Assessing cloud-aerosol interactions as a source of climate predictability

Po-Lun Ma

Atmospheric Sciences and Global Change
Pacific Northwest National Laboratory

March 14, 2022
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

- 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?

Kiehl (2007)

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

Forster et al (2013)

- All CMIP5 mean: 1.7, 90%: 0.9
- Selected CMIP5 mean: 1.3, 90%: 0.6

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)


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

- 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.

Ma et al. (2015)

- 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.

Terai et al. (2020)

How do we better integrate high-resolution-high-fidelity data/model into ESMs?
Improve the representations of aerosols and cloud-aerosol interactions in E3SM

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

Aerosol-radiation-cloud-precipitation interactions

Modern software for exascale computation

Sea spray aerosols
Mineral dust
Wildfire aerosols
Biogenic SOA
Anthropogenic carbonaceous & sulfate aerosols

Composition, hygroscopicity

Radiative effects

Cloud albedo effects

Precipitation effects and cloud lifetime effects

High resolution
Inform long-term large-scale environment

Aerosol plume
Inform short-term small-scale features

Low resolution

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

Combine expertise in climate science, data science, software engineering

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

Measurements of aerosols, clouds, precipitation, and meteorology

AI-assisted analytics to improve understanding and design parameterizations

Big training data: O(100TB)

Data-driven & physically informed ML emulator

Software infrastructure incorporating AI/ML in Earth system models

Next step: • 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

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

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

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?

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

Wang et al. (2021)

Ma et al., in prep.
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