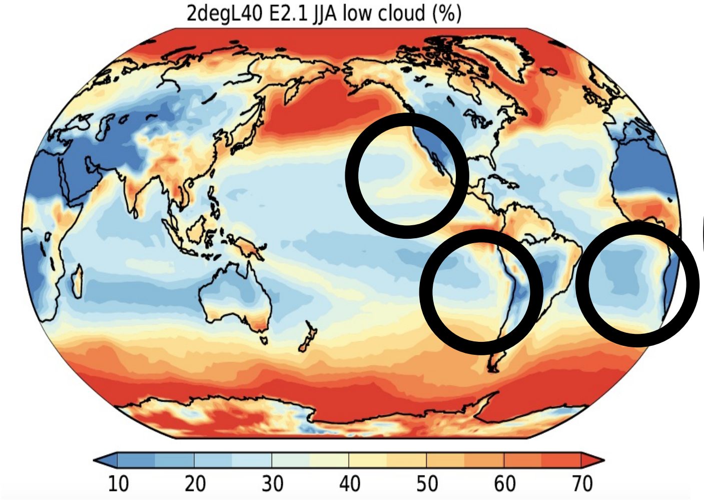
NASA GISS ESM Development from a Cloud Physics Perspective: Strategies and Recent Results

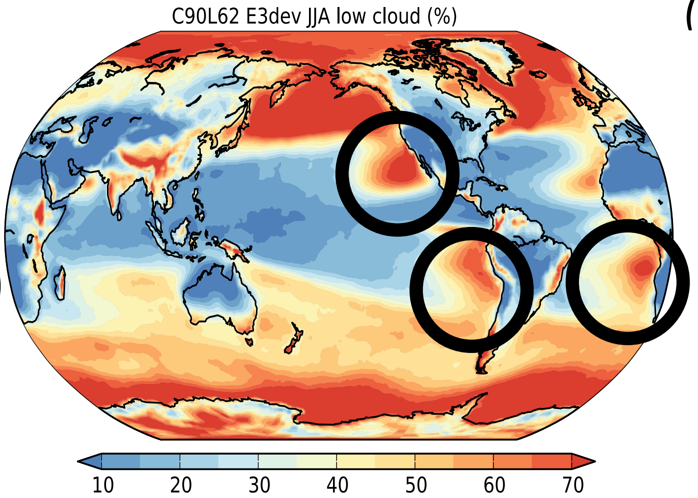
- **LES modeler:** *We don't even understand how most atmospheric ice crystals are formed!*
- **Climate modeler:** *We need to deliver a climate model now...*

— Ann Fridlind, NASA GISS (opinions my own)

GISS ModelE2.1



GISS ModelE3-devel



subtropical Sc decks

source: Andrew Ackerman / GISS

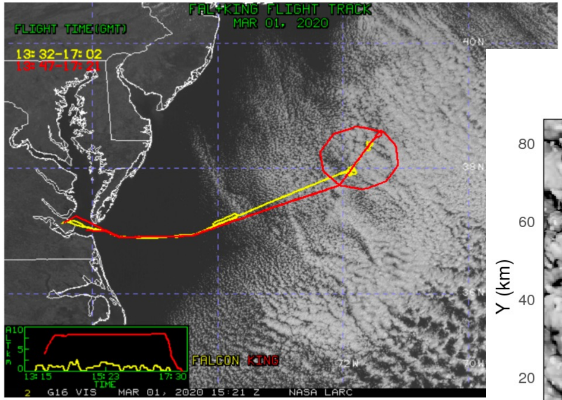
Background: Clouds in Earth system models (ESMs)

- across ESMs, differences in cloud-related physics contribute substantially to large differences in simulated climate change
  - during ESM development, cloud physics parameters are commonly slightly tuned to bring simulations into line with targets such as preindustrial TOA radiative balance (e.g., Schmidt et al. GMD 2017)
  - as Earth warms in a 2X CO_2 experiment, ESMs predict differing cloud changes, which feed back on warming (cloud-climate feedbacks)
  - e.g., CMIP6 ESM-predicted range of 1.8–5.6 K surface warming was found to be inconsistent with other estimates of 1.5–4.5 K, "tied to the physical representation of clouds" (Zelinka et al. GRL 2020)
  - clouds participate in a complex coupled Earth system environment

ModelE3 development approach

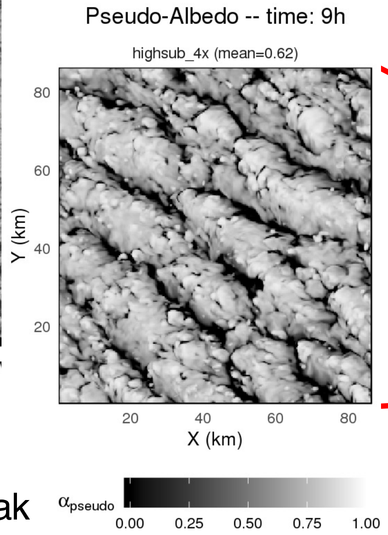
Global data → ESM tuning

Field campaigns → LES → SCM

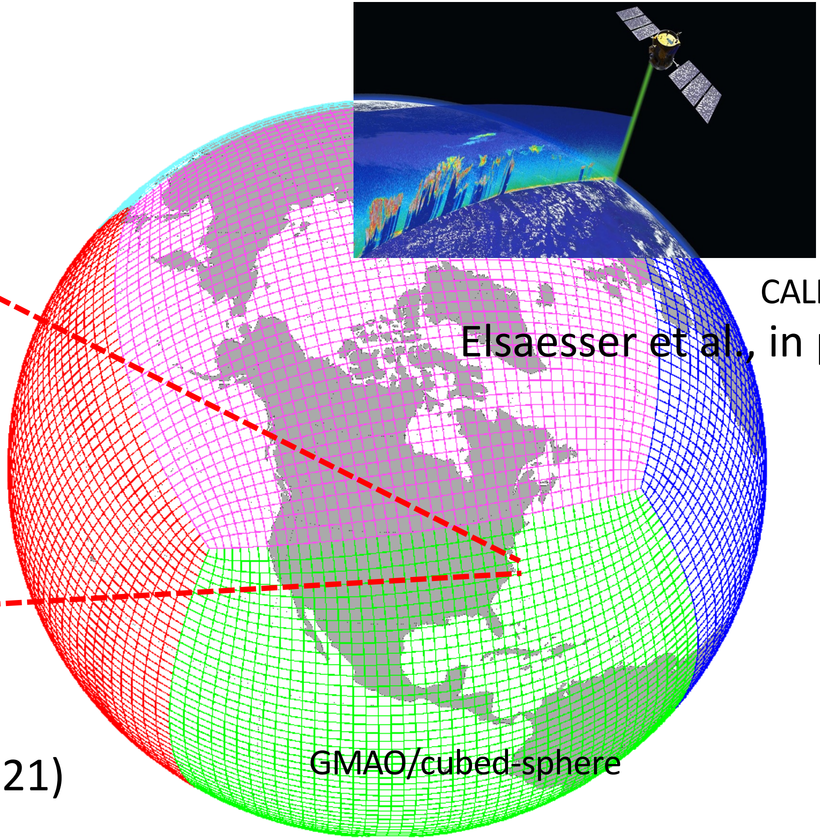


From https://satcorps.larc.nasa.gov

ACTIVATE Flight RF13
1 March 2020
mixed-phase cold-air outbreak



Tornow et al. (ACP 2021)



CALIPSO

Elsaesser et al., in prep.

GMAO/cubed-sphere

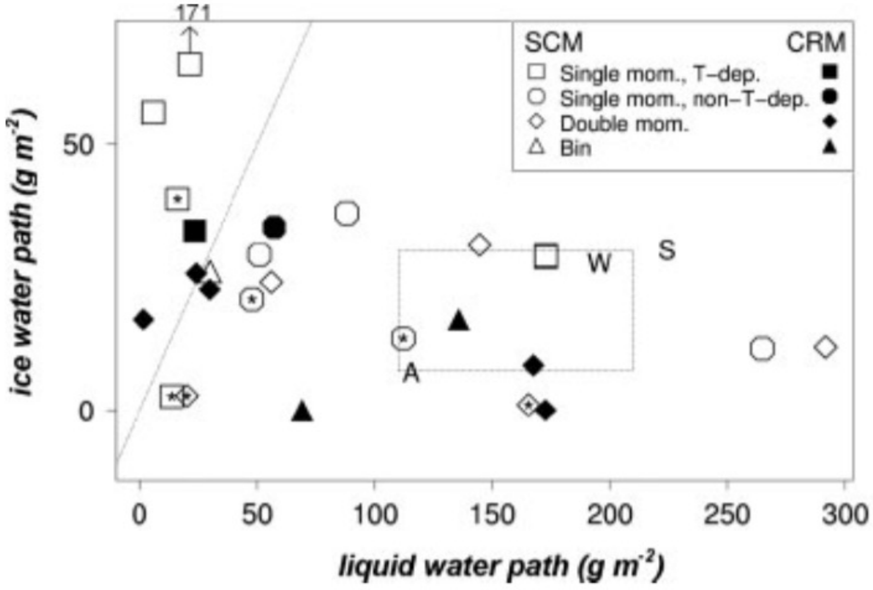
Field campaigns —> LES —> Single-column model (SCM)

Conditions	Case study	Aerosol aware?
dry convective boundary layer	idealized [Bretherton and Park 2009]	—
dry stable boundary layer	GABLS1 [Cuxart et al. 2006]	—
marine stratocumulus	DYCOMS-II RF02 [Ackerman et al. 2009]	observed (2 modes)
marine trade cumulus (shallow)	BOMEX [Siebesma et al. 2003]	no
marine trade cumulus (deep, raining)	RICO [van Zanten et al. 2011]	no
marine stratocumulus-to-cumulus *	SCT [Sandu and Stevens 2011]	no
continental cumulus ^	RACORO [Vogelmann et al. 2015]	observed profile (3 modes)
Arctic mixed-phase stratus	M-PACE [Klein et al. 2009]	observed (2 modes)
Antarctic mixed-phase stratus *	AWARE [Silber et al. 2019, 2021, 2022]	estimated (1 mode)
tropical deep convection	TWP-ICE [Fridlind et al. 2012]	observed profile (3 modes)
mid-latitude synoptic cirrus *	SPARTICUS [cf. Mühlbauer et al. 2014]	no
mid-latitude cold-air outbreak *^	ACTIVATE [Tornow et al., 2021, 2022, in prep.]	observed profile (3 modes)
high-latitude cold-air outbreak *^	COMBLE [Tornow et al., in prep.]	observed/estimated profiles (3 modes w/INP)
marine cumulus and congestus *^	CAMP2Ex [Stanford et al., in prep.]	observed profiles (3 modes)
subtropical marine deep convection *^	SEAC4RS [Stanford et al., in prep.]	observed profiles (TBD)
continental sea breeze convection *^	TRACER [Matsui et al., in prep.]	observed profiles (TBD)

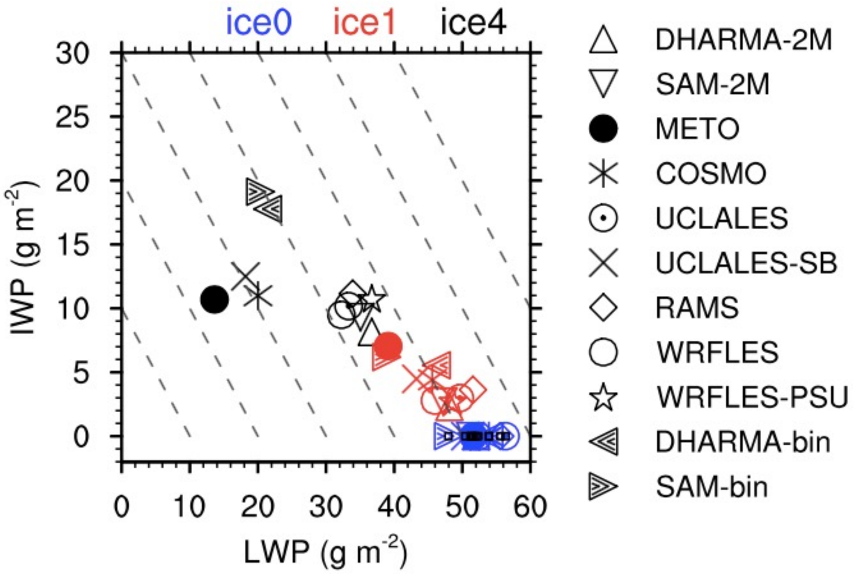
*Lagrangian (cf. Neggers JAMES 2015, Pithan et al. NatGeo 2019)

^ensemble (cf. Neggers et al. JAMES 2019)

M-PACE to ISDAC progress



Klein et al. (2009)



Ovchinnikov et al. (2009)

see also Fridlind and Ackerman (2018)

Background: Ice formation in supercooled clouds

- esp. large uncertainties remain in supercooled cloud physics
  - ice spontaneously melts at 0°C but does not spontaneously form until near –38°C owing to energetic barriers to forming a more organized state
  - within that temperature range, supercooled liquid appears to be a gateway to persistent weak ice formation, attributable to ice-nucleating particle activation (Silber et al. 2020 based on NSA and AWARE data)
  - however, ice crystals are commonly orders of magnitude more abundant than can be explained by that weak pathway, especially in clouds with riming and/or large drops (Rangno and Hobbs, 2002; Korolev et al., 2021)
  - exactly how much more abundant is often unknown owing to lack of reliable measurements (Korolev et al. 2021; Morrison et al. 2020)

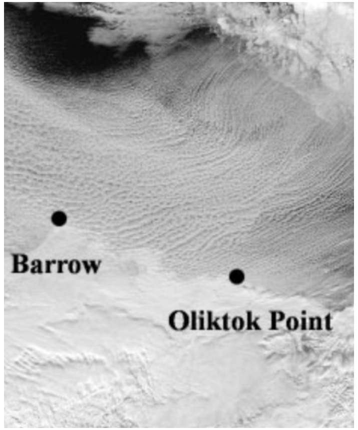
Ice formation approach in ModelE3

- Only physically-based mechanisms and parameterizations
- Avoid unnecessary complexity
- Each mechanism should be demonstrably active in observed case studies
- Heterogeneous freezing mechanisms should be linkable to aerosol properties
- But start with diagnostic INP
  - DeMott et al. 2010 * f_{scale_iifn}
  - $f_{scale\_iifn} < 1$ can crudely account for efficient precipitation scavenging (Fridlind et al. JAS 2012)

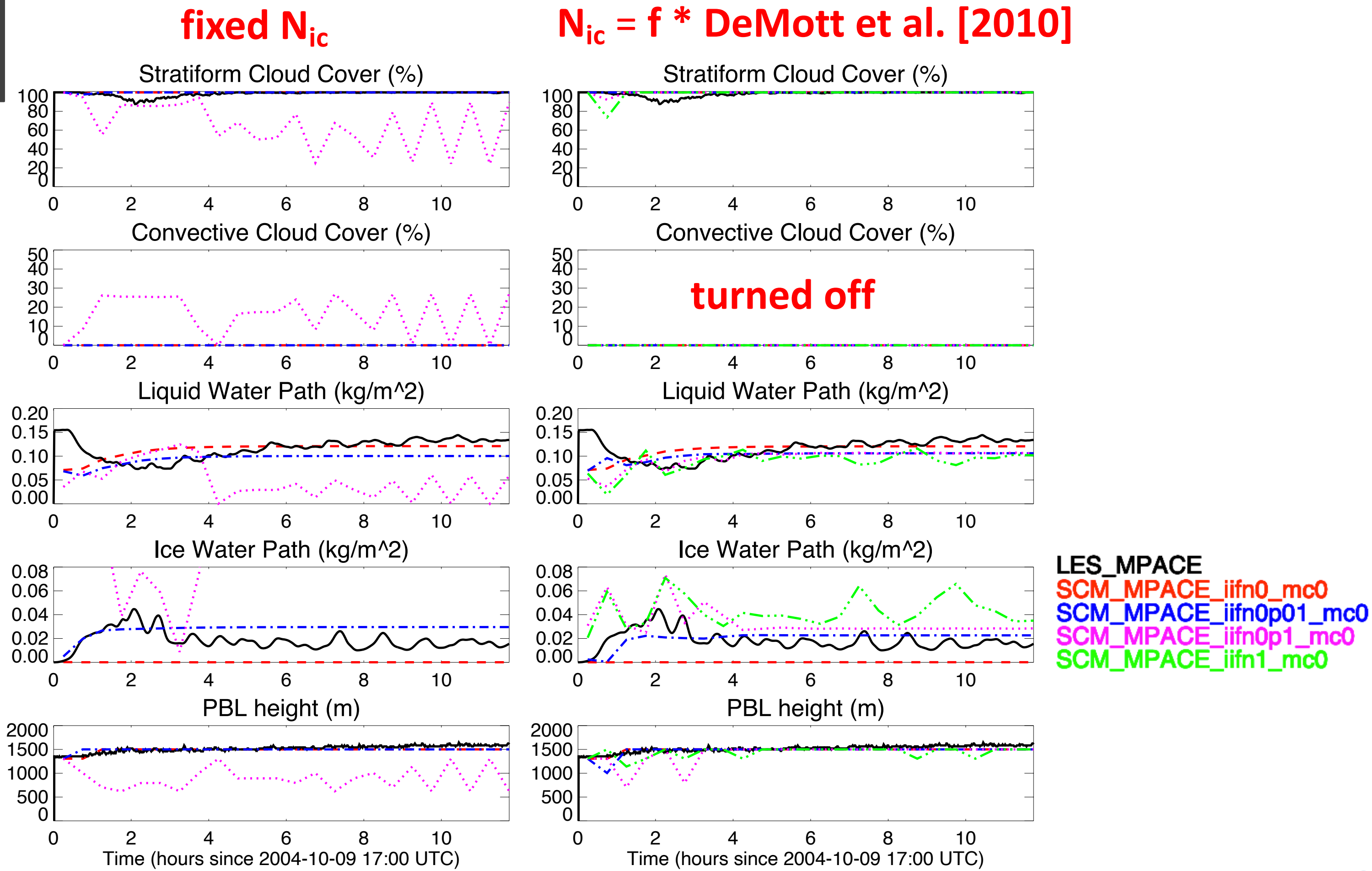
Mechanism	Include?	Comments
Primary		
homogeneous freezing	Y	aerosol, cloud droplets, rain
immersion freezing	Y	aerosol, cloud droplets
deposition freezing	Y	aerosol
contact freezing	N	lab/field support currently lacking
Secondary		
rime-splintering	Y	lab/field support poorly constrained
drop fragmentation*	N	lab/field support currently lacking
ice-ice collisions*	N	lab/field support currently lacking
Other common elements		
Bigg [PPSB 1953]	N	no link to aerosol properties
Bergeron enhancement	N	ice vapor growth already included

* additive to Gettelman and Morrison (2015)

M-PACE



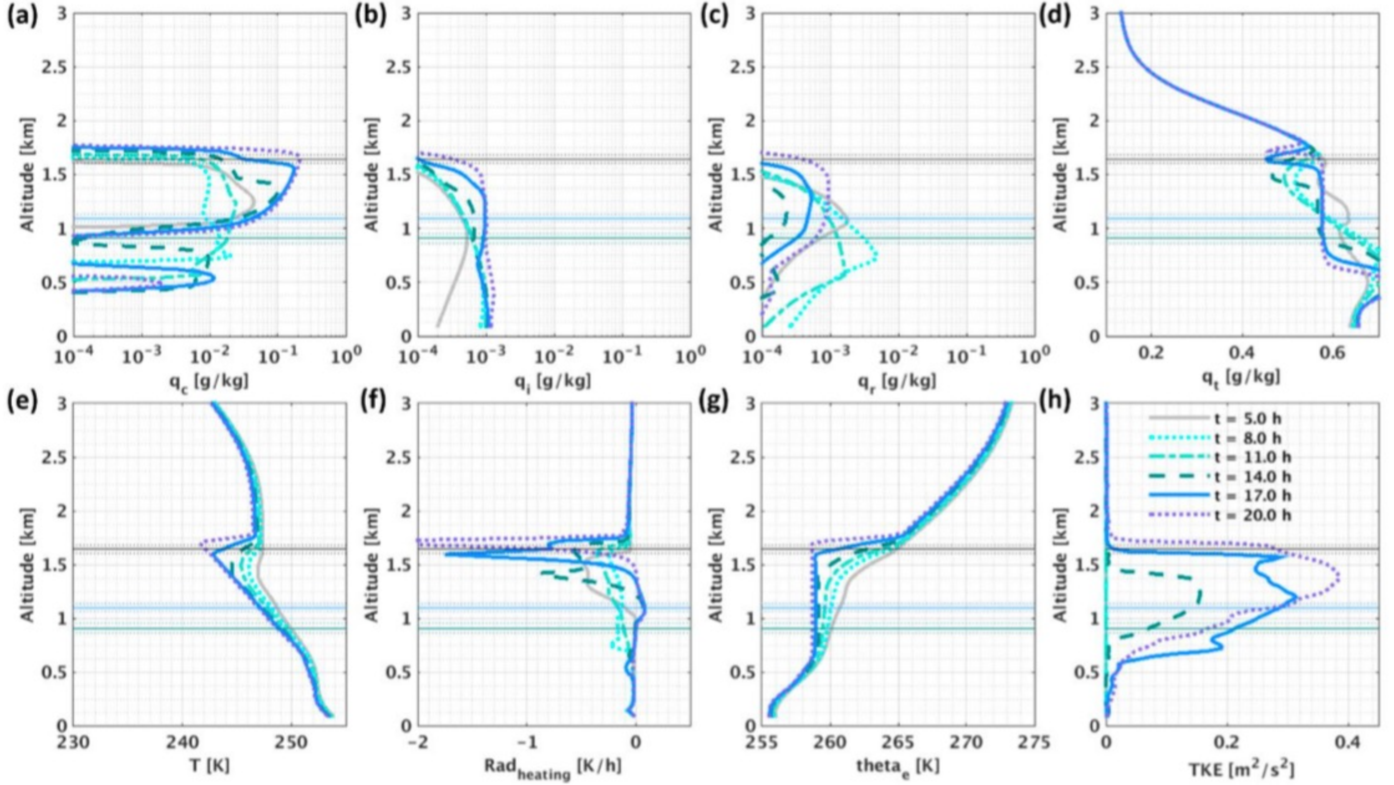
Barrow
Oliktok Point



fixed N_{ic}
N_{ic} = f * DeMott et al. [2010]
Stratiform Cloud Cover (%)
Convective Cloud Cover (%)
turned off
Liquid Water Path (kg/m^2)
Ice Water Path (kg/m^2)
PBL height (m)
Time (hours since 2004-10-09 17:00 UTC)
LES_MPACE
SCM_MPACE_Ni0p1
SCM_MPACE_Ni1
SCM_MPACE_Ni10
LES_MPACE
SCM_MPACE_iifn0_mc0
SCM_MPACE_iifn0p01_mc0
SCM_MPACE_iifn0p1_mc0
SCM_MPACE_iifn1_mc0

Highly supercooled drizzle over Antarctica

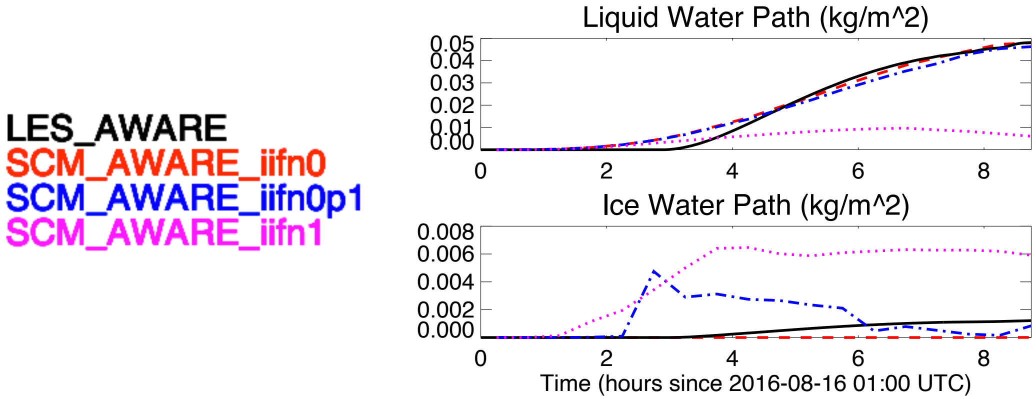
- CTT ≈ –25°C
- initially stable atmosphere
- large-scale ascent —> thin supercooled cloud layer
- LW cooling —> thickening turbulent layer
- $N_c \approx 20/cm3$, $N_i \approx 0.1/L$



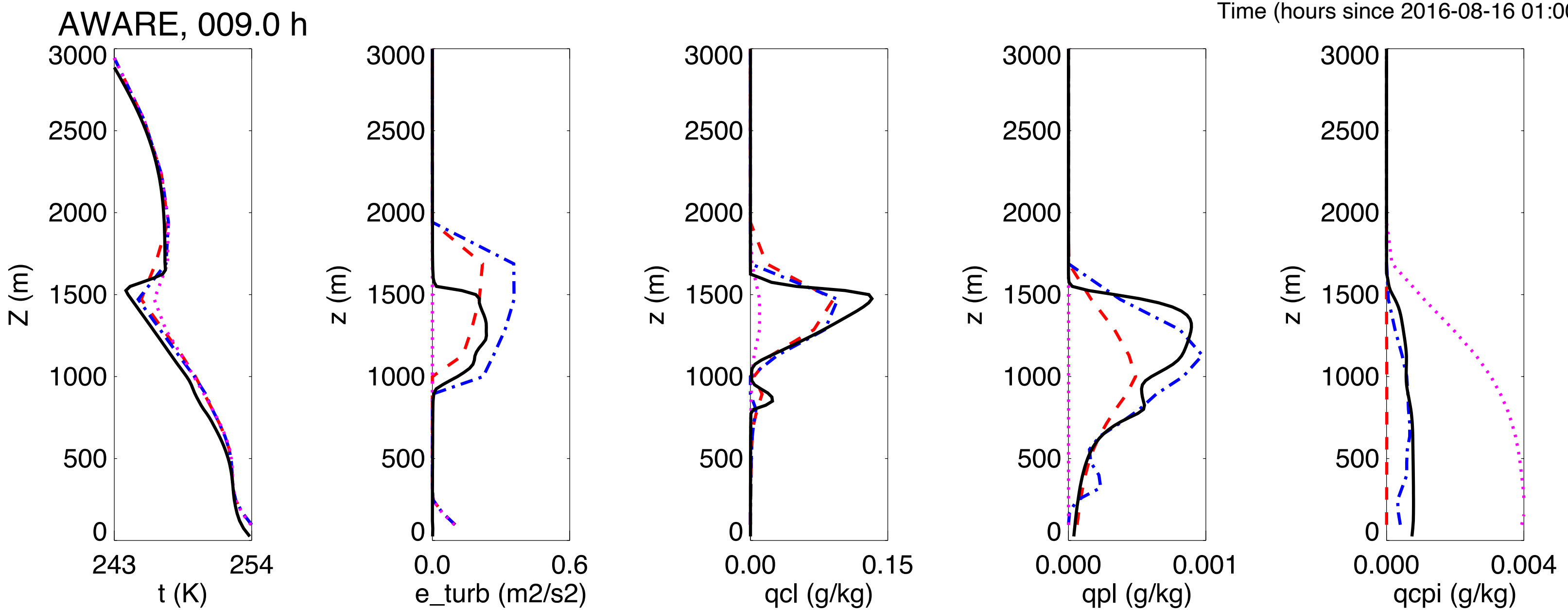
AWARE campaign case study (Silber et al. JGR 2019)

AWARE case study

- SCM performs quite well
- stable conditions common
  (Silber et al. ACP 2020; GRL 2021)

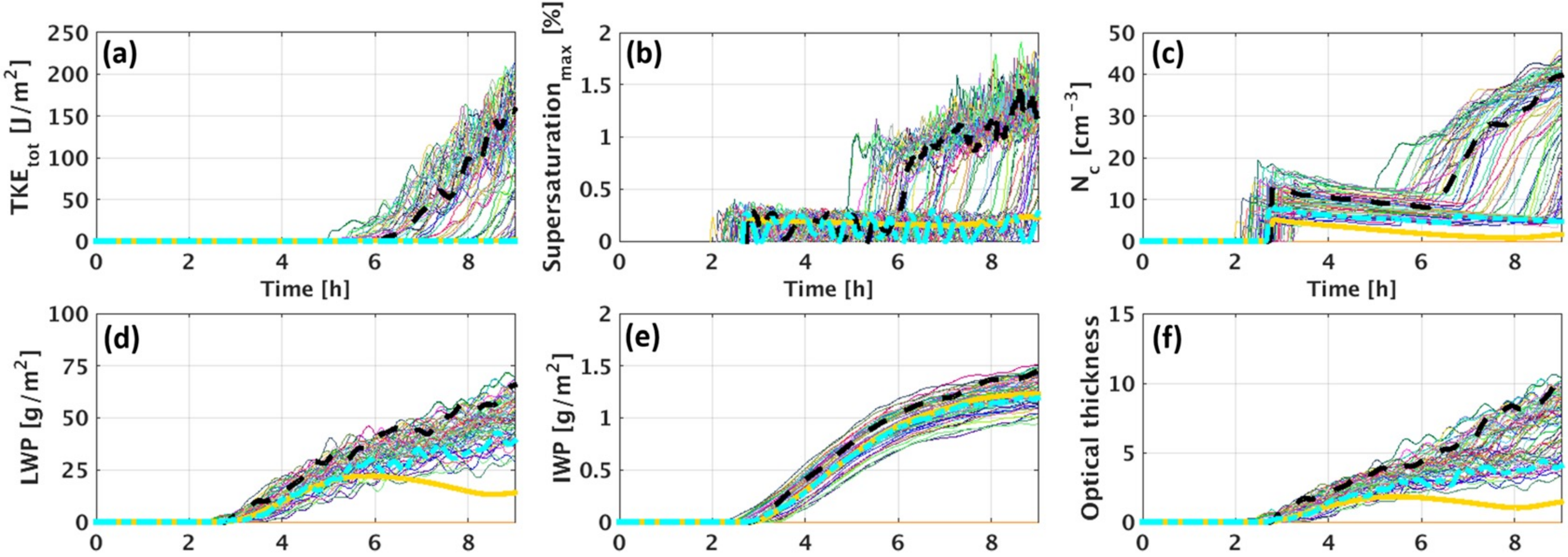


see Silber et al. [GMD 2022]



AWARE case with realistic aerosol—and gravity waves

- stable atmospheres propagate gravity waves
- ascents drive higher N_c, stronger LW cooling, turbulence formation, higher LWP



time (h)

Silber et al. (GRL 2020)

Tuning Protocol

- scale_iifn is one of 45 parameters taken to be poorly constrained
- LES/SCM used to estimate parameter ranges
- new satellite datasets used in tuning
- satellite dataset uncertainties are specified

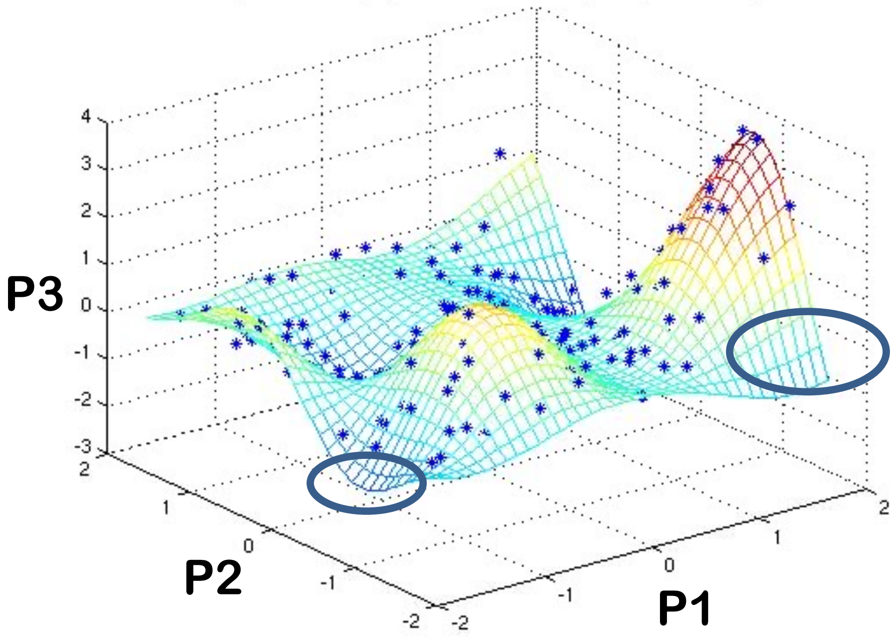
source: Greg Elsaesser

Metrics (36 in total)	Data Source
Radiation (Longwave [LW], Shortwave [SW])	CERES-EBAF-Ed4.1
Cloud Radiative Forcing (LWcrf, SWcrf)	CERES-EBAF-Ed4.1
Column Water Vapor (CWV)	*Obs4MIPS RSS, G-VAP
Specific Humidity profiles (qv)	*Obs4MIPS AIRS, MLS
Temperature profiles (T)	*Obs4MIPS AIRS, MLS, GNSS-RO
Total Liquid Water Path (TLWP)	*MAC-LWP, GPM/TRMM
Total Ice Water Path (TIWP)	*CloudSat, MODIS
Total Precipitation (Pr)	*GPCP, GPM/TRMM
Convective Precipitation (Prc)	GPM/TRMM
Total Cloud Cover (TCC)	CloudSat/CALIPSO, ISCCP
Low (Shallow Cu, StratoCu) Cloud Cover	CloudSat/CALIPSO
Cloudtop Droplet Number Concentration	*MODIS (Bennartz, Grosvenor)
Surface Wind (W)	*WindSat, QuikSCAT
Liquid-to-ice transition Temperature/Height	CALIPSO

ModelE3 emulator based on 450 1-year atmosphere runs

Latin Hypercube sampling in a 45-dimensional parameter state space. Lots of empty state space; emulator (neural network) fills in the gaps.

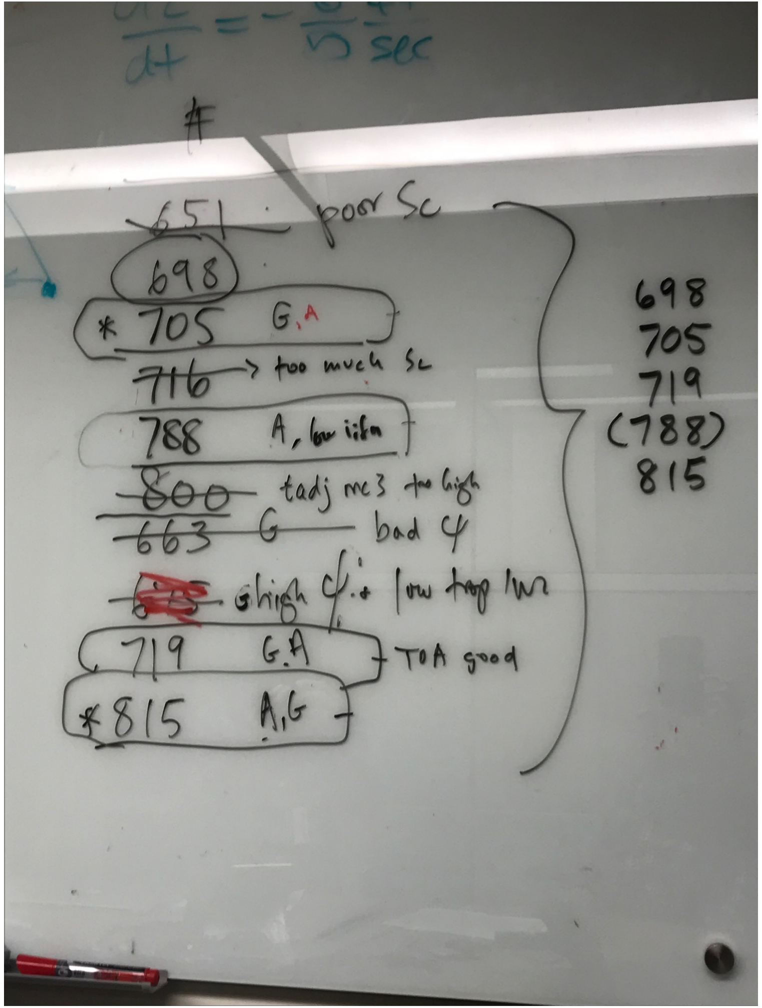
Example Penalty State Space Transect for any given model metric



source: Marcus van Lier-Walqui

After the Machine

- photo of white board at GISS

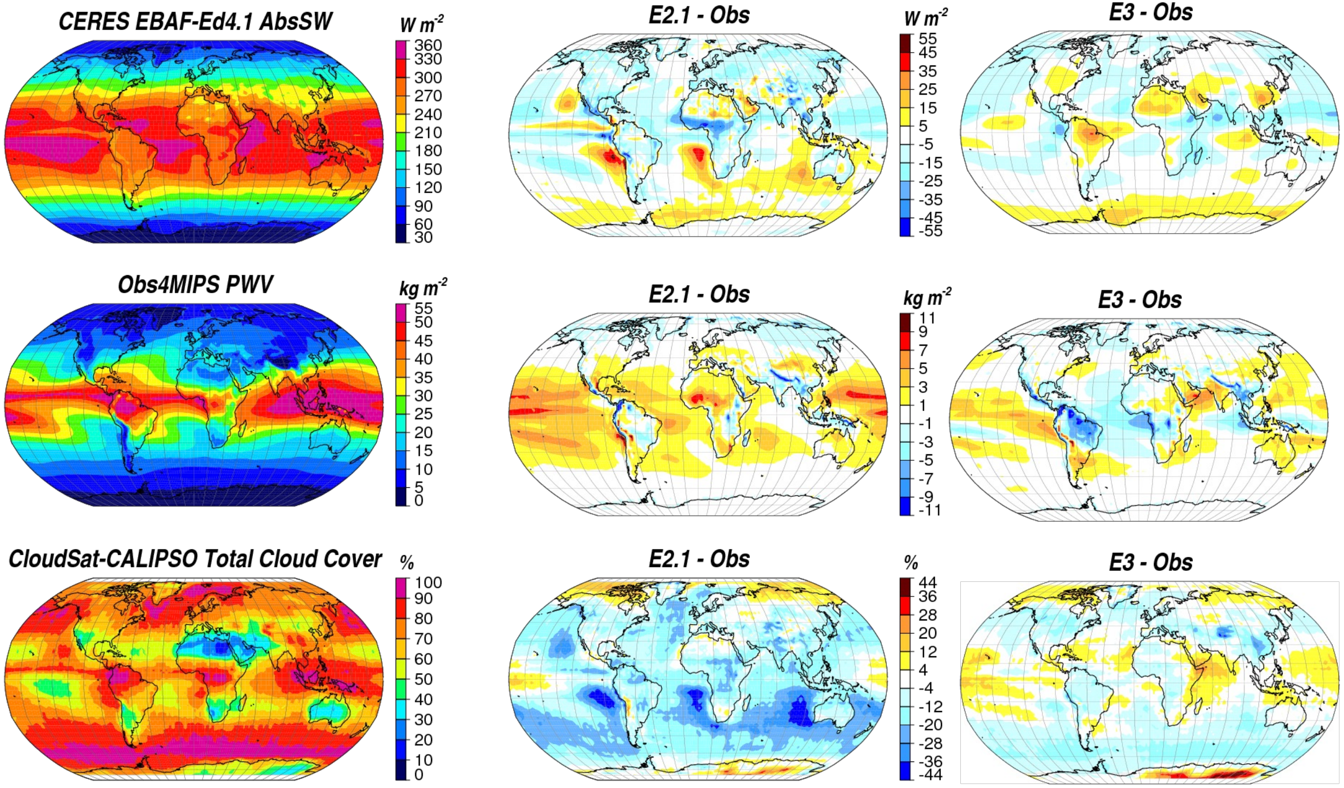


Obs | E2.1 – Obs | E3.tun2 – Obs

AbsSW

PWV

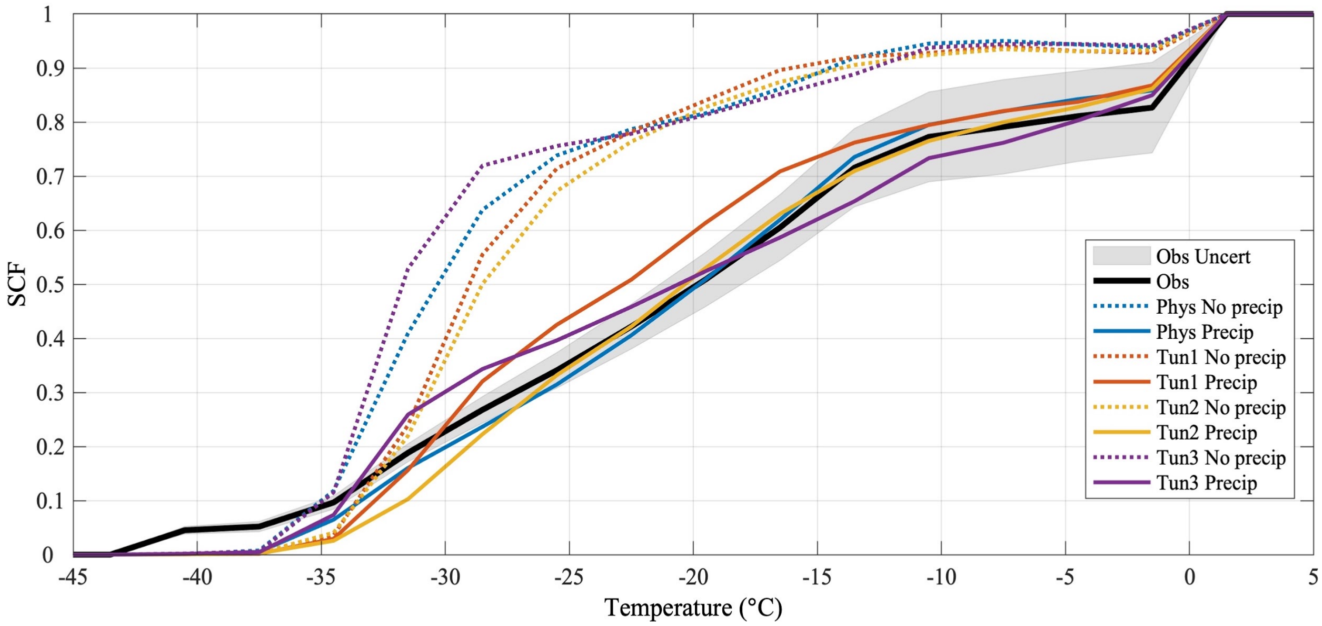
TCC



source: Greg Elsaesser

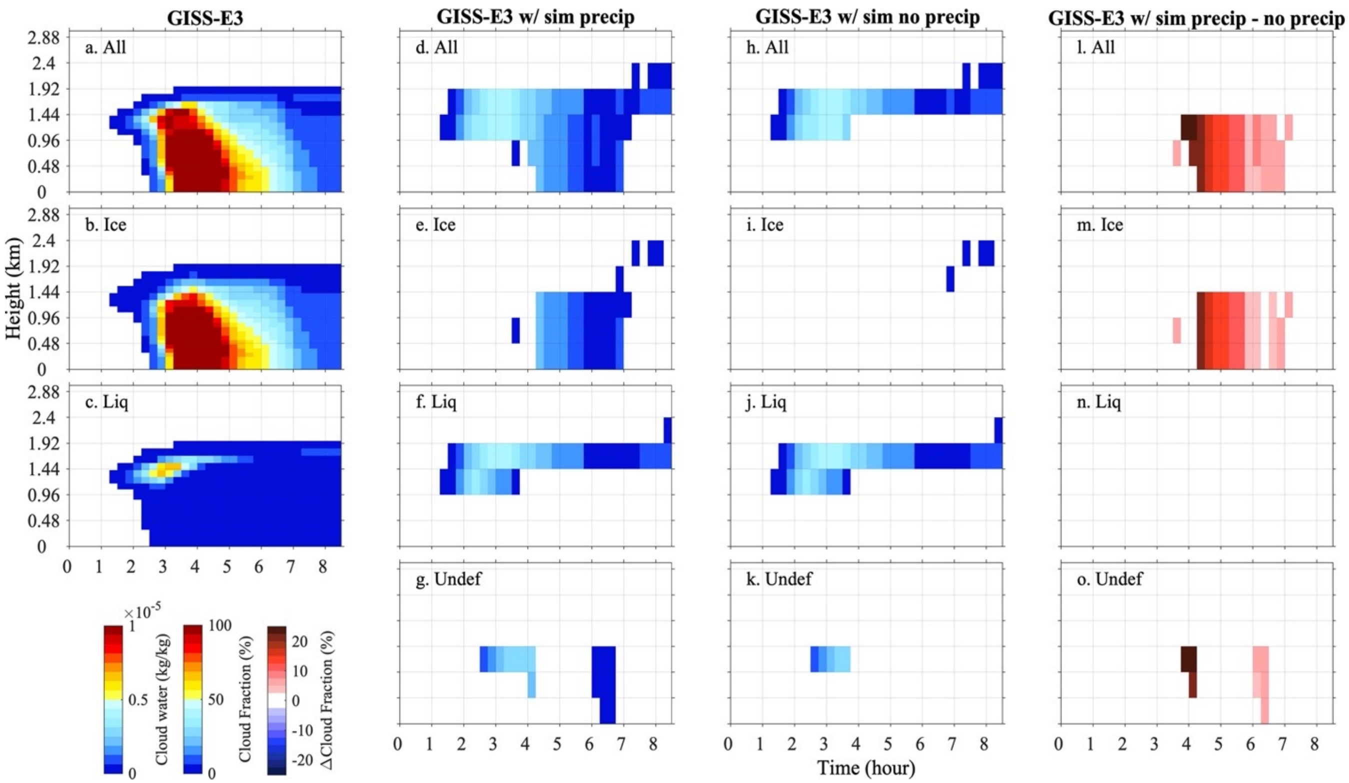
ModelE3 supercooled cloud fraction vs CALIPSO

- COSP simulator modified to see ”precipitation”
- note: cloud ice is continuous with precipitating ice (e.g., Fridlind et al. JAS 2012)
- ”precipitation” also affects cloud feedbacks across ModelE3s



Cesana et al. (GRL 2021, Fig. S6)

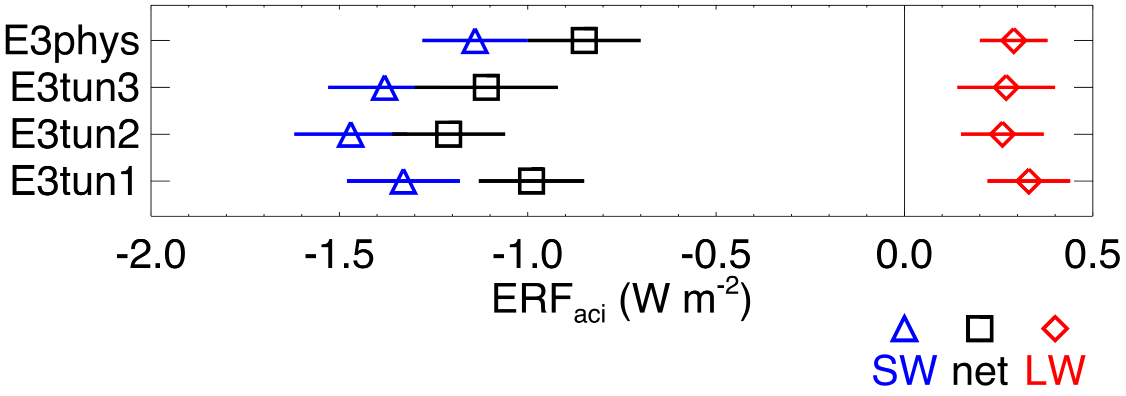
COSP simulator revision tested on SCM AWARE case

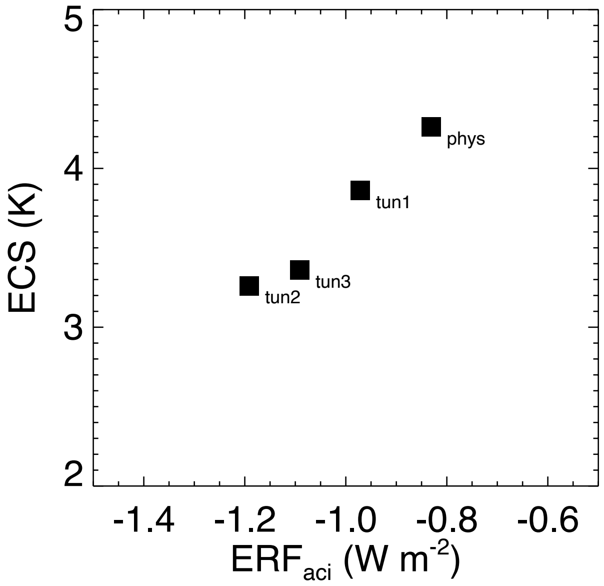


Cesana et al. (GRL 2021, Fig. S1)

Aerosol indirect effect and ECS from E3 candidates

- AIE from 2000-2010 AMIP runs, PD minus PI offline aerosol for droplet activation only
- ECS from 30-year Q-flux PI runs



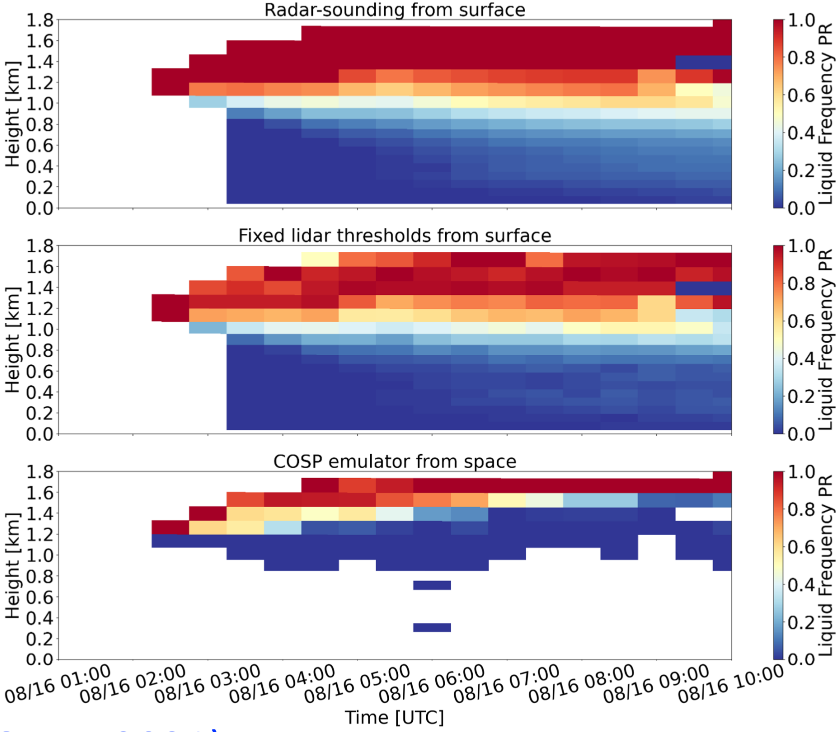


source: Andy Ackerman

A new ground-based lidar/radar simulator: EMC^2

- Earth Model Column Collaboratory
- Python open source, community code base
- tool to evaluate supercooled cloud fraction, cloud base and surface precipitation, ...

***EMC^2* microphysics**



from surface: sounding approach

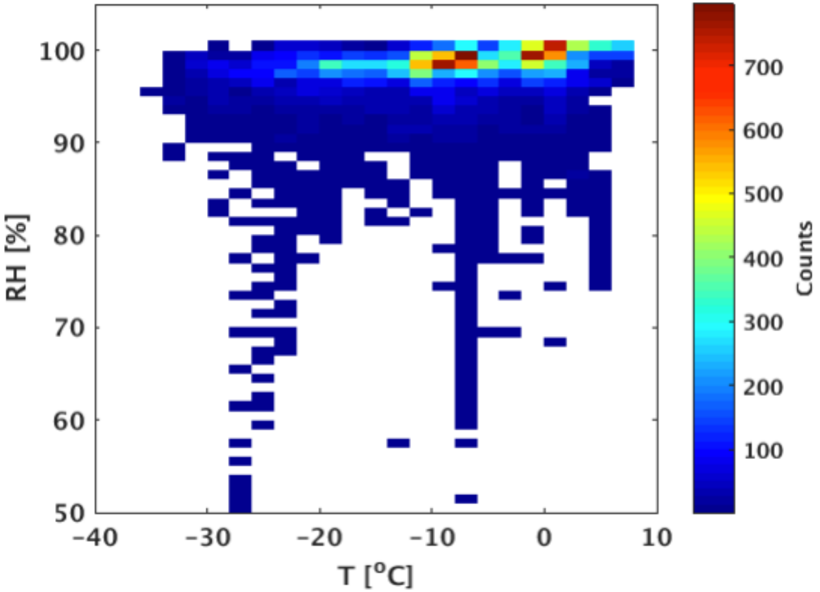
from surface: lidar approach

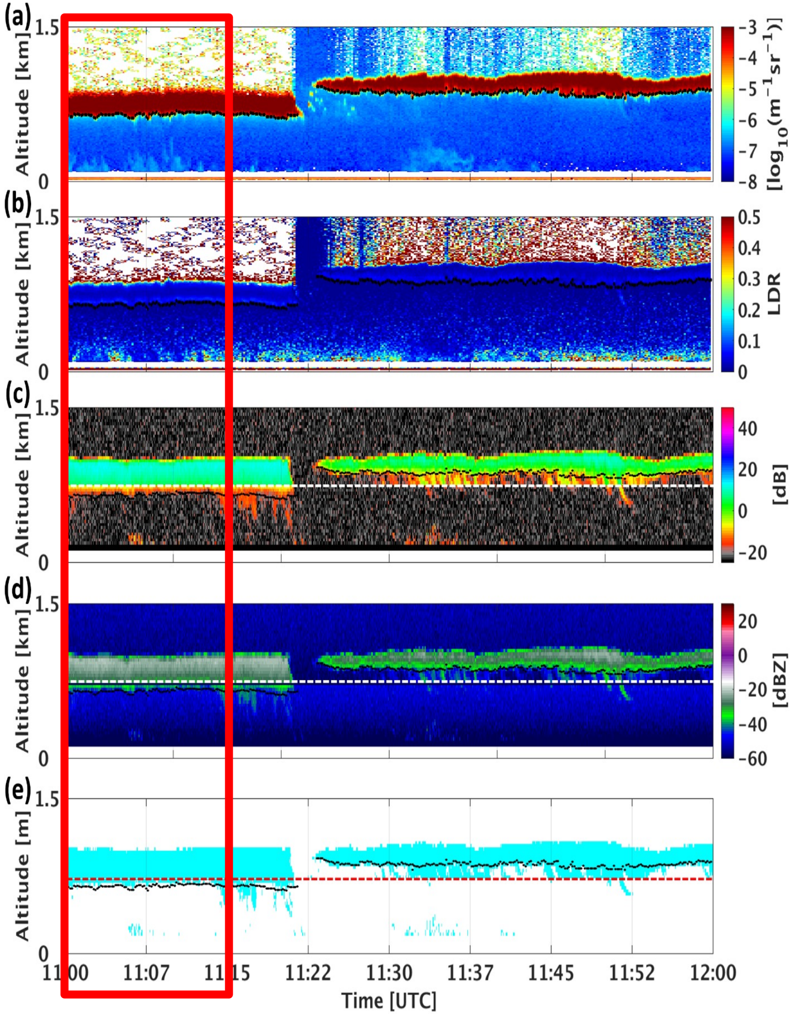
from space

Silber, Jackson, Collis et al. (GMD, 2021)

Observing supercooled layers

- lidar attenuated? use soundings
- colocated radar reflectivity identifies precipitation at sounding cloud bases



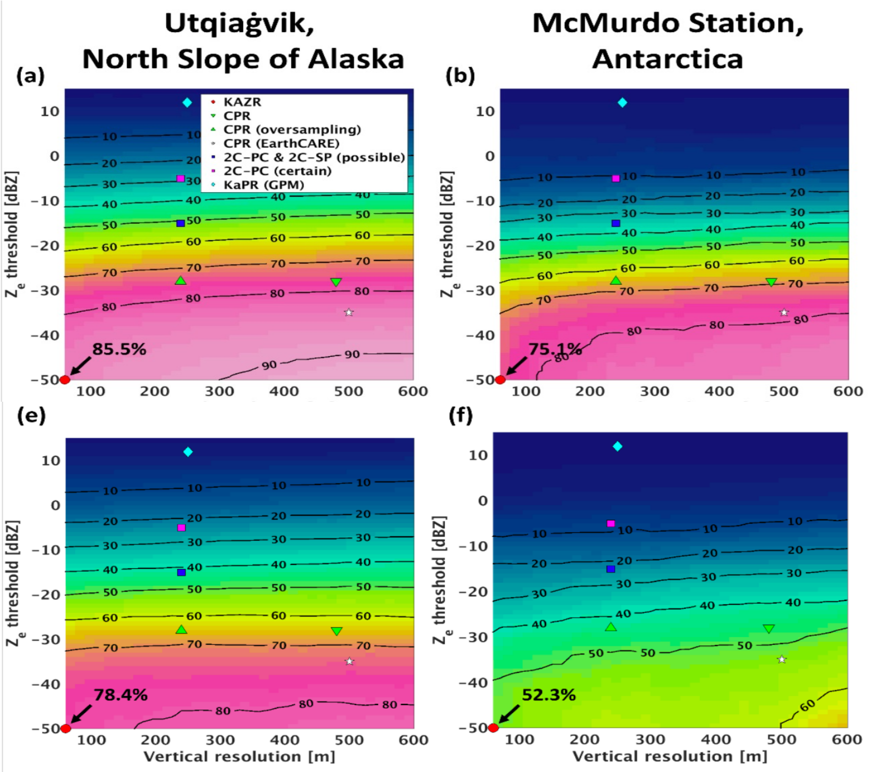


Silber et al. (ACP 2021)

Precipitation from supercooled clouds

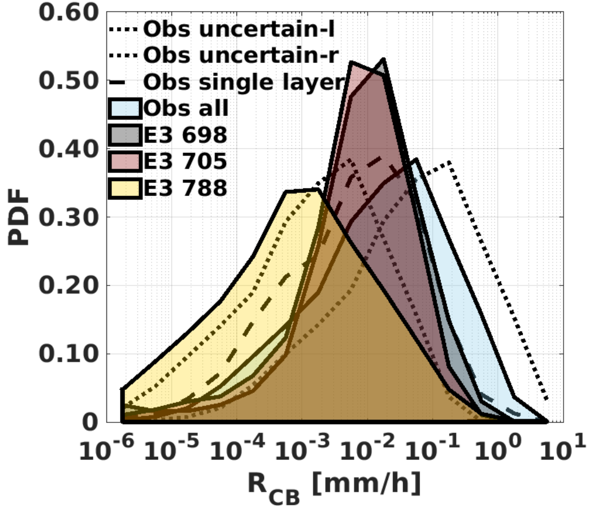
at cloud base

at surface



Silber et al. (ACP, 2021)

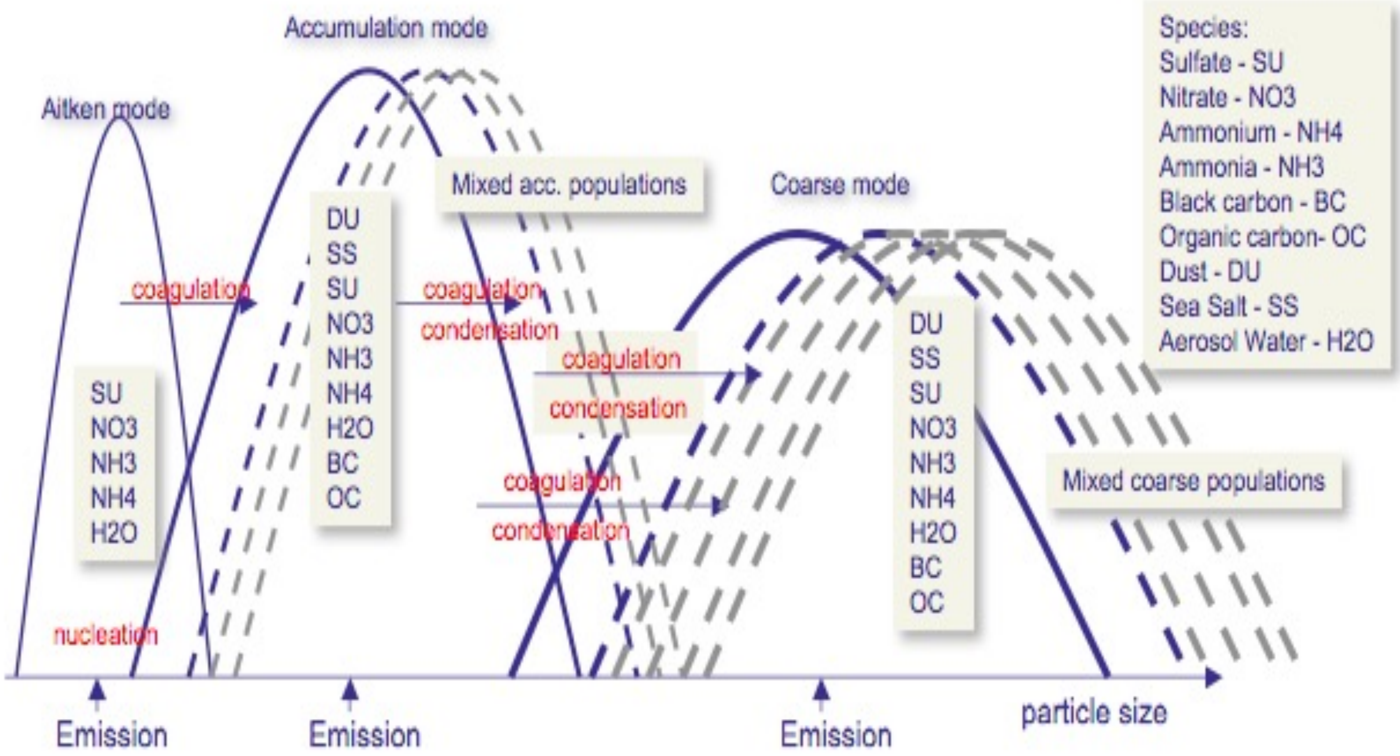
ModelE3 vs retrieved cloud base precipitation rate



source: Israel Silber, using EMC^2

MATRIX scheme

Bauer et al. [ACP 2008, 2010]
Gao et al. [GMD 2017]



Stony Brook University
School of Marine and Atmospheric Sciences

AEROICESTUDY: An ARM Southern Great Plains Pilot Study to Assess a Field-Observational Approach to Conduct Aerosol-Ice Formation Closure

Knopf, D. A., Barry, K. R., Brubaker, T. A., Jahl, L. G., Jankowski, K. A., Li, J., Lu, Y., Monroe, L. W., Moore, K. A., Rivera-Adorno, F. A., Sauceda, K. A., Shi, Y., Tomlin, J. M., Vepuri, H. S. K., Wang, P., Lata, N. N., Levin, E. J. T., Creamean, J. M., Hill, T. C. J., China, S., Alpert, P. A., Moffet, R. C., Hiranuma, N., Sullivan, R. C., Fridlind, A. M., West, M., Riemer, N., Laskin, A., DeMott, P. J., Liu, X.

U.S. DEPARTMENT OF ENERGY

ASR Atmospheric System Research

Knopf et al. (BAMS 2021)

Goals and Objectives

- *Identify ice nucleation parameterizations that produce the most robust predictions of INP number concentrations.*
- *What are the crucial aerosol physicochemical properties to guide ice nucleation representations in models and long-term INP measurements?*
- *What level of parameter details needs to be known to achieve aerosol-INP closure?*
- *What are the leading causes for climate model bias in INP predictions?*

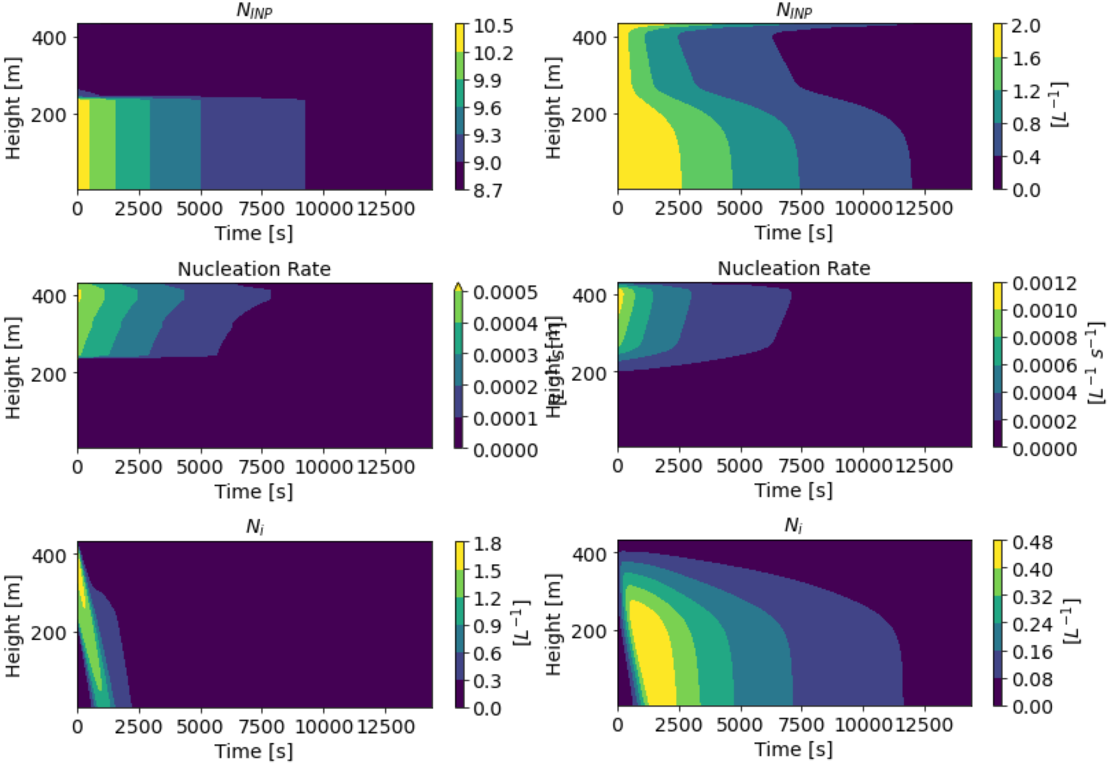
→ **Apply ambient aerosol to evaluate the aerosol composition-INP relationship.**

INP reservoir dynamics in a 1D model

- 1D Python model prognosing INP, N_{ice}
- if INP are rapidly activated in mixed-phase clouds, loss to precipitation will be important (cf. Fridlind et al. 2012)
- if an INP scheme introduces INP diversity within a modal class, tracking loss adds complexity

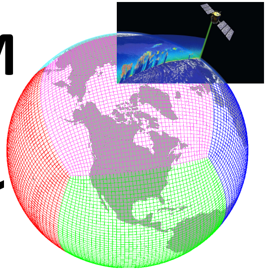
Knopf et al. (submitted)

DeMott et al. (2015) | Knopf and Alpert (2013)



• primary and secondary ice formation
+ rain formation and mesoscale structure
+ gravity waves, surface fluxes, ice properties, aerosol-cloud interactions, ...

ESM



calibration

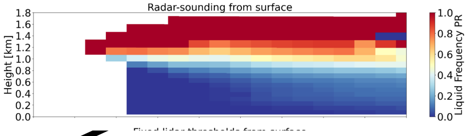
satellite + COSP
long-term ground + EMC²

PARCEL + 1D

development

AEROICESTUDY
KIT laboratory SIP

SCM

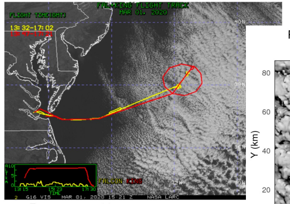


development

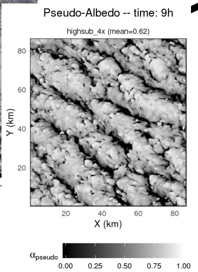
• ESM development workhorse
• pre-calibration tool
• simulator testbed
• cloud feedback analysis tool

• proposing LES-SCM-MIP to CMIP7

LES



From https://satcorps.larc.nasa.go



aircraft field campaigns
long-term ground

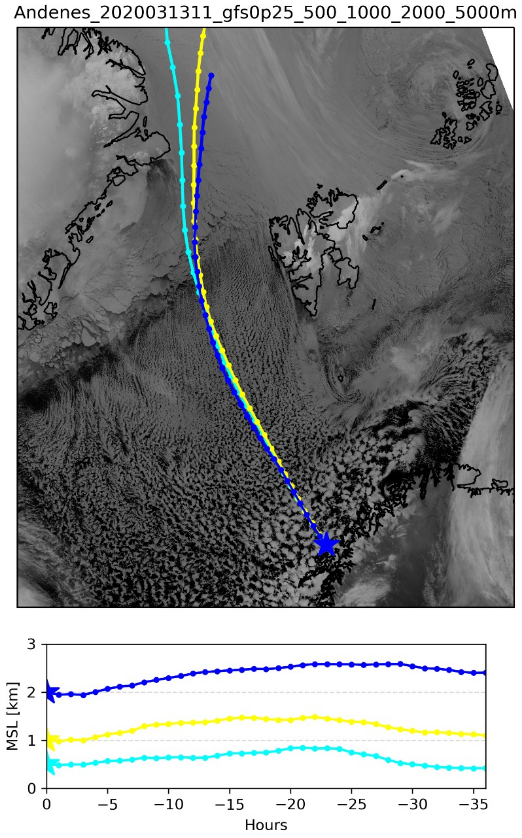
Case study set-up specifications	M-PACE	SHEBA	ISDAC	COMBLE	CONSTRAIN*
nudged horizontal wind profile	Y	Y	Y	Y	geostrophic
subsidence profile	Y	Y	Y	Y	Y
sensible and latent heat fluxes	Y	Y	Y		parameters
hygroscopic aerosol size distribution	Y	Y	Y	Y	fixed Nd
ice nucleating aerosol (somehow)	Y			Y	—
in-cloud ice number concentration		Y	Y		
ice properties (shape, capacitance, fall speed)			Y		
nudged temperature and water vapor			Y		
parameterized longwave radiative cooling			Y		
collision-coalescence turned off			Y		
set-up for SCM and LES	Y			Y	
Lagrangian following PBL trajectory				Y	Y

*de Roode et al. [JAMES 2019] following Field et al. [2014] cold-air outbreak case

COMBLE LES/SCM case study

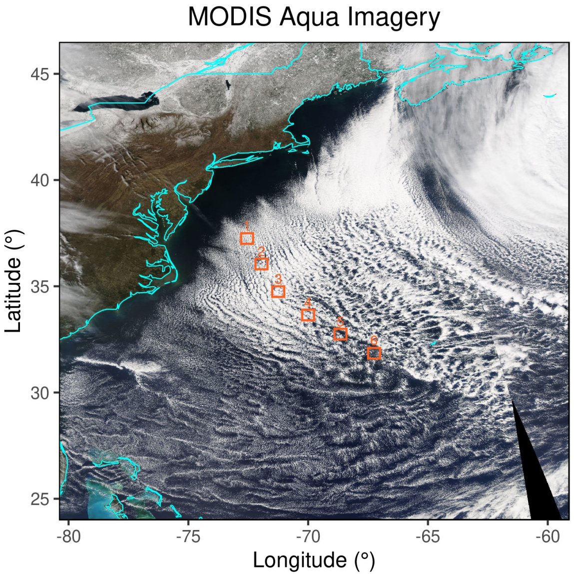
Geerts et al. (BAMS 2021)

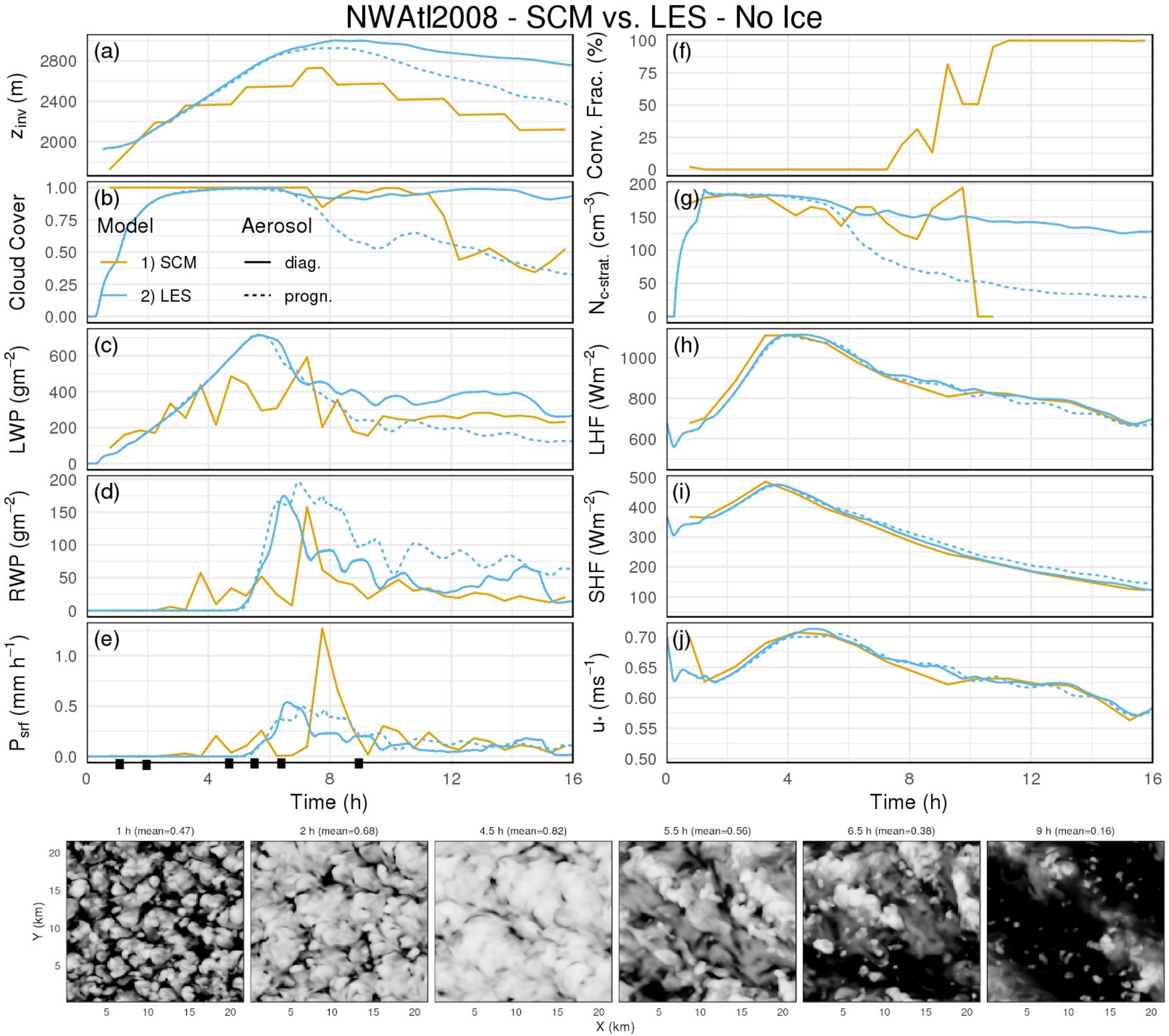
- accepted by GEWEX Atmospheric System Study (GASS) steering committee as an international modeling project (July 2022)
- led by Tim Juliano (NCAR) and Florian Tornow (NASA GISS)
- many observational and modeling PIs involved, now using Cumulus together following French DEPHY file standard
- US and international participants will join introductory webinar (Nov 4th)



ACTIVATE

courtesy Florian Tornow





based on Tornow et al. [ACP 2021]

A roadmap for addressing cloud physics uncertainties

JAMES | Journal of Advances in Modeling Earth Systems

2020

COMMISSIONED MANUSCRIPT
10.1029/2019MS001689

Key Points:

- Microphysics is an important component of weather and climate models, but its representation in current models is highly uncertain
- Two critical challenges are identified: representing cloud and precipitation particle populations and knowledge gaps in cloud physics
- A possible blueprint for addressing these challenges is proposed to accelerate progress in improving microphysics schemes

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Confronting the Challenge of Modeling Cloud and Precipitation Microphysics

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[1]National Center for Atmospheric Research, Boulder, CO, USA, [2]NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, New York, NY, USA, [3]NASA Goddard Institute for Space Studies, New York, NY, USA, [4]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA, USA, [5]Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany, [6]Observation Based Research Section, Environment and Climate Change Canada, Toronto, Ontario, Canada, [7]Atmospheric Numerical Prediction Research, Environment and Climate Change Canada, Dorval, Quebec, Canada, [8]Institute of Geophysics, Faculty of Physics, University of Warsaw, Warsaw, Poland, [9]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [10]North Carolina Institute for Climate Studies, North Carolina State University, Asheville, NC, USA, [11]University of Hyogo and RIKEN Center for Computational Science, Kobe, Japan

Following the ideas outlined in this paper, we highlight six specific recommendations for advancing the representation of microphysics in models:

1. *Sustained support for laboratory facilities to study microphysical processes*, addressing major gaps in cloud physics knowledge and providing data to develop physically based parameterizations and to support or refute cloud physics theories.
2. *Sustained support for new airborne and ground-based instrument development and next-generation instruments in space* to provide the field data that are required to constrain microphysics in global as well as regional models.
3. *Increased emphasis on critical evaluation of model performance using field observations*, including statistically robust sampling from in situ or remote-sensing approaches and targeted data collection in well-defined regions where microphysical properties can be robustly characterized for model evaluation.
4. *Development of new frameworks to facilitate rigorous model evaluation and constraint by observations*, leveraging statistical modeling tools and accounting for observational uncertainty characteristics. This includes the use of machine learning, not as a replacement for microphysics schemes but as a tool to understand scheme behavior (e.g., via emulation).
5. *Increased focus on systematic quantification of parameter and structural uncertainty in schemes*, which can help direct efforts for scheme improvement and point to particular needs for observational constraint.
6. *Continued development and use of new methods for microphysical modeling*, especially Lagrangian particle-based schemes.

1. What kind of support for lab facilities is needed?

- BERAC benchmarking report suggests establishment of a chamber facility to study a broad array of processes such as ice multiplication, on a par with the AIDA facility in Germany
  - several chambers, calibration facilities, permanent staff carrying out experiments, support for hosted experiments and visitors, national lab-based
  - how would such a crucial national investment be critically evaluated by the community for adequacy for purpose?
  - BSSD COV report raised concerns about how facilities are established
  - a multi-agency NASEM process could help plan such crucial investments across US agencies (e.g., wind tunnels, calibration and chamber facilities)

2. What kind of support for new instruments?

- airborne and ground-based instrument development in the US faces barriers that could be substantially reduced
  - instrument developers tend to find that they need to leave academia owing to funding structure, academia loses the student pipeline
  - instrument development even at national labs appears arduous
    - 2020 DOE COV report discussed FIMS instrument development
    - not coincidental that a high-profile FIMS-based paper is highlighted in chapter 6 of the BERAC benchmarking report
- US climate modeling centers are not adequately engaged in the NASA EOS design process

A call for climate OSSEs for PBL Mission Incubation

National Aeronautics and Space Administration

TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

THE NASA PBL INCUBATION STUDY TEAM REPORT

João Teixeira [(1)], Jeffrey R. Piepmeier [(2)], Amin R. Nehrir [(3)], Chi O. Ao [(1)], Shuyi S. Chen [(4)], Carol A. Clayson [(5)], Ann M. Fridlind [(6)], Matthew Lebsock [(1)], Will McCarty [(2)], Haydee Salmun [(7)], Joseph A. Santanello [(2)], David D. Turner [(8)], Zhien Wang [(9)], Xubin Zeng [(10)]

2021

- see Section 6.3

A climate OSSE approach proposed to AI4ESP

2021

A Grand Challenge "Uncertainty Project" to Accelerate Advances in Earth System Predictability: AI-Enabled Concepts and Applications

Authors
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- a framework to simultaneously enable multi-ESM climate observing system simulation experiments (COSSEs), and provide a systematic assessment of the key knowledge gaps that require additional laboratory, field and process study to reduce uncertainties in societally relevant predictions

Earth's Future

2017

RESEARCH ARTICLE

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Designing the Climate Observing System of the Future

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Key Points::

- A significantly expanded climate observing system could address major science questions and meet important societal needs
- Careful independent testing can evaluate whether proposed systems can address critical observing needs
- Future investments in climate observations offer large societal benefits and economic return on investments

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- a detailed roadmap to climate OSSEs (see Section 3)