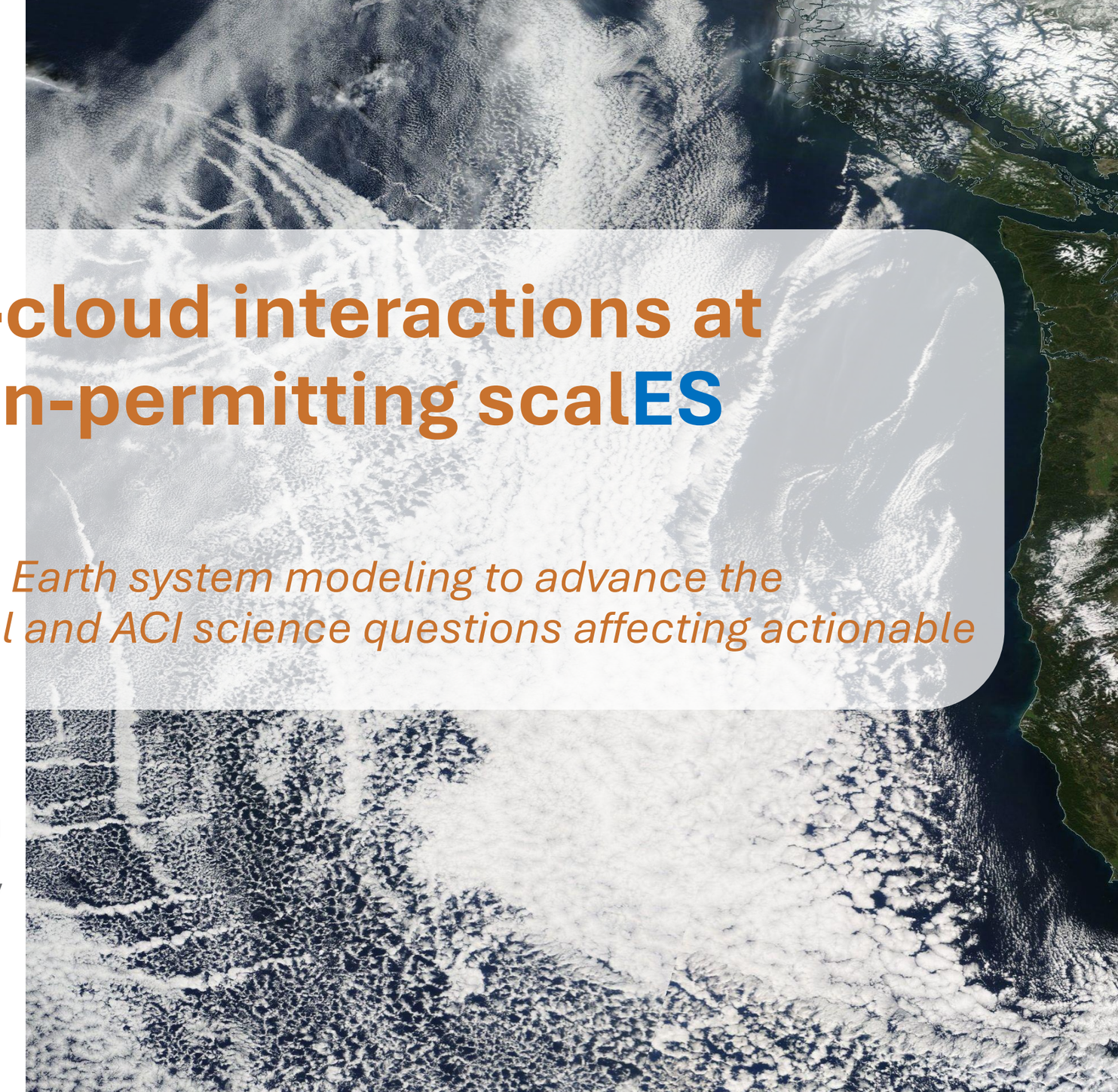
EAGLES

Enabling Aerosol-cloud Interactions at GLobal convection-permitting scalES



Enabling Aerosol-cloud interactions at GLobal convection-permitting scalES (EAGLES)

Transforming aerosol and ACI in Earth system modeling to advance the understanding of critical aerosol and ACI science questions affecting actionable predictions

Po-Lun Ma

Pacific Northwest National Laboratory

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

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Enabling Aerosol-cloud Interactions at GLobal convection-permitting scalES

Transforming aerosol and ACI in Earth system modeling

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

TEXAS A&M UNIVERSITY

THE UNIVERSITY OF ARIZONA

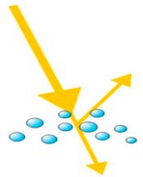
UCIRVINE

UNIVERSITY of WASHINGTON

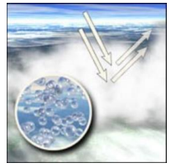
UWM UNIVERSITY of WISCONSIN MILWAUKEE

Theme 1: Aerosol

Theme 2: ARI and ACI

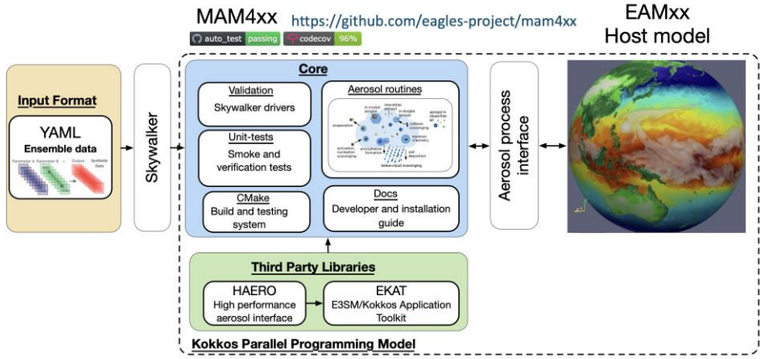


Aerosol-radiation interactions



Aerosol-cloud-precipitation-turbulence interactions

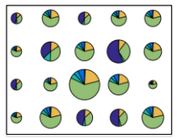
Theme 3: Computation



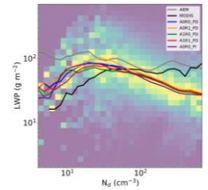
Modern software enables global km-scale simulations with advanced aerosol and ACI

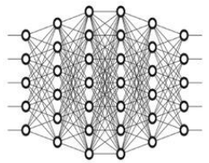
Theme 4: Testbeds

Measurements



Process model & large eddy simulations





Process-oriented diagnostics & Data informed parameterization

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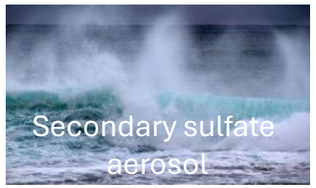
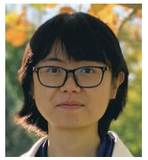
T1 Aerosol: Improving aerosol lifecycle and properties



- Lu et al (2023): New wildfire aerosol parameterization improves aerosol vertical distribution
- Hassan et al (2023): High-resolution anthropogenic emission improves simulation fidelity
- Yao et al (2024): New giant aerosol parameterization improves significantly improves ACI and aerosol impacts on precipitation.
- Zhao et al (2024): New particle formation mechanisms from carbonaceous aerosol that account for more than half of CCN
- Kang et al, TBS: New DMS chemistry improves aerosol and ACI over Southern Ocean.
- Shi et al, in review: New anthropogenic dust parameterization improves global aerosol simulation
- Wu, Zaveri, et al, in prep: Aged carbon improves aerosol aging and mixing
- Zaveri, Wu, et al, in prep: Dynamic partitioning enhances small particle growth







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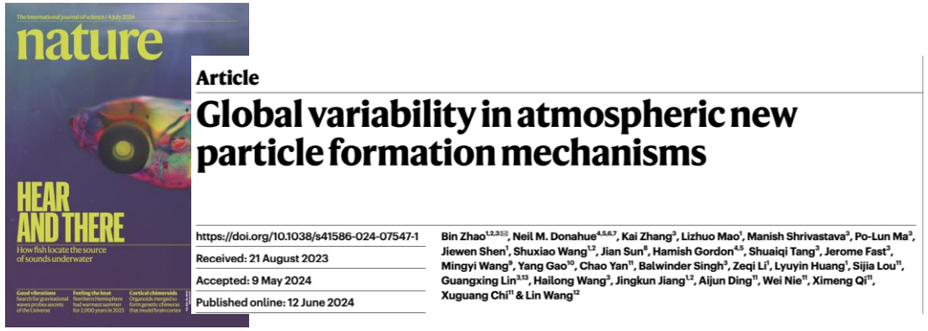
Highlight: Secondary natural aerosol plays a critical role



Article

Global variability in atmospheric new particle formation mechanisms

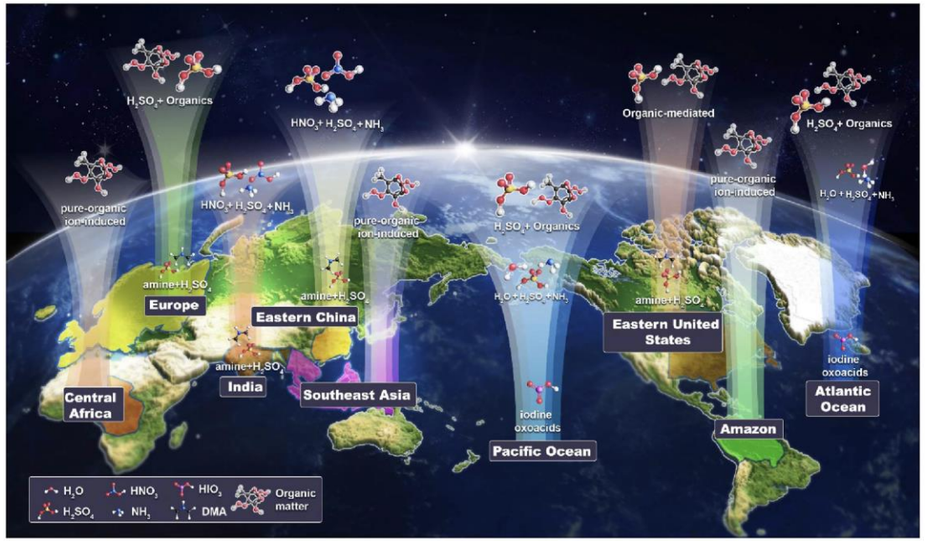
https://doi.org/10.1038/s41586-024-07547-1

Received: 21 August 2023

Accepted: 9 May 2024

Published online: 12 June 2024

Bin Zhao[1,2,3✉], Neil M. Donahue[4,5,6,7], Kai Zhang[3], Lizhuo Mao[1], Manish Shrivastava[3], Po-Lun Ma[3], Jiewen Shen[1], Shuxiao Wang[1,2], Jian Sun[8], Hamish Gordon[4,5], Shuaiqi Tang[3], Jerome Fast[3], Mingyi Wang[9], Yang Gao[10], Chao Yan[11], Balwinder Singh[3], Zeqi Li[1], Lyuyin Huang[1], Sijia Lou[11], Guangxing Lin[3,13], Hailong Wang[3], Jingkun Jiang[1,2], Aijun Ding[11], Wei Nie[11], Ximeng Qi[11], Xuguang Chi[11] & Lin Wang[12]

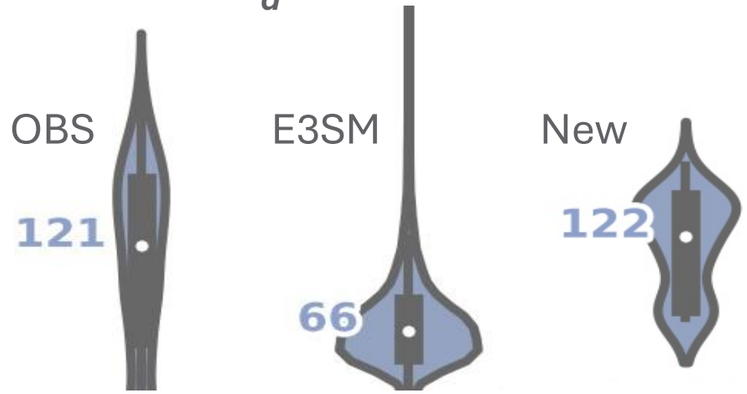


Zhao et al (2024)

Model biases Thu-161

Jerome Fast

PDF of N_d in Southern Ocean



Kang et al, to be submitted

- The new model incorporates various **new DMS and SOA chemical mechanisms** to form secondary sulfate and organic aerosols.
- These new mechanisms play **different roles in different regions**, accounting for **up to 80% of CCN** that are previously neglected, significantly alleviate the stubborn low Nd bias.
- This improves the estimation and source attribution of the **climate effects of aerosols.**

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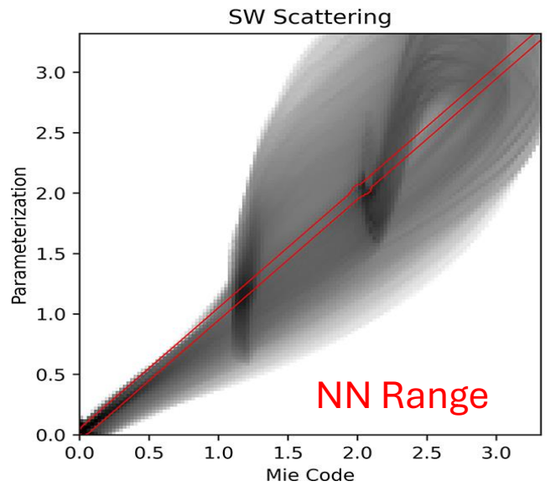
Enabling Aerosol-cloud Interactions at GLobal convection-permitting scalES

T2 Aerosol-cloud and aerosol-radiation interactions

- Geiss et al (2023): ML-based aerosol optics achieve high accuracy at low cost.
- Geiss and Ma (2024): NeuralMie
- Silva et al (2021): ML-based aerosol activation reduces significantly reduces model bias
- Yu et al (2023): 2-stage workflow to develop ML emulator efficiently
- Larson et al: Activation-turbulence coupling

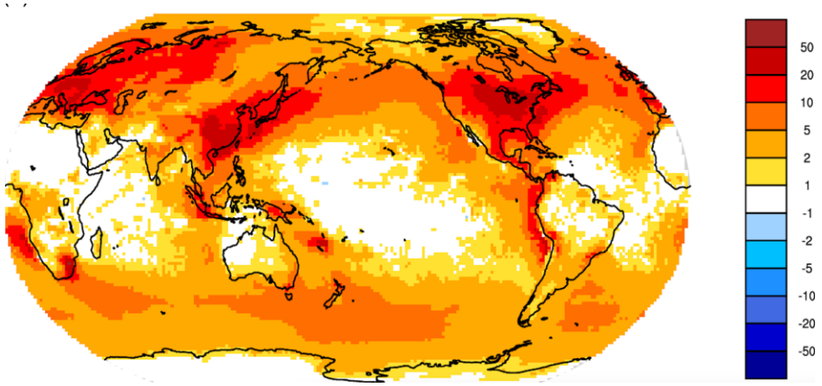






- **1000x** faster and more accurate
- **Core-shell** optics becomes possible

DNN – E3SM Nd difference



- **Online** implementation in E3SM
- ML aerosol activation significantly alleviate **low Nd bias**
- Negligible computational cost

Andrew Gettelman

Model Frameworks
Thu 2:12pm

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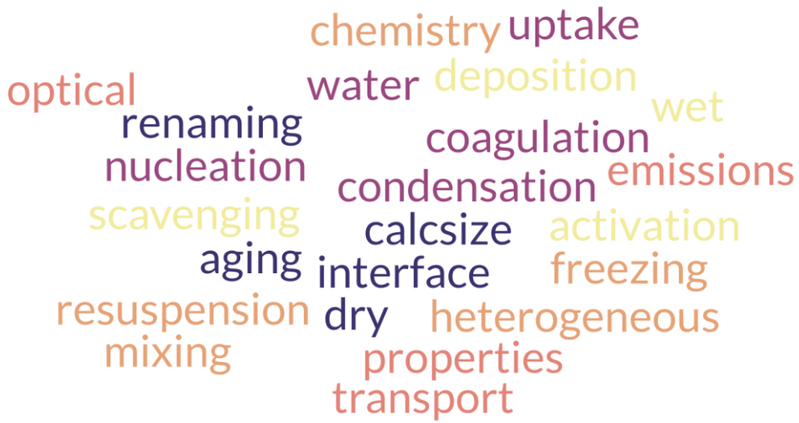
T3 Computation: MAM4xx

MAM4 process modules



Balwinder Singh

Testing

Computational Innovation

Thu-129

Oscar Diaz Ibarra

MAM4xx

Digital Earth

Wed-110

Motto: How can I help?

Testing → Refactor → Testing → Porting to C++ → Testing → MAM4xx hooks

Remove 106,700 lines of code

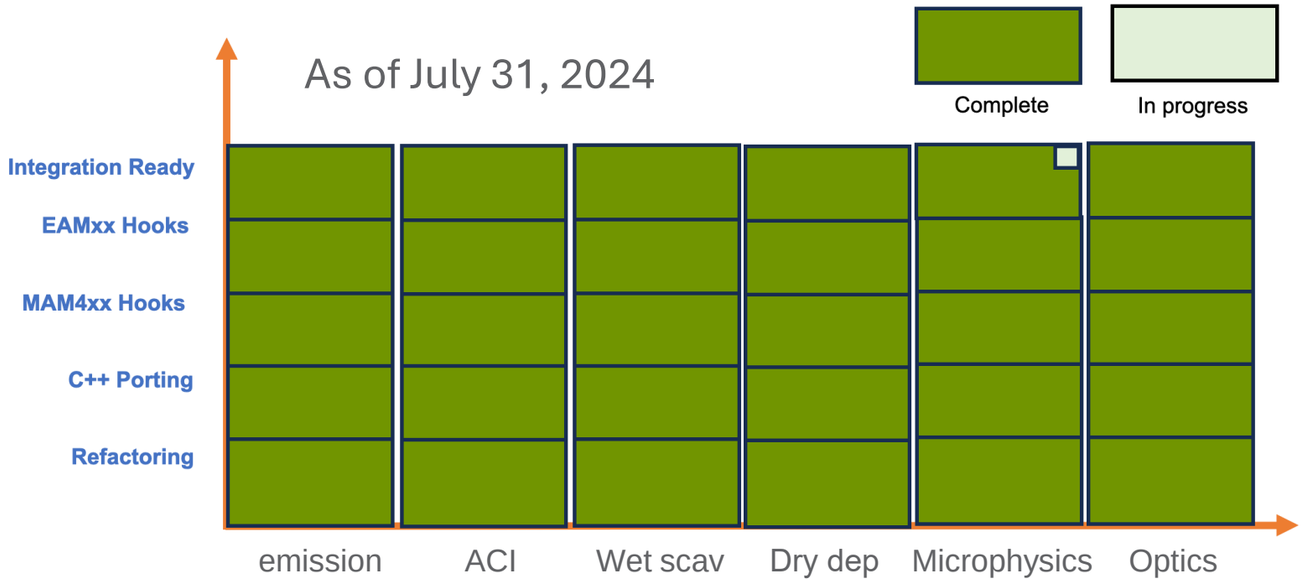
16,000 lines of new code (P3: 8,704; SHOC: 9,741)

Testing → EAMxx hooks → Testing

Testing takes more time than code porting!

7 interfaces, 5,000 lines of new code

(8 interfaces in EAMxx for P3, SPA, SHOC, COSP, nudging, Cloudfrac, RRTMGP, TMS)



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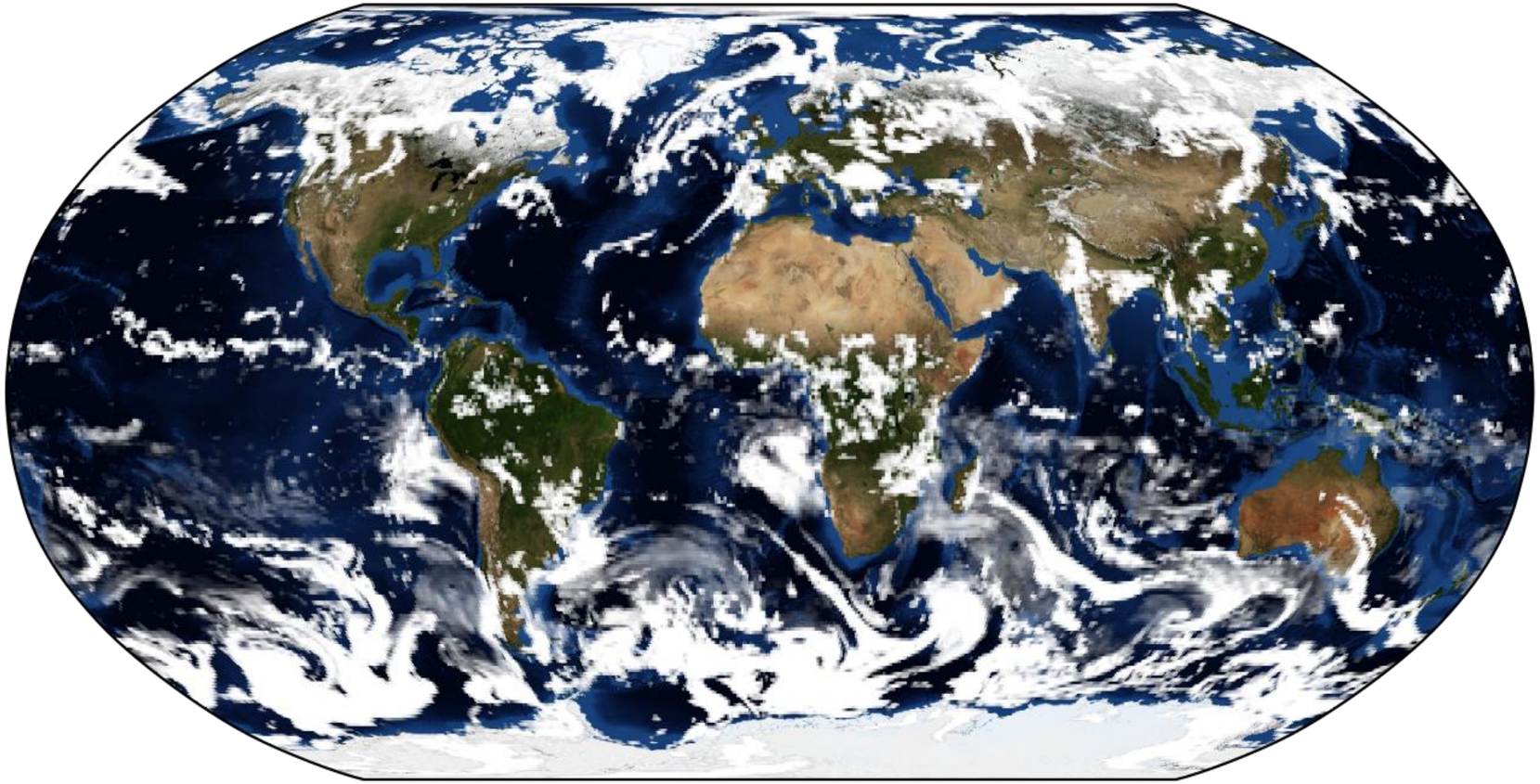
T3 Computation: Global km-scale simulations

EAMxx

Running at ne1024pg2 resolution on Frontier GPUs

Cloud



Before *MAM4xx porting*

EAGLES

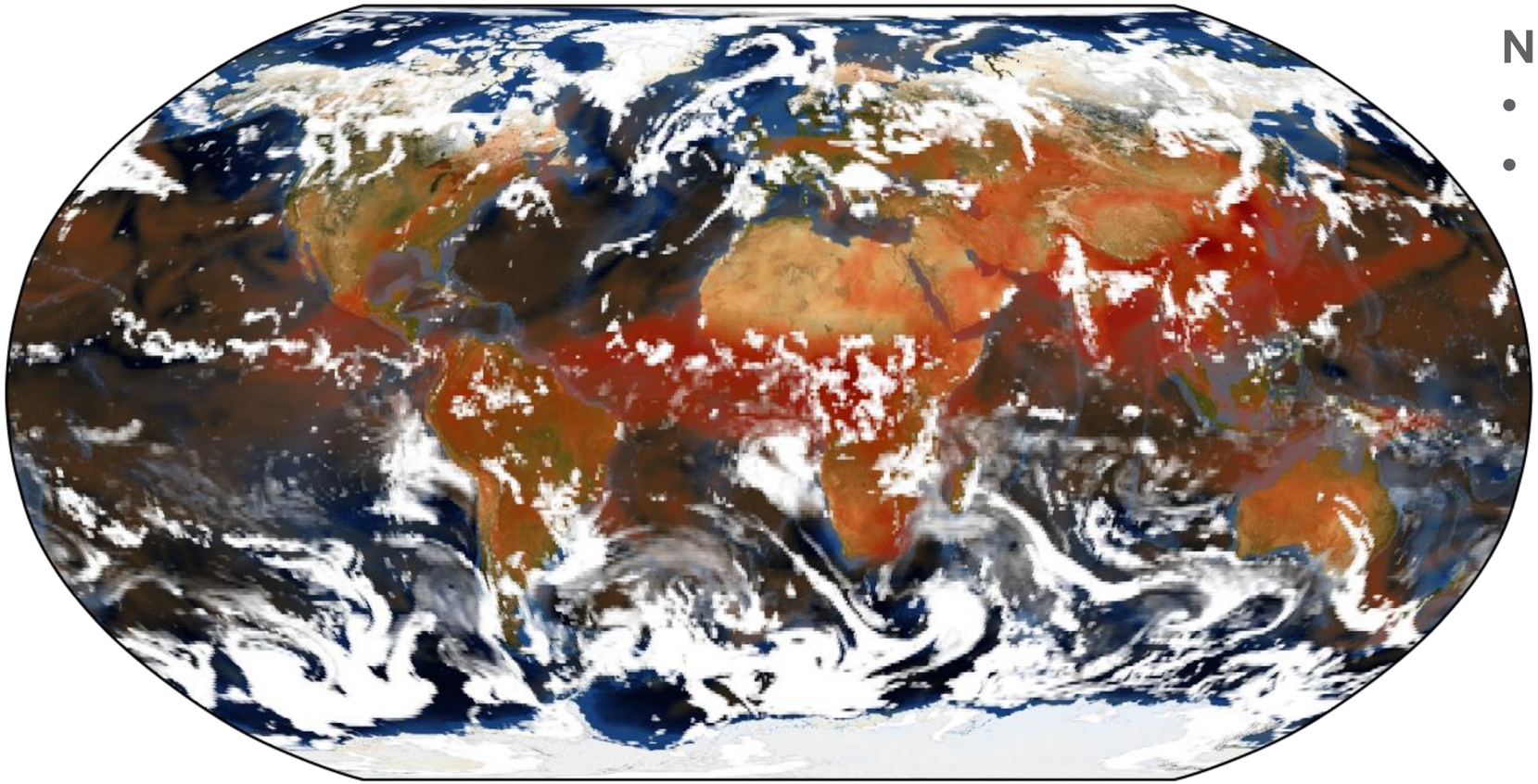
Enabling Aerosol-cloud Interactions at GLobal convection-permitting scalES

T3 Computation: Global km-scale simulations

EAMxx-MAM4xx

Running at ne1024pg2 resolution on Frontier GPUs

Cloud
Aerosol



Next steps:

- Scientific evaluation
- Simulation campaigns

After *MAM4xx porting*

Fast et al, in prep

First global km-scale model with ***advanced interactive aerosol!***

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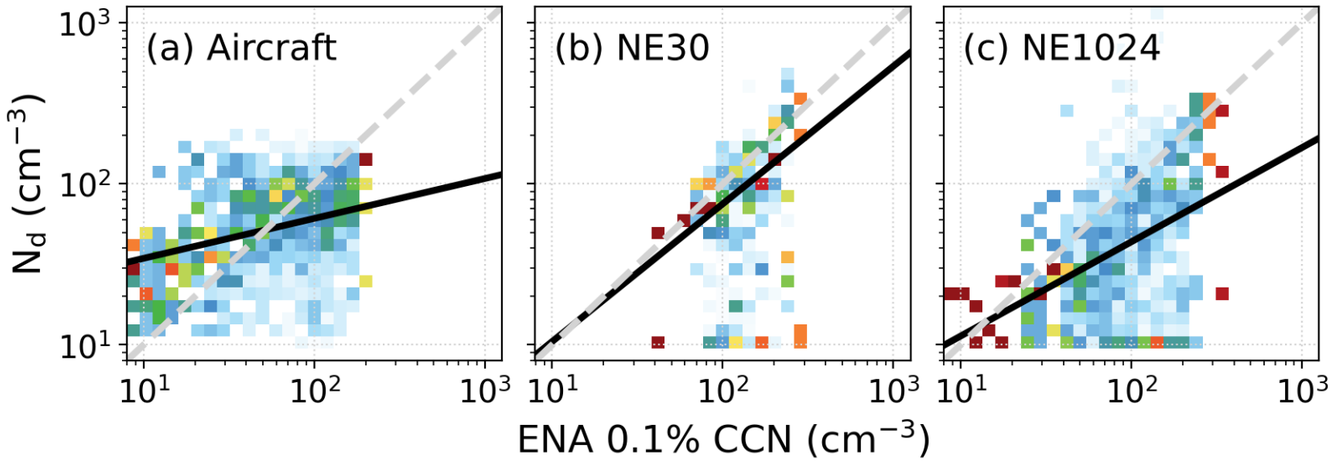
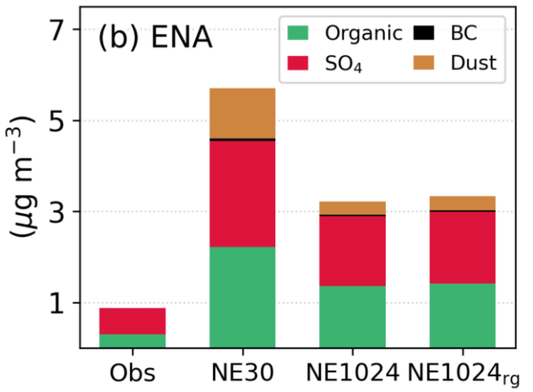
T4 Testbeds: Understand km-scale aerosol and ACI using RRMs

Cloud Aerosol

$\triangle x = 100\ km$ $\triangle x = 3\ km$

- Kilometer-scale simulations look much more realistic
- Nd-CCN relationship in km-scale is in better agreement with observations
- Many aerosol biases are insensitive to resolution.





Meng Huang

Testbeds
Thu-150

Huang et al, to be submitted

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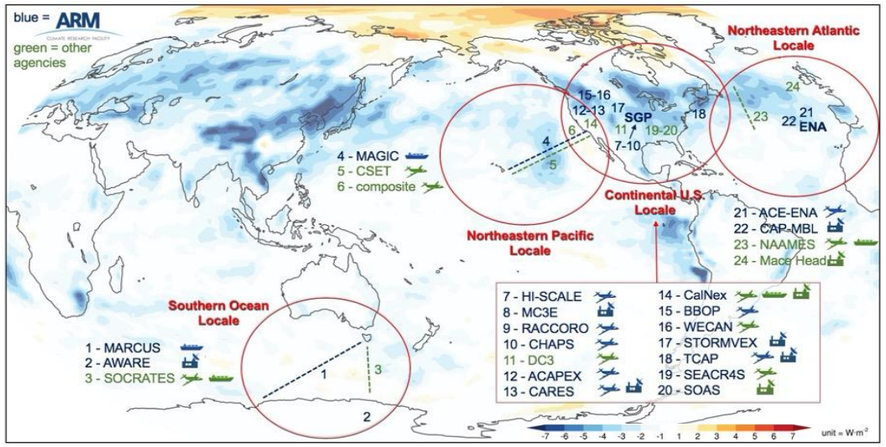
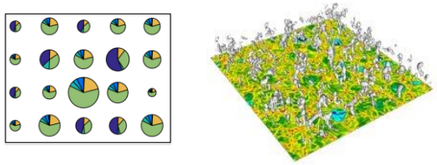
T4 Testbeds: Diagnostics tools for aerosol and ACI



Measurements

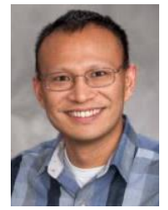
LES & process model



Metrics
Thu 3:15pm

Matt Christensen

- Tang et al (2022, 2023): ESMAC diagnostics package: Open-source Python package for aerosol, cloud, ACI
- Varble et al (2023): Assessing albedo susceptibility using ARM and satellite measurements
- Beall et al (2023): Constraining warm rain processes
- Fierce et al (2023): Quantify structural error of aerosol size distribution
- Christensen et al (2022): Assessing aerosol ERF using a Lagrangian framework
- Kaul et al: LES library for ACI
- Ovchinnikov (2024): Constraints for warm rain process
- Mülmenstädt et al (2024): Constraining the cloud lifetime effects
- Qin et al: Aerosol ERF decomposition







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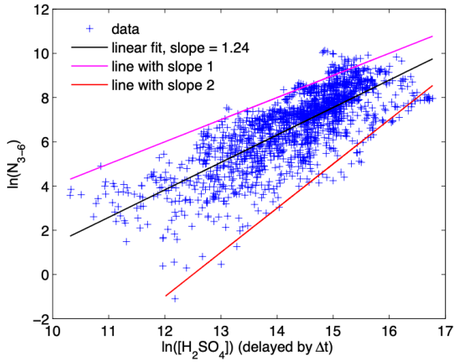
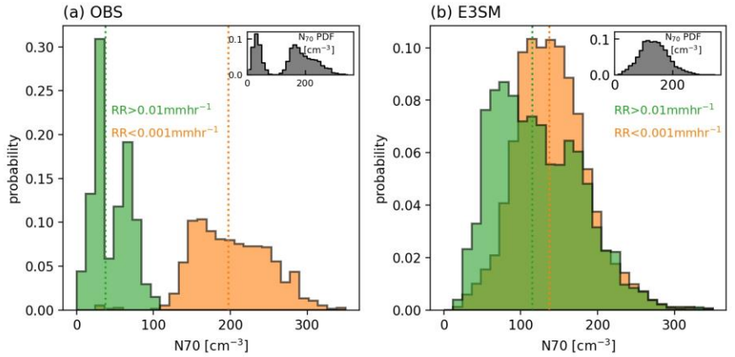
Looking forward: Challenges and opportunities

- **Answer climate-relevant aerosol and ACI science questions using global km-scale simulations**
  - Understand and represent complex **adjustments and feedbacks**
  - **Software improvements** for performance, extensibility, trustworthiness

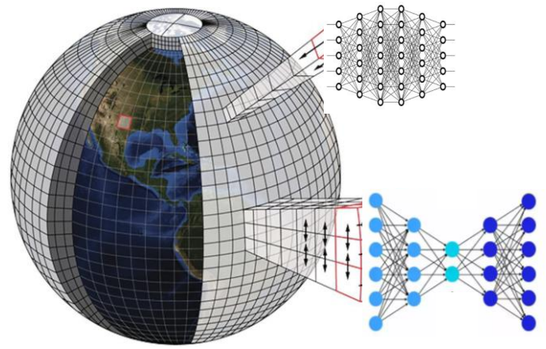
- **Better physics**
  - Chemical mechanisms for **secondary aerosols**
  - **Ultrafine** particles
  - Aerosol interactions with **ice and mixed-phase** clouds
  - **Subgrid variability** affecting aerosol and ACI
  - **Wet scavenging** of aerosol



Parameterization based on Sihto et al (2006)



Parameterization based on Dana and Hales (1974)



- **Incorporate AI/ML for better and faster simulations**
  - Surrogate for **complex physics** to achieve unprecedented accuracy
  - Surrogate for **numerical solvers** to achieve accurate solutions at low cost
  - Surrogate for **stochasticity and subgrid unresolved features** to bridge scales

Addressing significant challenges *together!*

E3SM
Energy Exascale Earth System Model

LES

PCMDI
Earth System Model Evaluation Project

ACI and cloud feedback

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University

Cloud, ACI, diagnostics

Integrated Cloud, Land-Surface,& Aerosol System Study
ICLASS

E3SM RRM for aerosol, cloud, precipitation during ARM field campaigns

THREAD
LLNL ASR SFA

E3SM RRM for ACI and turbulence

ARM

LASSO LES, measurements

NCAR

Cloud microphysics

Model Biases
Thu-154

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A fantastic team that makes this happen

- **Aerosol microphysics, emission, optics**: Kai Zhang, Rahul Zaveri, Yu Yao, Taufiq Hassan, Laura Fierce, Andrew Geiss, Hailong Wang (PNNL), Xiaohong Liu, Zheng Lu, Yang Shi (TAMU), Bin Zhao (TU), Guangxing Lin (IAP)
- **Aerosol-cloud interactions**: Jiwen Fan, Colleen Kaul, Mikhail Ovchinnikov, Yunpeng Shan, Jacob Shpund (PNNL), Mike Pritchard, Sungduk Yu (UCI), Vince Larson (UWM), Sam Silva (USC)
- **Diagnostics and Testbeds**: Shuaiqi Tang, Matt Christensen, Adam Varble, Jianfeng Li, Meng Huang, Charlotte Beall, Yi Qin, Johannes Mülmenstädt (PNNL), Roj Machand, Litai Kang (UW), Xiquan Dong (UA)
- **MAM4xx development**: Jerome Fast, Balwinder Singh, Kyle Pressel, Mingxuan Wu, Shuaiqi Tang, Brian Gaudet, Hui Wan, Jaelyn Litzinger, Cameron Rutherford (PNNL), Oscar Diaz Ibarra, James Overfelt, Michael Schmidt, Pete Bosler (SNL), Jeff Johnson (Cohere LLC)



EAGLES all-hands meeting, November 1-3, 2023