Assessing cloud-aerosol interactions as a source of climate predictability

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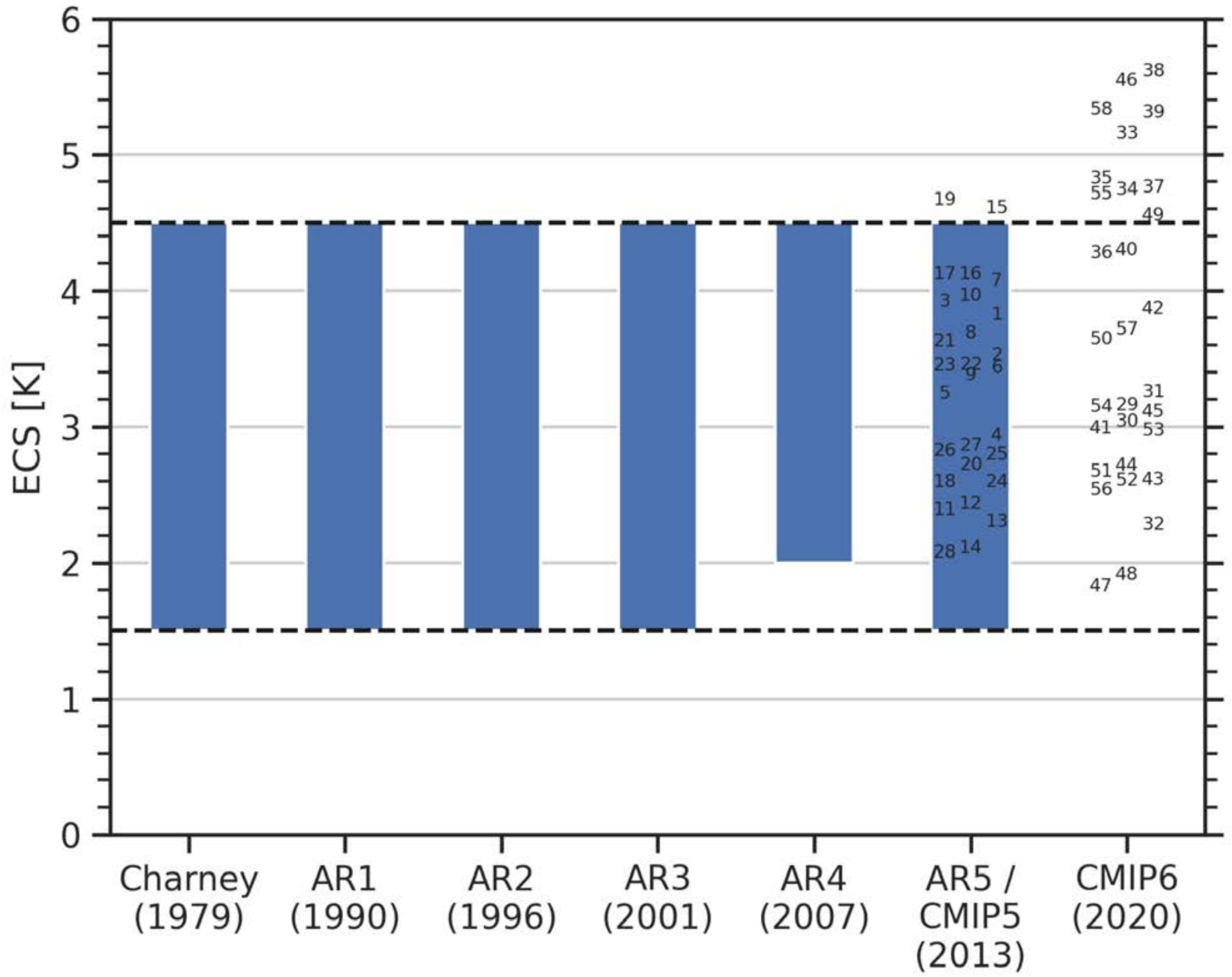
Equilibrium Climate Sensitivity (ECS)

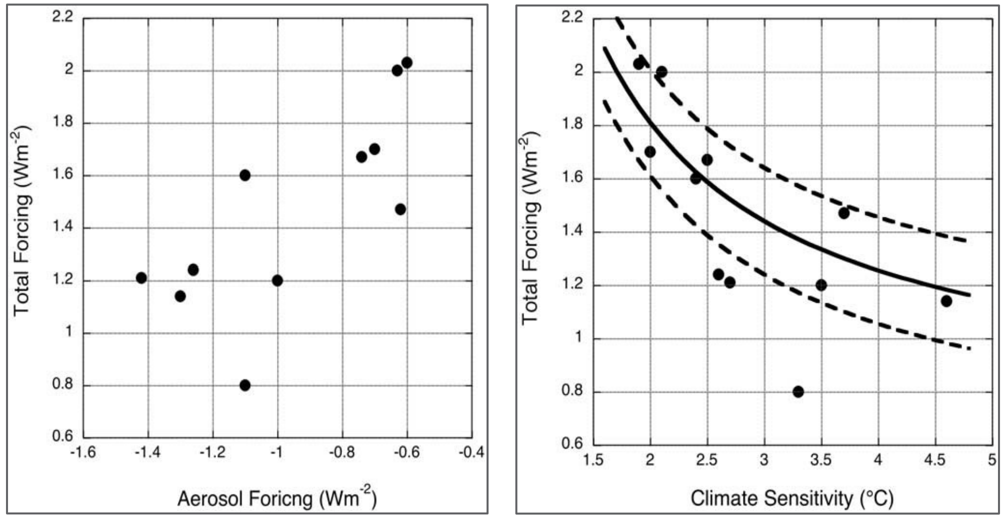
Schlund et al (2020)



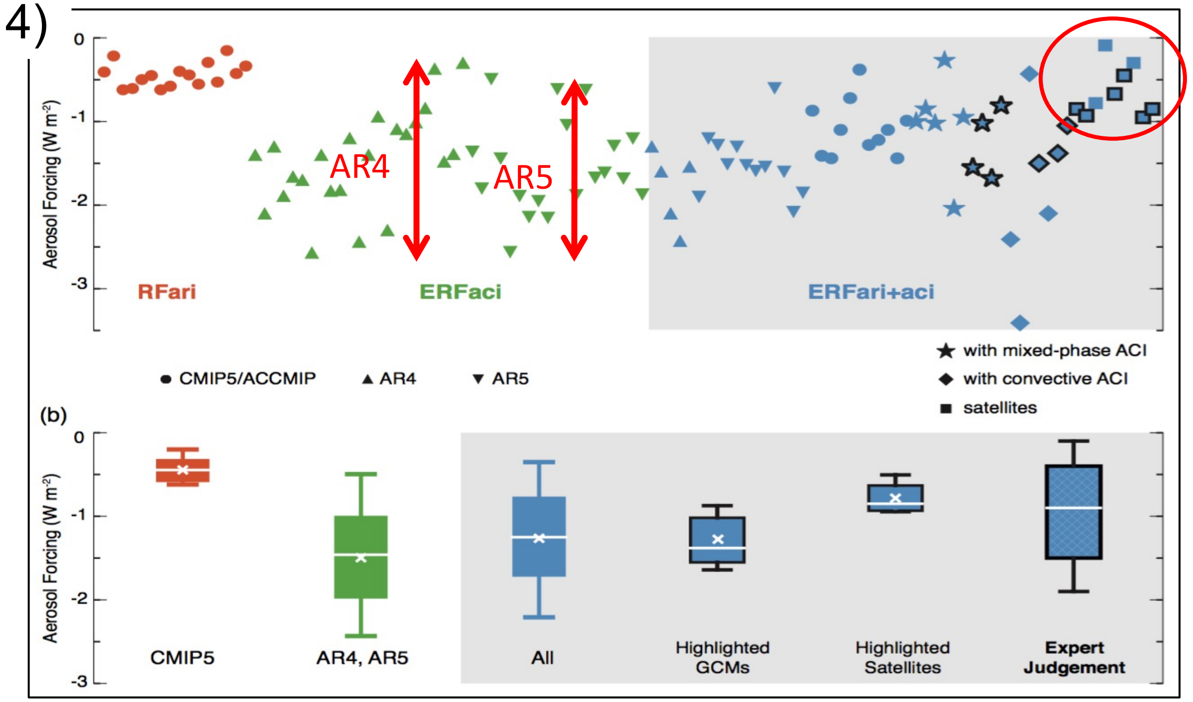
Aerosol effects and cloud feedbacks are two major sources of climate predictability

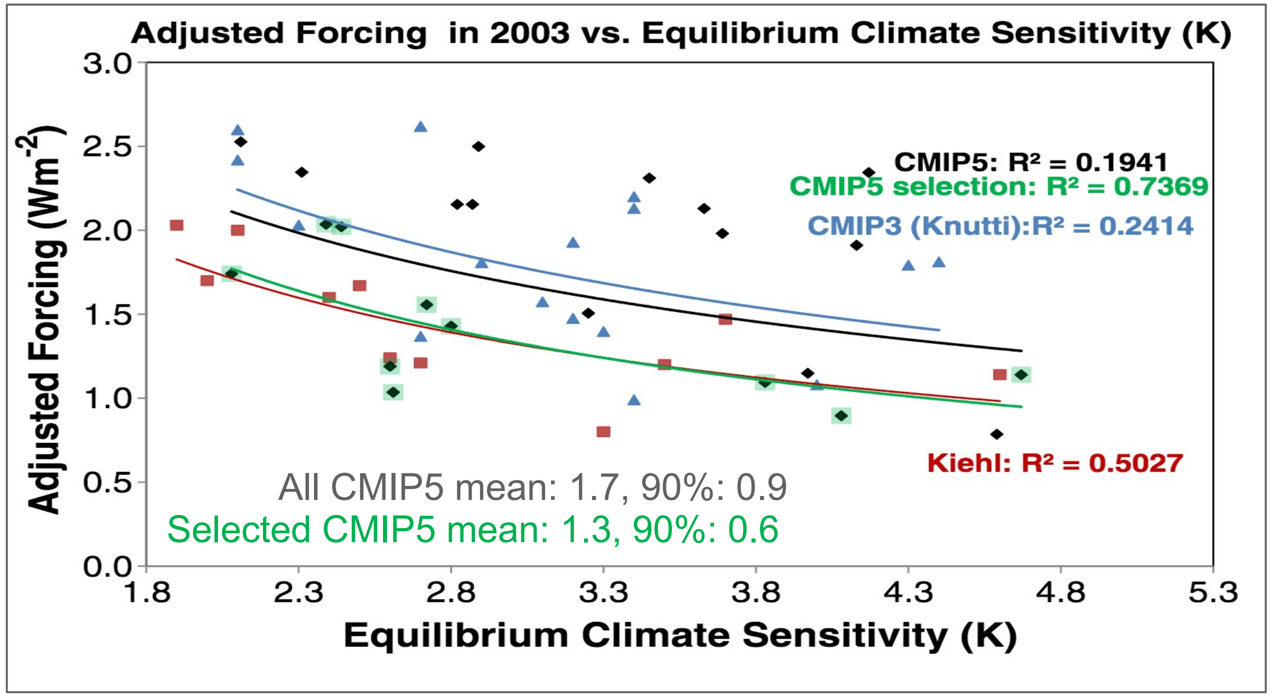
The role of aerosols: constraining forcing and historical climate to constrain climate projections

Kiehl (2007)



IPCC AR5 (2014)





Forster et al (2013)

- CMIP3-5: Stronger aerosol effects correlates with weaker total forcing and higher climate sensitivity

The role of aerosols: constraining forcing and historical climate to constrain climate projections?

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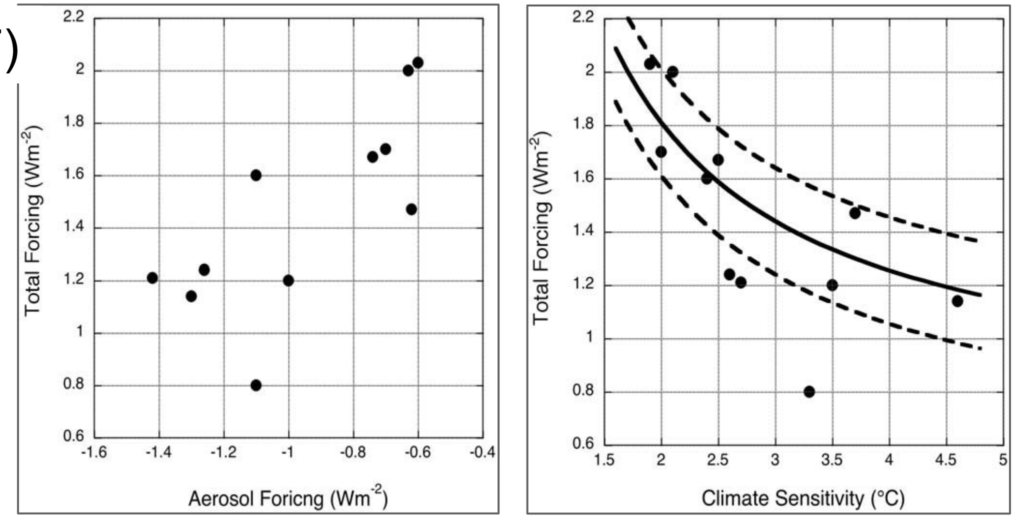
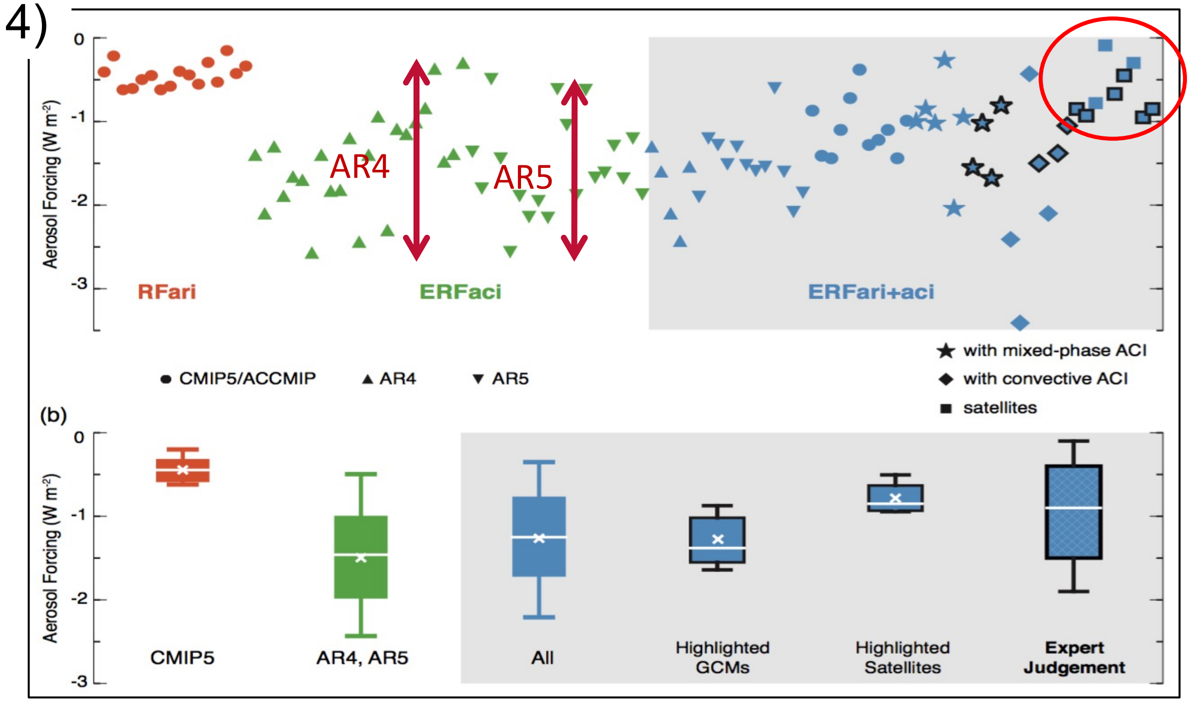
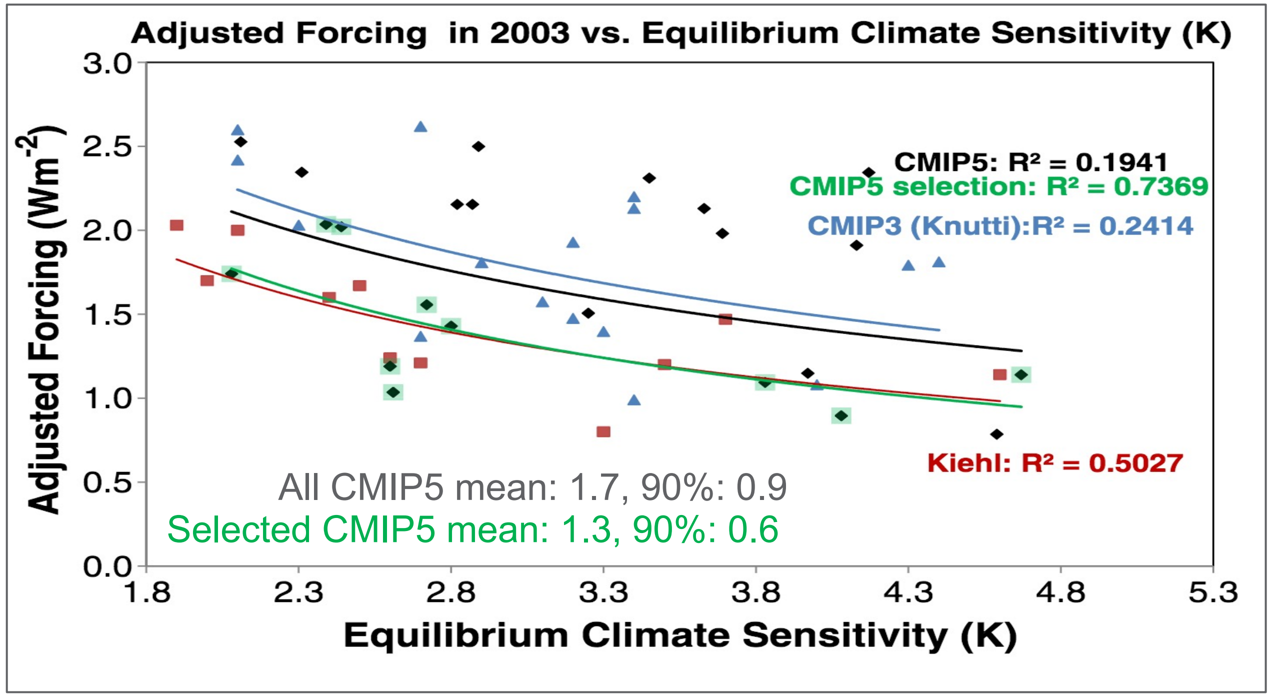
Kiehl (2007)



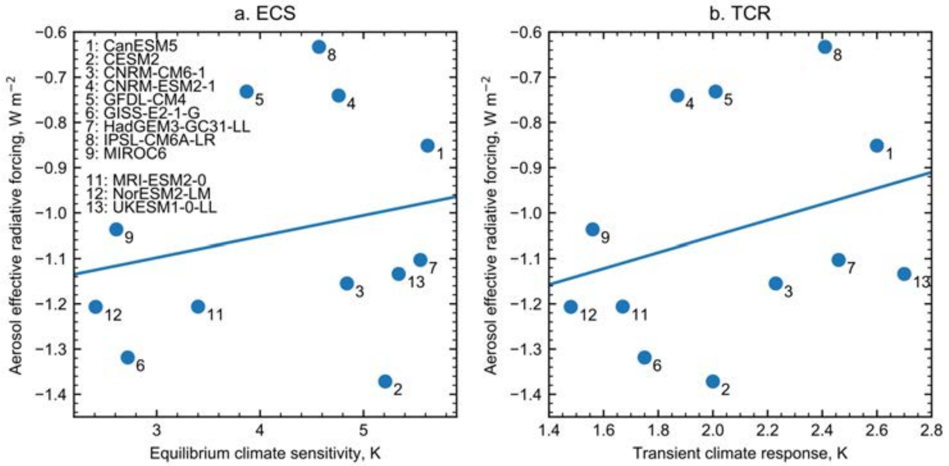
IPCC AR5 (2014)





Forster et al (2013)

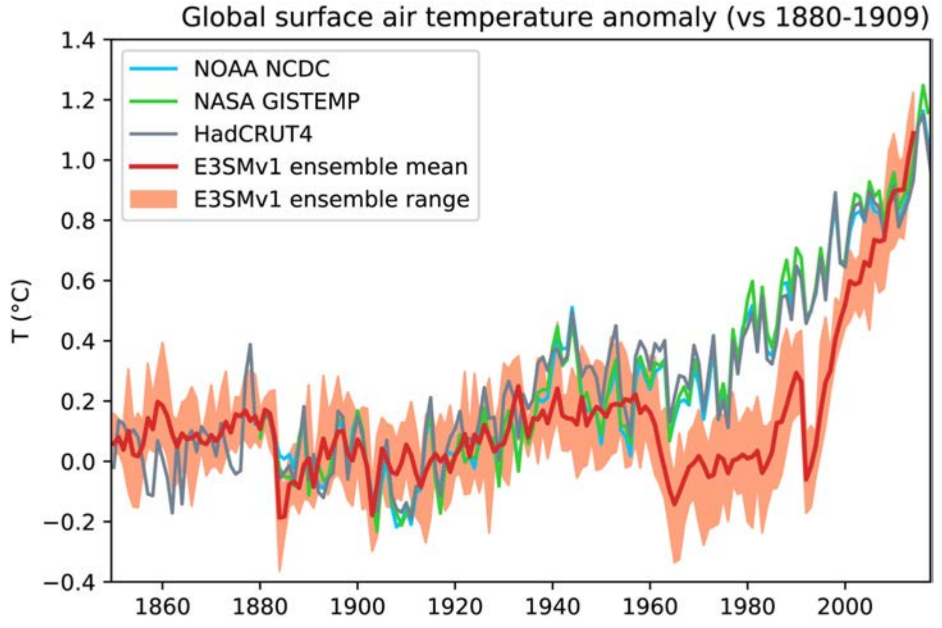
Smith et al (2020)

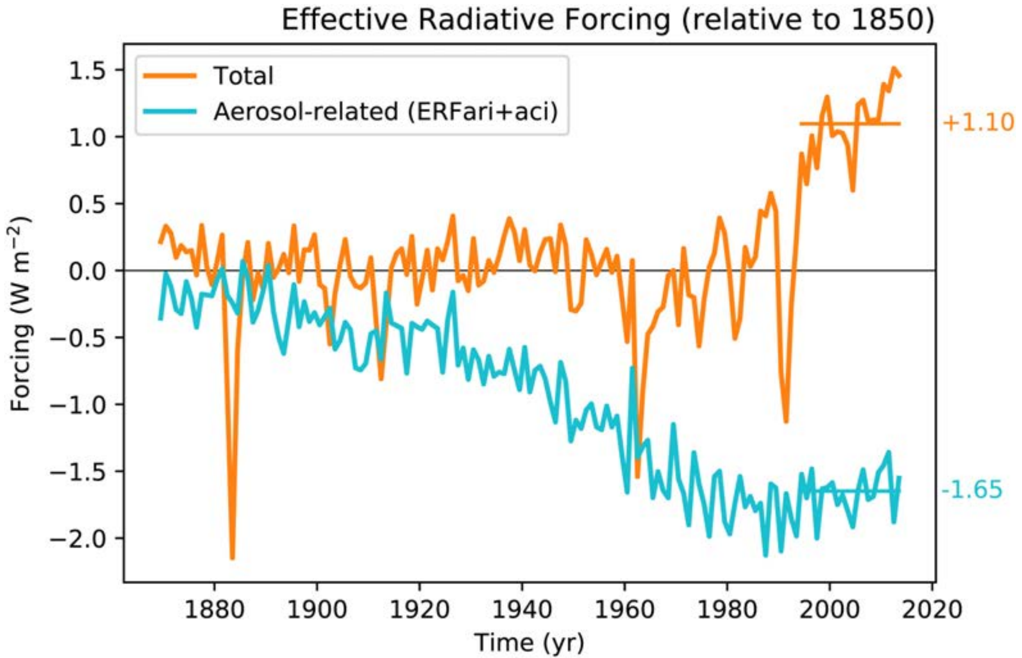


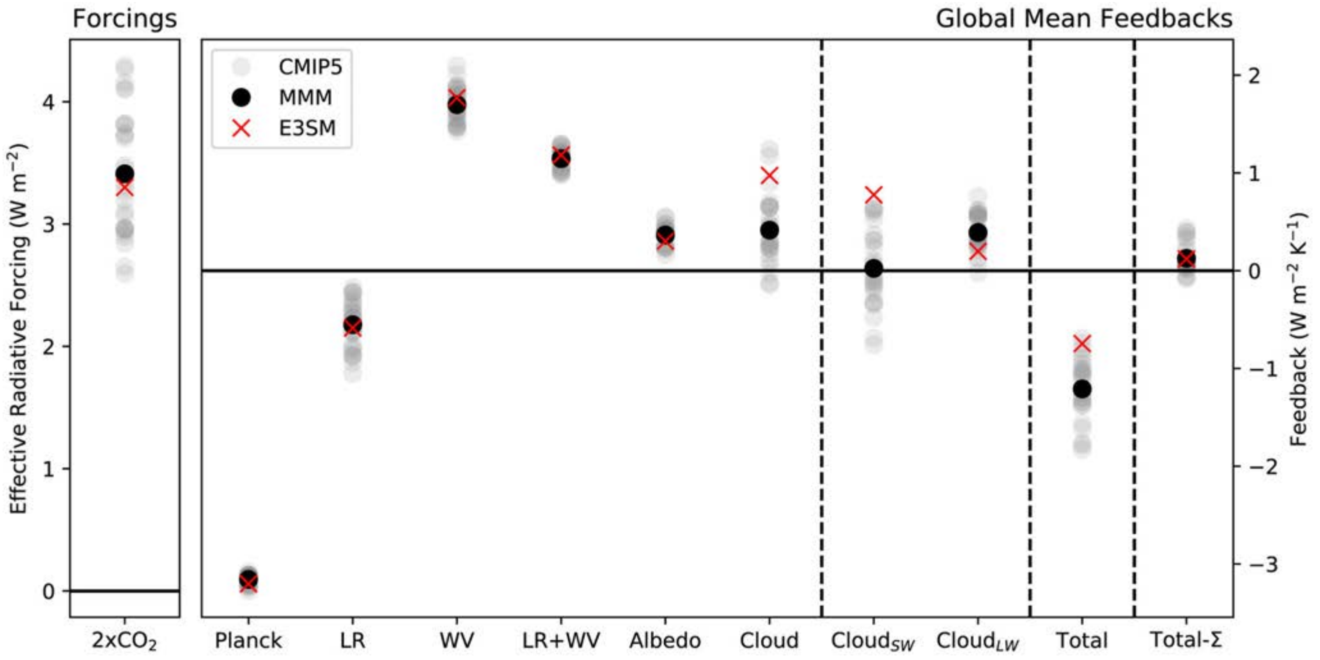
- CMIP3-5: Stronger aerosol effects correlates with weaker total forcing and higher climate sensitivity
- CMIP6: New (no?) relationship

Energy Exascale Earth System Model (E3SM)

Golaz et al (2019)



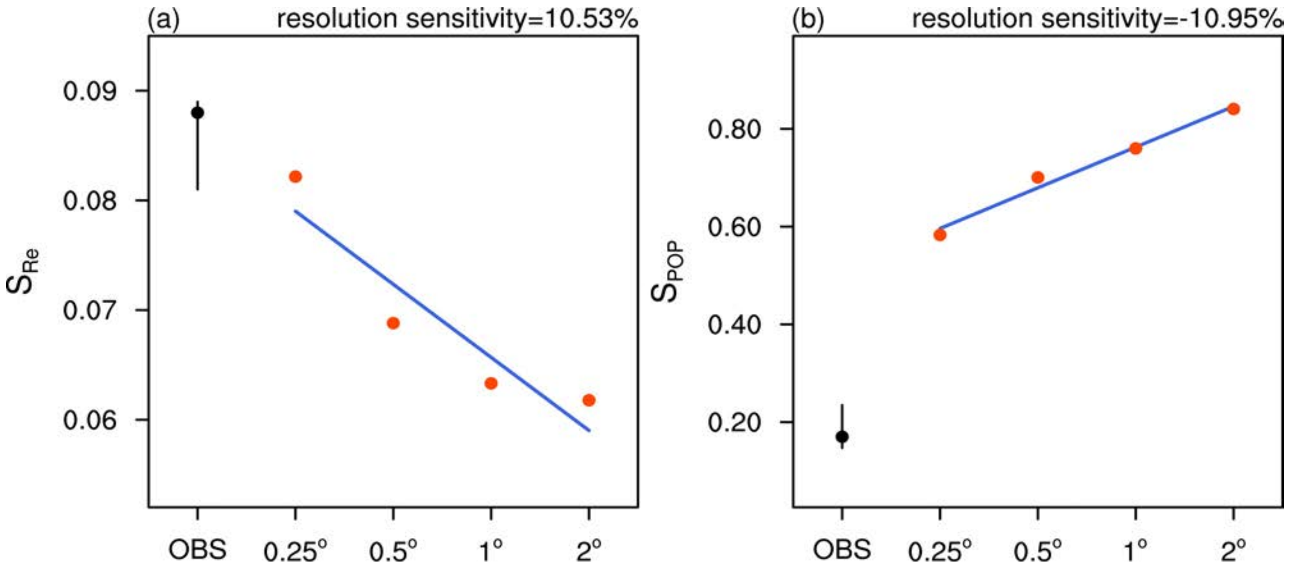




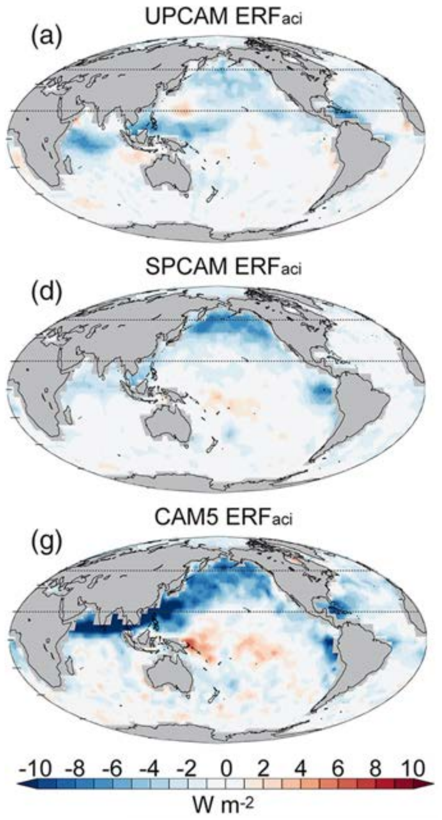
Bellouin et al., 2020:

- -1.6 to -0.6 Wm^{-2} (68% likelihood)
- -2.0 to -0.4 Wm^{-2} (90% likelihood)

Increase resolution improves agreement between model and observational estimates of ACI



Ma et al. (2015)



Terai et al. (2020)

- Increasing resolution improves small-scale meteorological features critical for aerosol-cloud interaction, increasing the agreement of cloud and precipitation susceptibility with observations even though the same physical parameterizations are used.

- Weaker ERFaci is caused by a combination of weaker increase in LWP in non-raining clouds and a smaller fraction of raining clouds in UPCAM

How do we better integrate high-resolution-high-fidelity data/model into ESMs?

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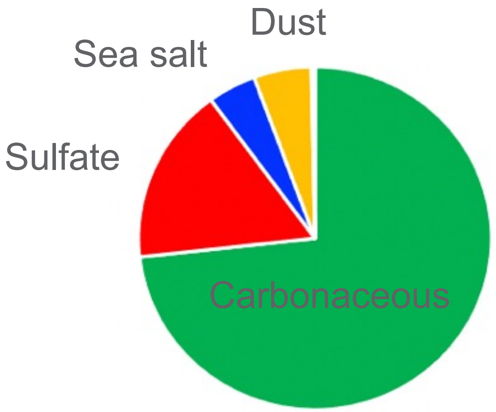
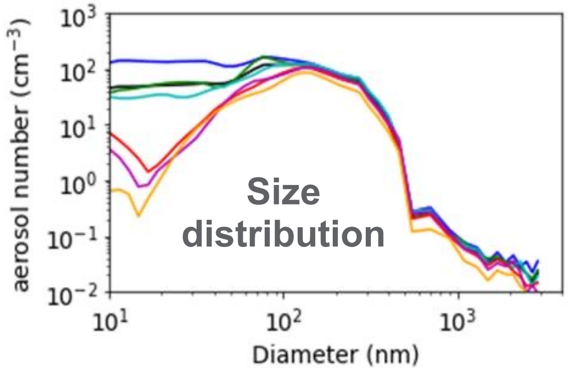
Improve the representations of aerosols and cloud-aerosol interactions in E3SM

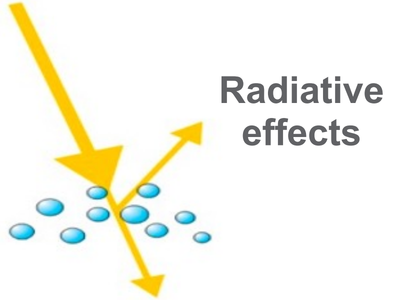
Emission, transport, chemical/physical processes predicting aerosol properties, lifecycle, and distribution

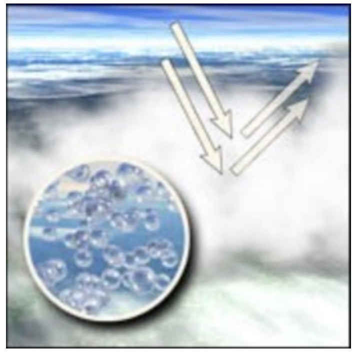


Composition, hygroscopicity

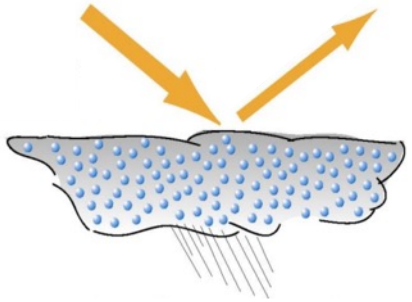


Aerosol-radiation-cloud-precipitation interactions



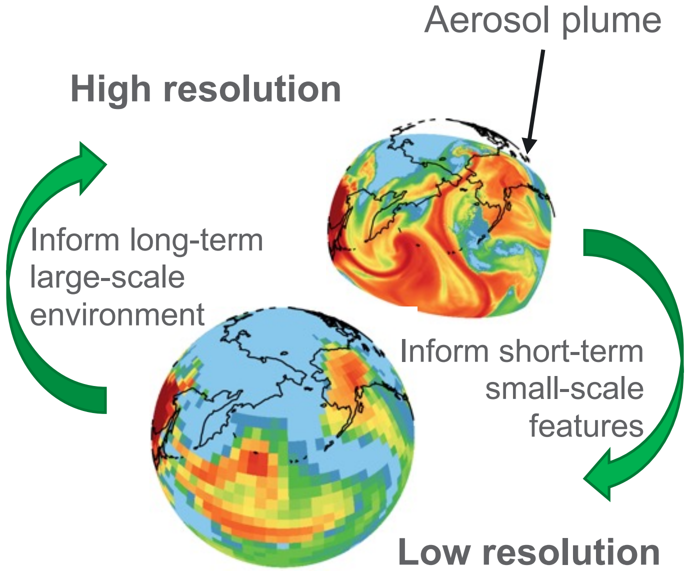


Cloud albedo effects



Precipitation effects and cloud lifetime effects

Modern software for exascale computation



Accurate and fast simulations at various resolutions to address science challenges

Employ AI/ML to integrate data and models to improve aerosols and cloud-aerosol interactions in E3SM

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Sandia National Laboratories

TEXAS A&M UNIVERSITY

THE UNIVERSITY OF ARIZONA

UCIRVINE

UNIVERSITY of WASHINGTON

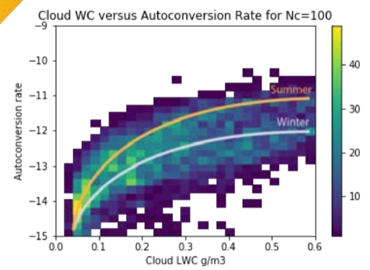
UWM UNIVERSITY of WISCONSIN MILWAUKEE

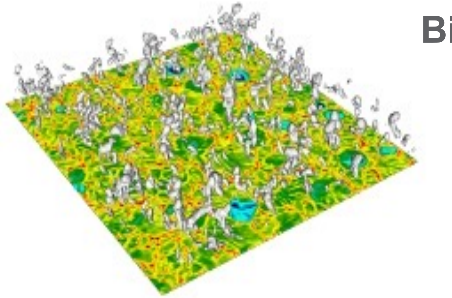
Combine expertise in climate science, data science, software engineering

ARM

Measurements of aerosols, clouds, precipitation, and meteorology

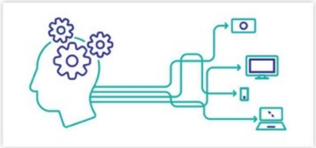
+





World's largest detailed process model and LES ensemble provides information on aerosols, clouds, precipitation, and meteorology

Big training data: O(100TB)



AI-assisted analytics to improve understanding and design parameterizations

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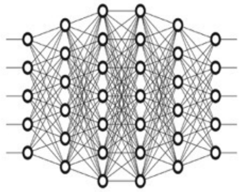


Data-driven & physically informed **ML emulator**

Software infrastructure incorporating AI/ML in Earth system models

E3SM Energy Exascale Earth System Model

Next steps:

- More **physically informed ML emulator** for aerosols and aerosol-cloud processes based on **big data**
- **Quantify the uncertainty** associated with the ML approach
- Use **explainable artificial intelligence** (XAI) to improve understanding and trustworthiness

Improving aerosol's cloud albedo effect: Emulating aerosol activation using deep neural network

Silva, Ma, Pritchard, Yu, Singh, et al.

Challenge

- Traditional parameterization neglects kinetic limitations
- Explicit parcel model calculations way too expensive to employ in Earth system models

Objective

- Improve aerosol activation in E3SM by correcting the E3SM bias introduced by the original parameterization without adding computational cost

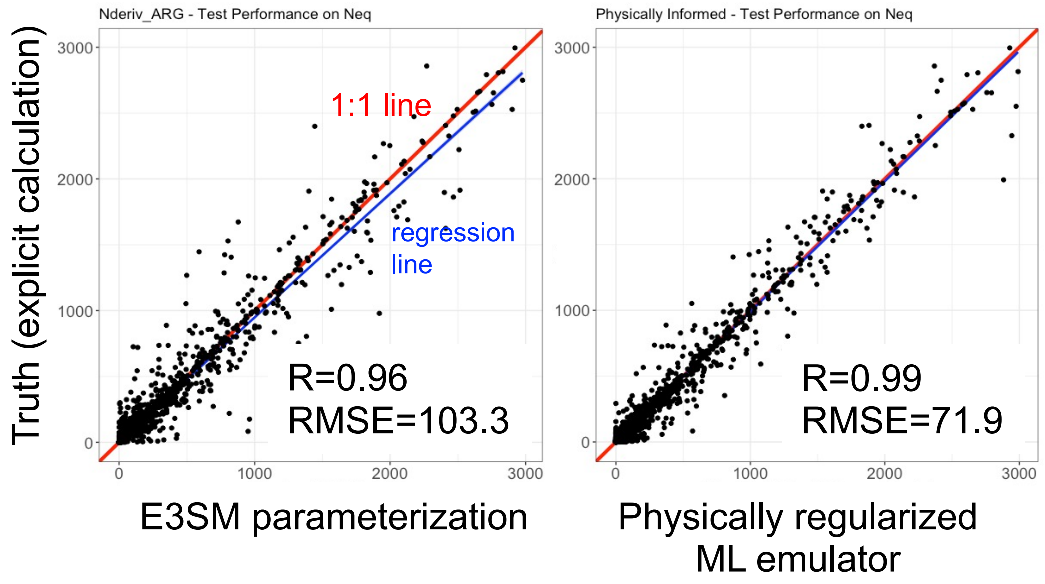
Approach

- Build **ML emulators based on explicit cloud parcel model** results
- Train on big data (over 100M samples)

Results

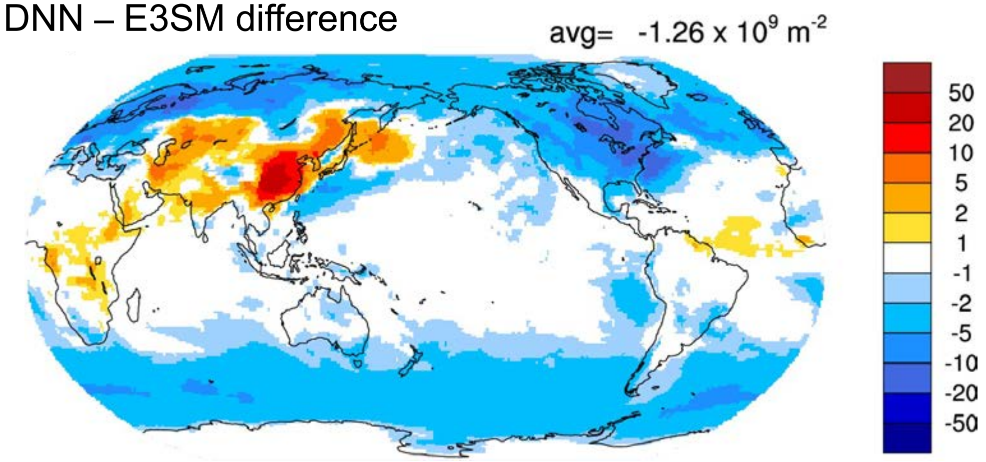
- Significant improvement on aerosol activation
- Computational cost is negligible
- Stable and more accurate global simulations
- Aerosol-induced radiative effects reduced

Silva et al (2020), *Geosci Model Dev*



New DNN-based activation corrects the model bias in over-predicting activation in high-activation regime

DNN – E3SM difference



Compared to the default E3SM, DNN produces more droplets in Asia and less droplets in other mid- and high latitude regions

Improving aerosol’s cloud lifetime effects: Emulating warm rain initiation using deep neural network

Ma, Pritchard, Yu, Jones, Varble, Pressel, Kaul, Rader, Fan, Shpund, Singh, et al.

Challenge

- Traditional parameterization built on single cloud regime, not suitable for global models
- Limited predictability due to insufficient predictors

Objective

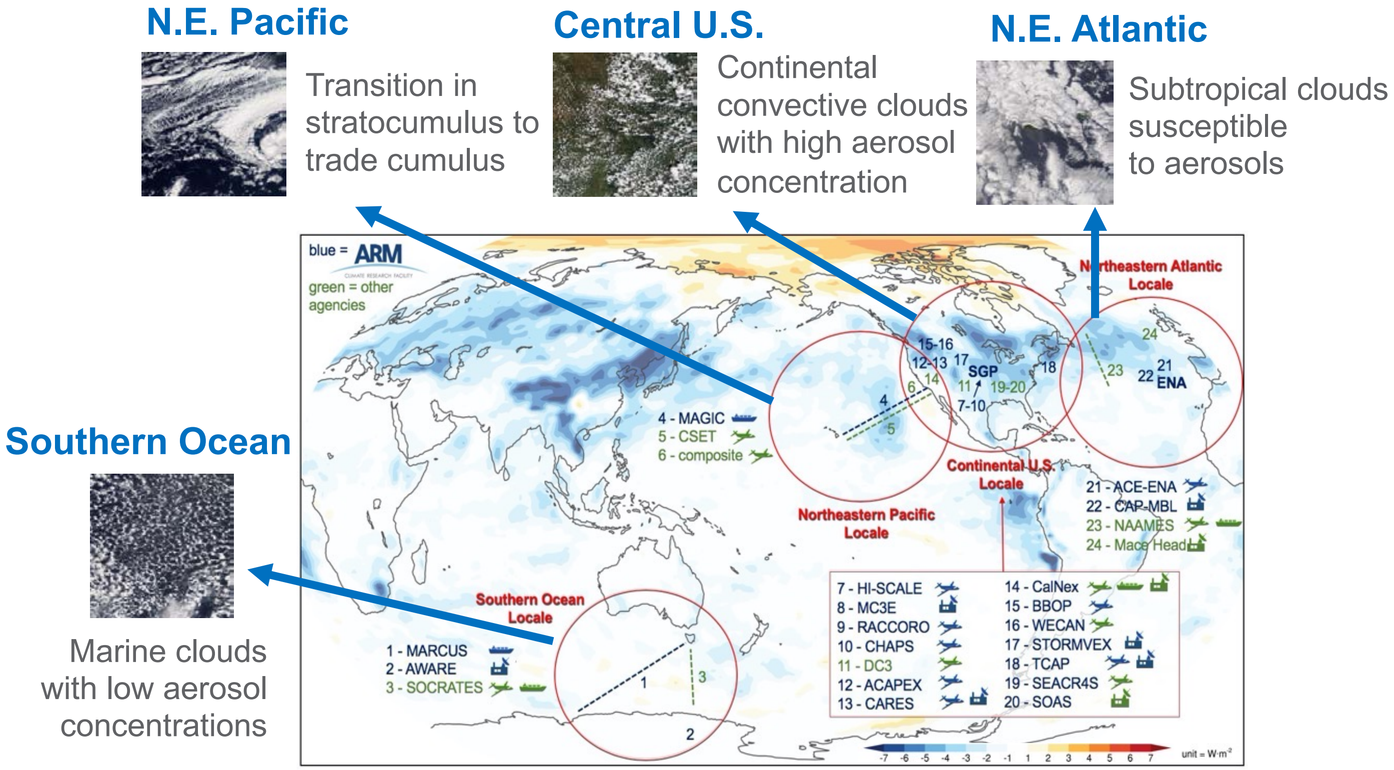
- Develop a representation of warm rain initiation (i.e., autoconversion) suitable for the global model E3SM

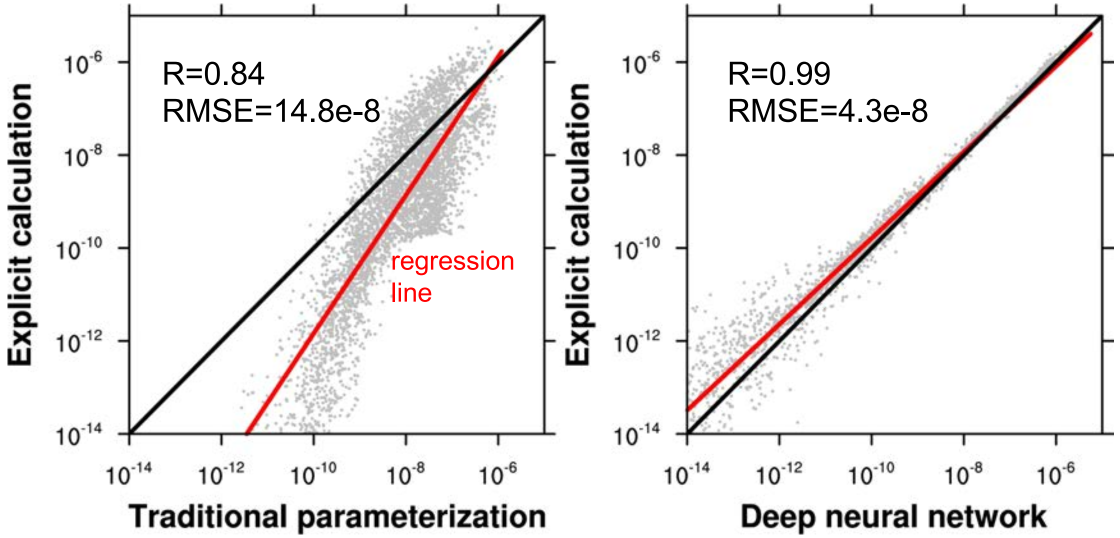
Approach

- Build **ML emulators based on explicit collision-coalescence** calculations **and environmental conditions**
- Train on **big data** covering a wide range of aerosol, cloud, meteorological conditions

Results

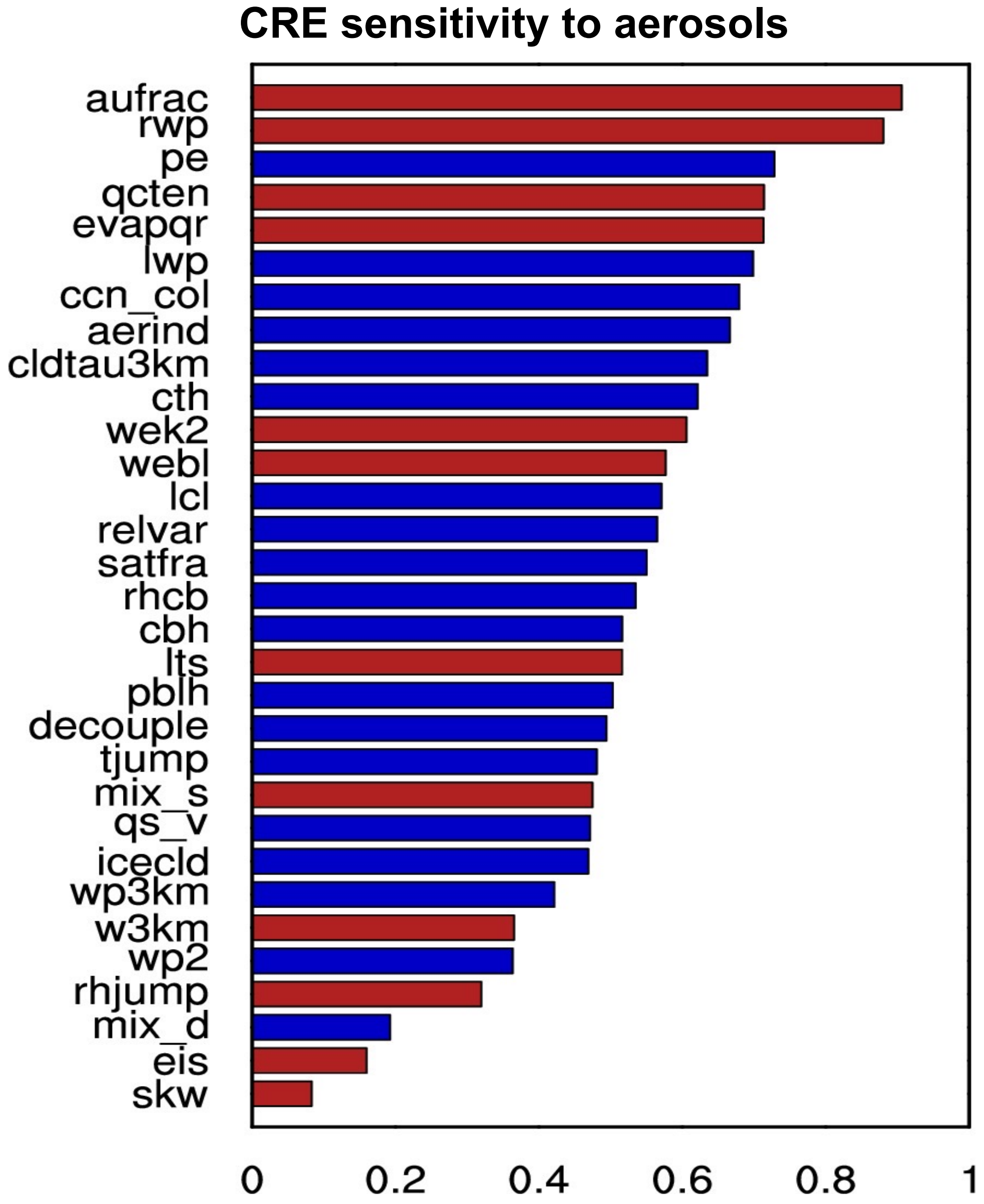
- Significant improvement using the globally suitable DNN emulator
- **Combination of expertise** in aerosol-cloud physics and machine learning leads to big **advancement in understanding and predictability** via co-designing the DNN emulator





Processes not directly relevant to cloud-aerosol interactions can affect cloud-aerosol interactions!

- E3SM PPE
  - activation
  - evaporation efficiency
  - autoconversion
  - accretion
  - subgrid variability
  - convective precipitation efficiency
  - cloud phase (Tan et al., 2016)
  - PDF width
  - skewness
  - sedimentation (Ackerman et al 2004, 2009; Bretherton et al 2007; Guo et al 2011)
  - convective entrainment (Knight et al 2007; Sanderson et al 2007; Rougier et al 2009; Zhao 2014; Zhao et al 2016)

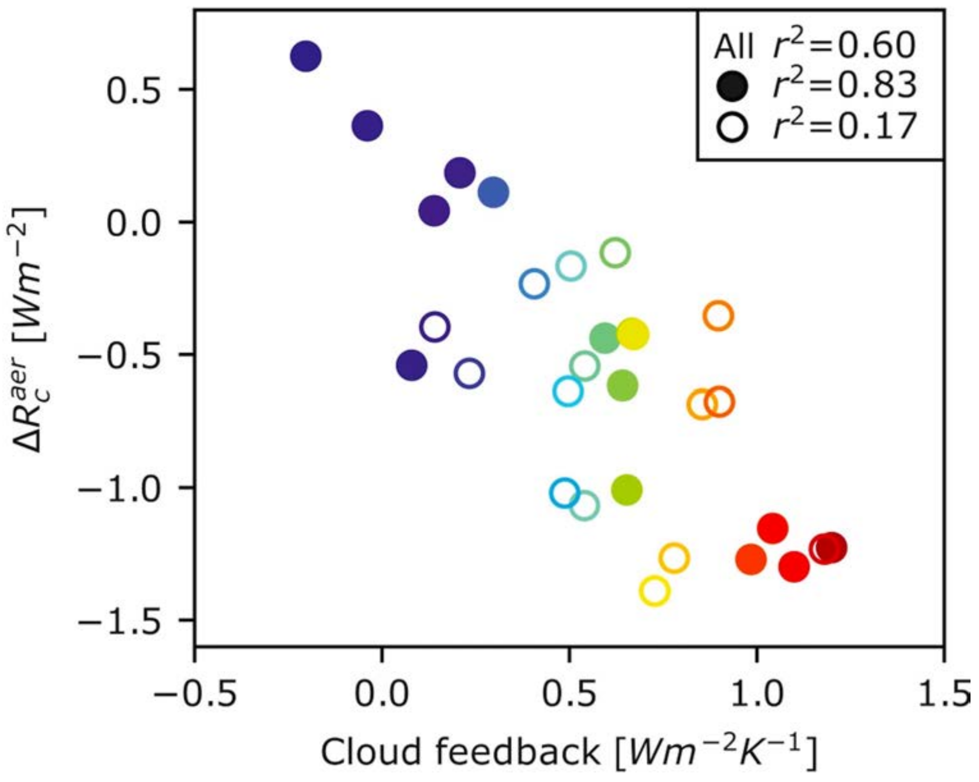


- Important mechanisms
  - Autoconversion fraction
  - Cloud top entrainment
  - PBL decoupling
  - Shallow mixing efficiency

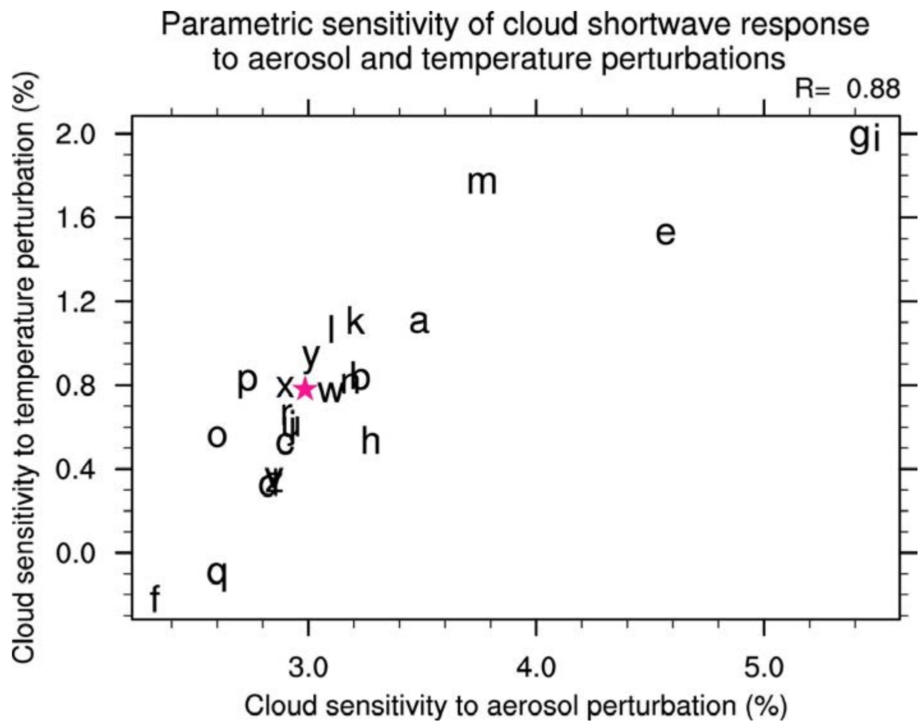
- Important state variables:
  - Rainwater
  - Evaporation of cloud and rain
  - Aerosols
  - COD
  - Cloud top height
  - LCL
  - Subgrid variability
  - PBL humidity and height

Ma et al., in prep.

Why are cloud-aerosol interactions and cloud feedbacks correlated?



Wang et al. (2021)



Ma et al., in prep.

- CMIP6 models and E3SM PPE show a correlation between cloud feedback and aerosol forcing.

Summary: A holistic view

- **Understand the predictability source**
  - Environmental conditions
    - Turbulence
    - Humidity
  - Cloud and aerosol state and processes
    - Size distribution
    - Composition
    - Subgrid variability
    - Many others
  - Connection between cloud-aerosol interactions and cloud feedbacks

- **Address the predictability source**
  - Increase model resolution to better resolve features relevant for cloud-aerosol interactions
    - Scale-adaptive parameterizations
  - Integrate high-resolution-high-fidelity data and models into ESMs using AI/ML

- **Evaluate, analyze, and constrain model predictions**
  - Process-oriented diagnostics
  - Instrument simulator
  - Scale consistency
  - System response and feedback