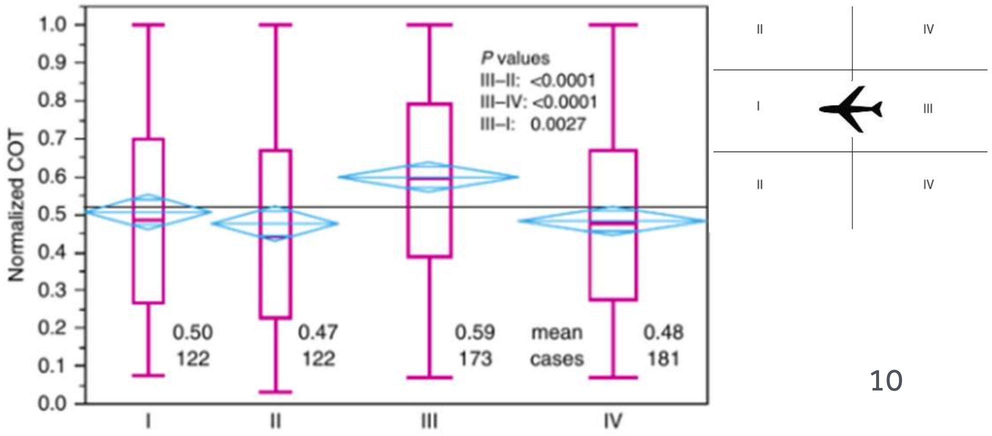
- Many potential mechanisms for aerosols affecting ice clouds, but most are untested.
- RFaci[ice] depends on the balance between homogeneous and heterogeneous nucleation in ice clouds, which is poorly known.
- It now seems likely that black carbon is not a good ice nucleating particle.

- Some evidence to support aerosol impacts on cirrus and convective clouds, but the associated sensitivities are unknown.



Thornton et al. (2017)



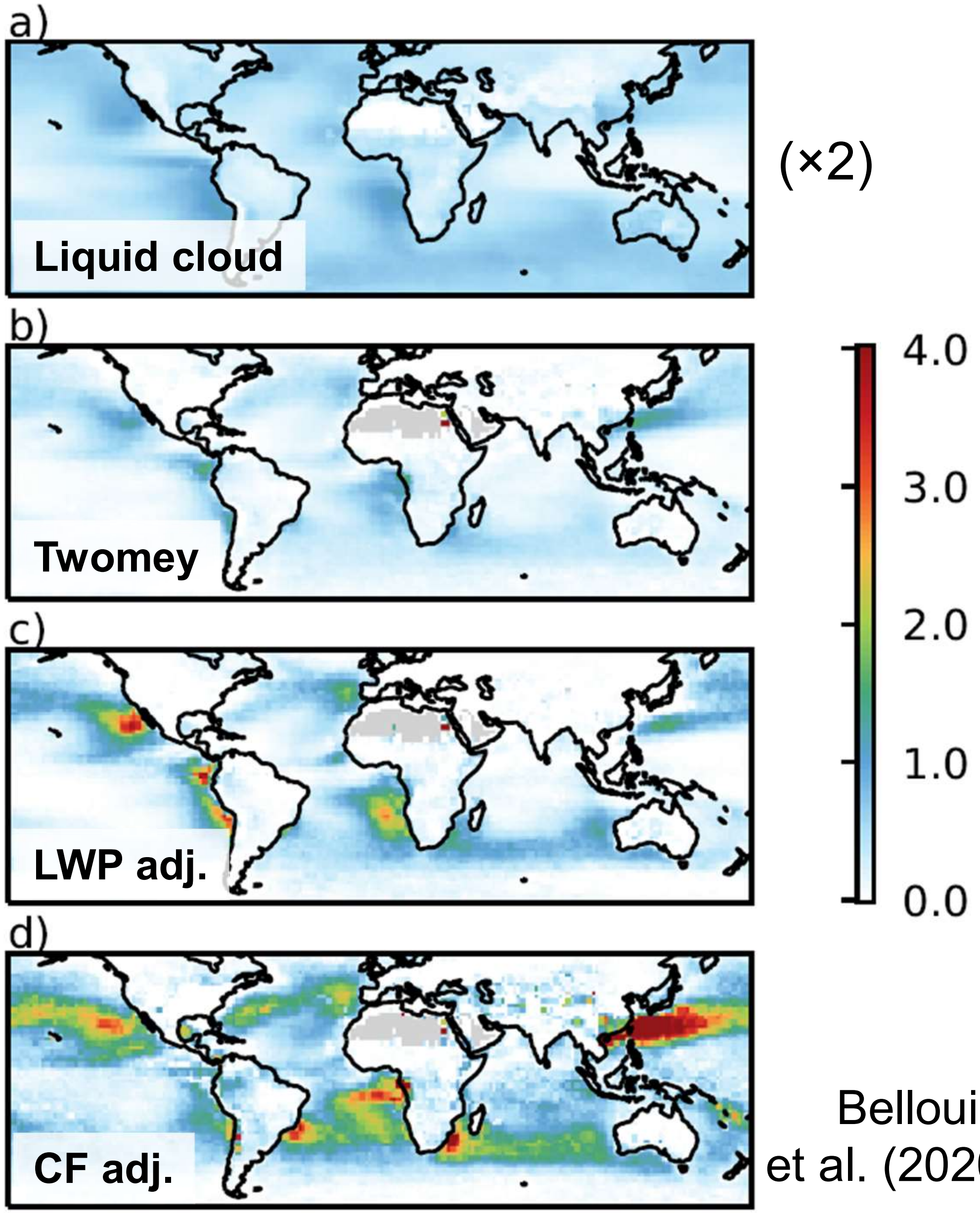
Tesche et al. (2016)

Effective cloud fractions

A forcing is exerted by:

- A perturbation;
- Sensitivity of radiation to the perturbation;
- Where cloud/moisture can respond, sensitivity of cloud/moisture to the perturbation.

Those requirements can be expressed as fractional areas analogous to cloud fractions.



Bellouin et al. (2020)

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Lines of evidence

Table 4

Ranges Obtained by This Review in the 16–84% Confidence Interval for the Variables of Equations (8), (15), and (24)

Section	Variable	Lower bound	Upper bound	Line of evidence
4	τ_a^{PD}	0.13	0.17	Satellite retrievals
4	$\Delta\tau_a$	0.02	0.04	Global modeling
4	$\Delta \ln \tau_a = \Delta\tau_a/\tau_a^{PD}$	0.14	0.29	Modeling/satellite
6	$\Delta \ln N_d = \Delta N_d / N_d$	0.05	0.17	Modeling/satellite
Aerosol-radiation interactions				
5	S_τ^{clear} [W m^{-2} τ_a^{-1}]	−27 (0.08)	−20 (0.06)	Global modeling
5	c_τ	0.59	0.71	Global modeling
5	S_τ^{cloudy} c_τ [W m^{-2}]	−0.1	+0.1	Global modeling
5	*RF of ari* [W m^{-2}]	*−0.37*	*−0.12*	
7	dR/dR_{atm}	−0.3	−0.1	Global modeling
7	$dR_{atm}/d\tau_a$ [W m^{-2} τ_a^{-1}]	17	35	Global modeling
7	*RA of ari* [W m^{-2}]	*−0.25*	*−0.06*	
7	*ERF of ari* [W m^{-2}]	*−0.58*	*−0.23*	
Aerosol-cloud interactions				
6	$\beta_{\ln N - \ln \tau}$	0.3	0.8	Modeling/satellite
6	S_N [W m^{-2}]	−27 (0.079)	−26 (0.076)	Satellite retrievals
6	c_N	0.19	0.29	Modeling/satellite
6	*RF of aci* [W m^{-2}]	*−1.10*	*−0.33*	
8	$\beta_{\ln \mathcal{L} - \ln N}$	−0.36	−0.011	Satellite analyses
8	$S_{\mathcal{L},N}$ [W m^{-2}]	−54	−56	Mixed
8	$c_{\mathcal{L}}$	0.21	0.29	Mixed
8	*RA of aci (liquid water path)* [W m^{-2}]	*0.01*	*+0.56*	
8	$\beta_{C - \ln N}$	0	0.1	Global modeling, LES
8	$S_{C,N}$ [W m^{-2}]	−91	−153	Satellite analysis
8	c_C	0.59	1.07	Mixed
8	*RA of aci (cloud fraction)* [W m^{-2}]	*−1.14*	*0.0*	
8	*ERF of aci* [W m^{-2}]	*−1.73*	*−0.27*	
11	**Total aerosol ERF** [W m^{-2}]	**−2.19**	**−0.61**	
11	(constrained by observational inferences)	−1.60	−0.61	

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Bellouin et al. (2020) relies on global modelling for

- industrial-era aerosol changes
- ari

and global satellite studies for

- aci.

Stronger lines of evidence like in-situ measurements and process modelling ended up not being used because nobody knows how to properly weigh their results into a global average.

Promising avenues

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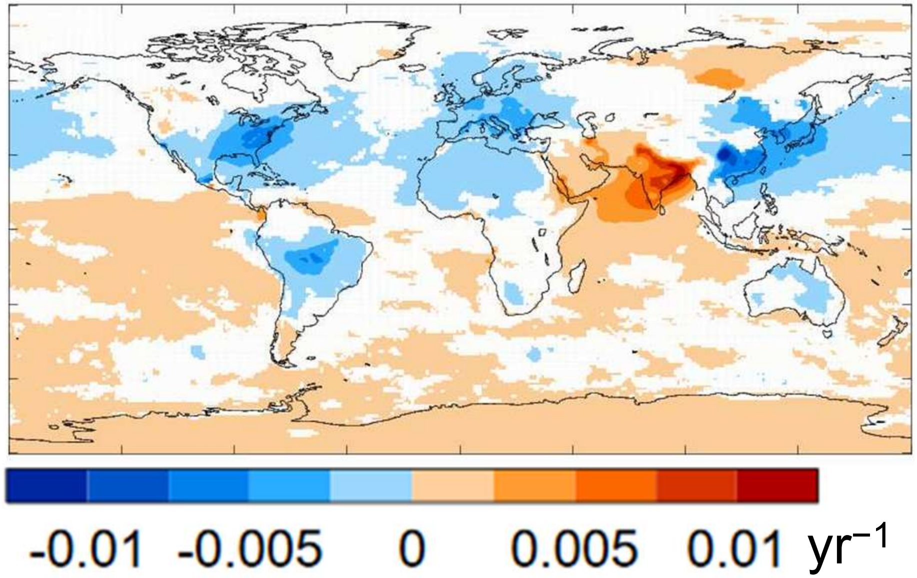
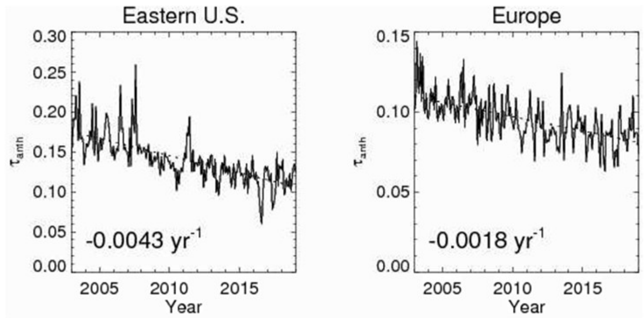
- Scale effects are increasingly being considered in model development. Global large eddy simulation is now becoming possible.
- Cloud responses to regional aerosol trends, and volcanic eruptions and ship tracks may provide insights into cloud regime shifts and ice cloud responses.
- Observational inferences are promising but their uncertainties need to be better understood. Large regional trends (right) may provide strong constraints.
- Models of all scales involve a large number of poorly known parameters, and statistical methods to explore model uncertainties are being adopted.

Deseasonalised linear trends in anthropogenic aerosol optical depth 2003—2019, based on CAMS Reanalysis





Update to Bellouin et al. https://doi.org/10.5194/essd-2019-251

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Thank you for your attention!

Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., et al. (2020). Bounding global aerosol radiative forcing of climate change. Reviews of Geophysics, 58, e2019RG000660. https://doi.org/10.1029/2019RG000660

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