Cloud Microphysics Across Scales for Seamless Prediction

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+ a huge cast

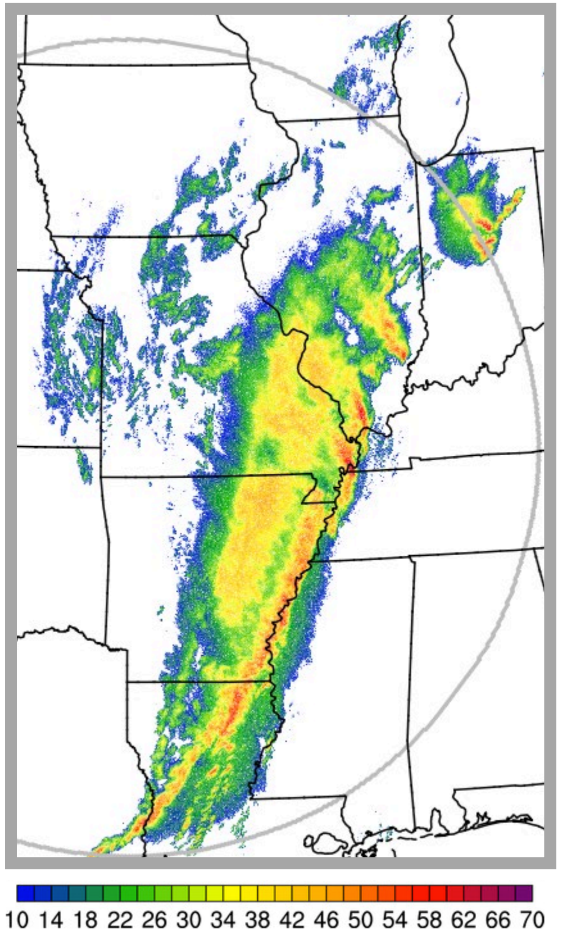
Outline

- Motivation/Statement of the ‘Cloud Problem’
  - Weather Extremes, Cloud Feedbacks, Aerosol Forcing
- What is cloud microphysics
- Some major issues for Weather and Climate
- Experiments and Progress towards seamless prediction
- Next Steps

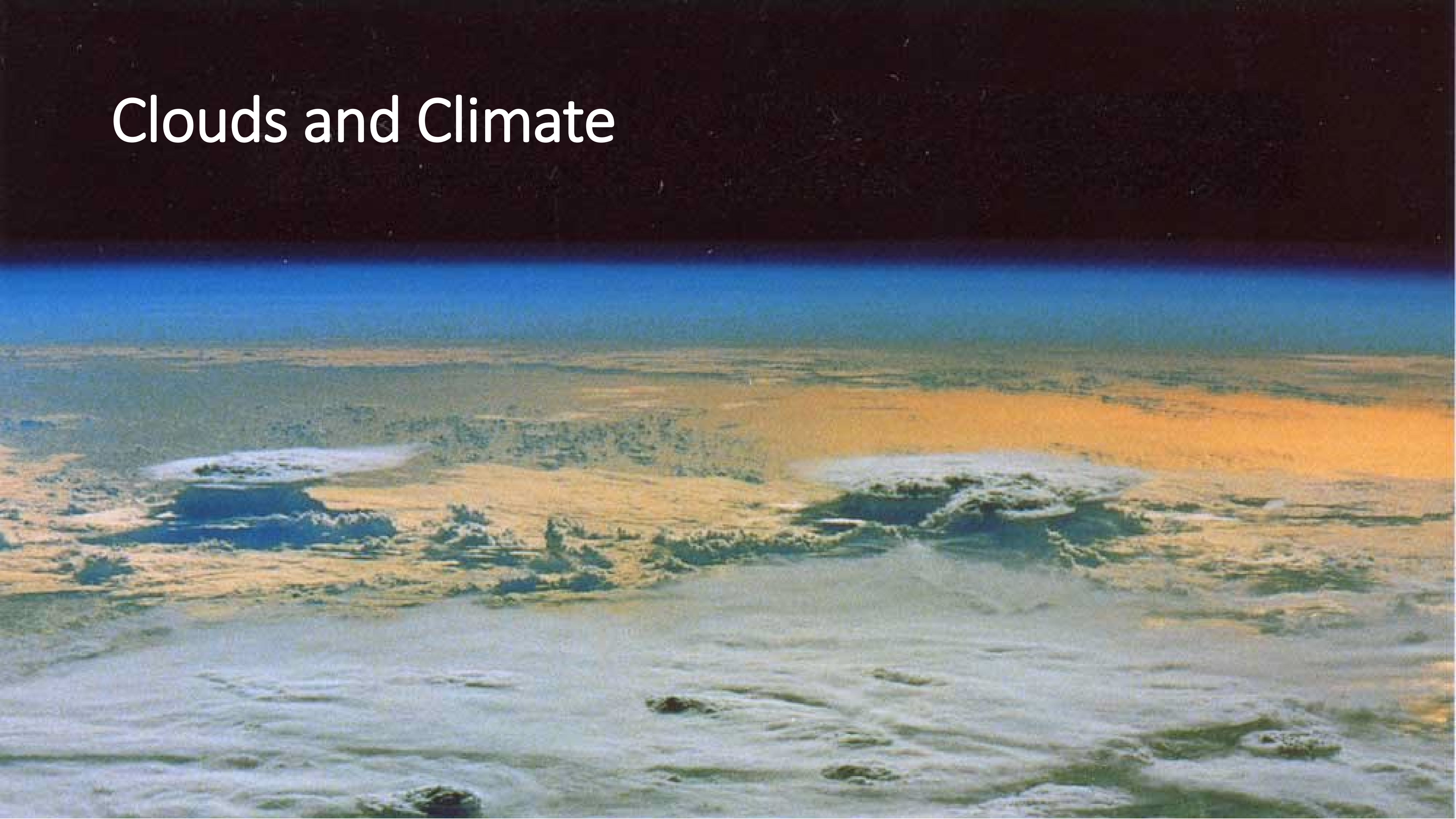
Weather: Cloud Microphysics Kills!

- Clouds are responsible for most severe weather
  - Tornadoes, Thunderstorms, Hail, Tropical Cyclones
- Critical processes depend on cloud microphysics (Thunderstorms, Hail, even Tornadoes)

Radar Reflectivity, 27 April 2017

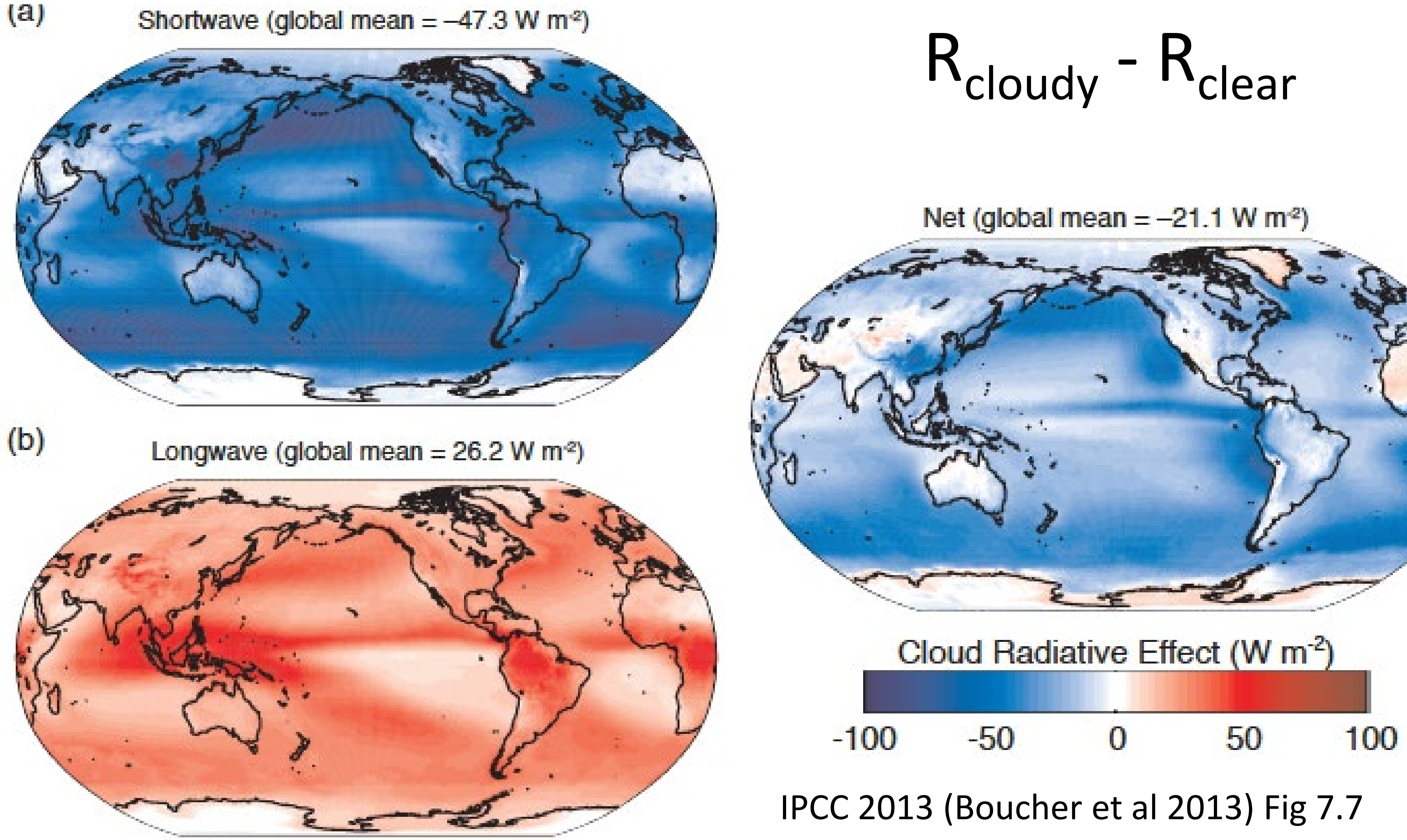


Clouds and Climate



Climate: Cloud Radiative Effects are Large

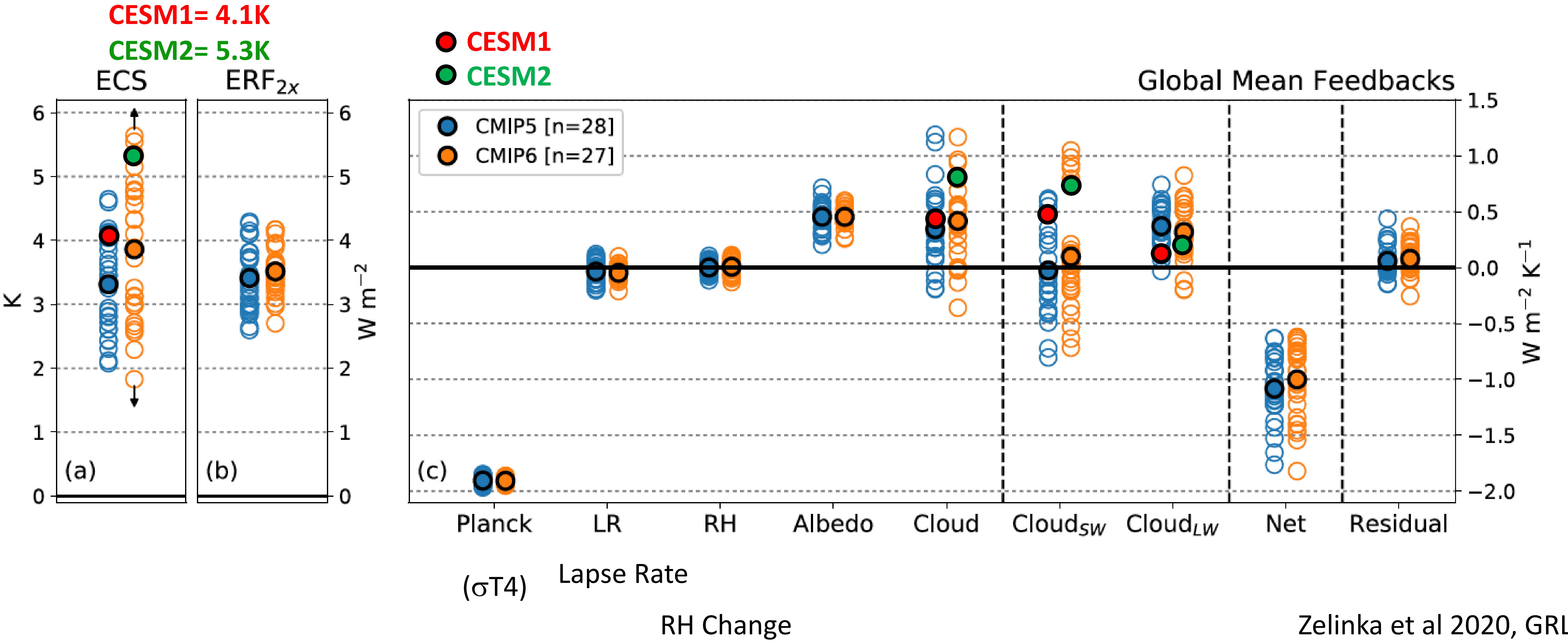
$R_{cloudy} - R_{clear}$



IPCC 2013 (Boucher et al 2013) Fig 7.7

Climate Feedbacks

Equilibrium Climate Sensitivity (ECS) Uncertainty: *It's all about cloud feedback*

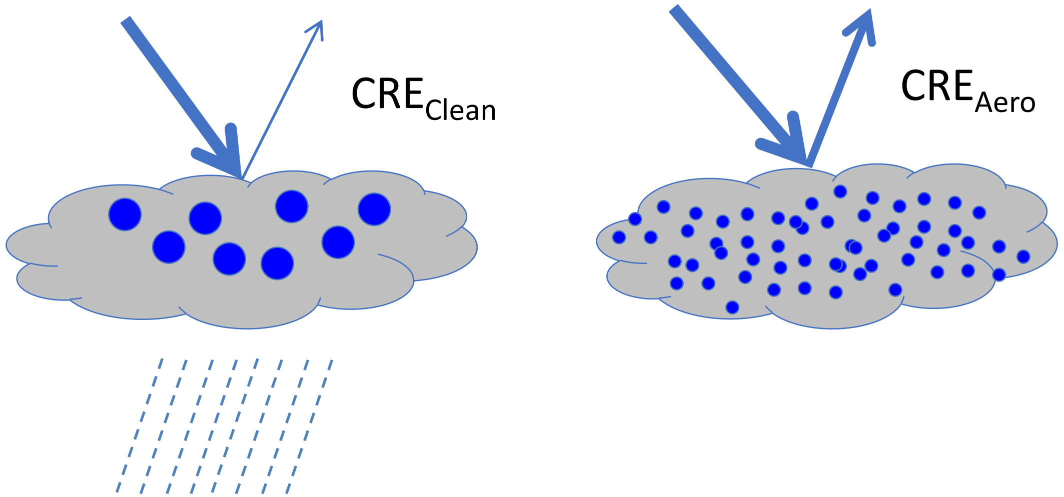


Zelinka et al 2020, GRL

Aerosol Effects on Clouds

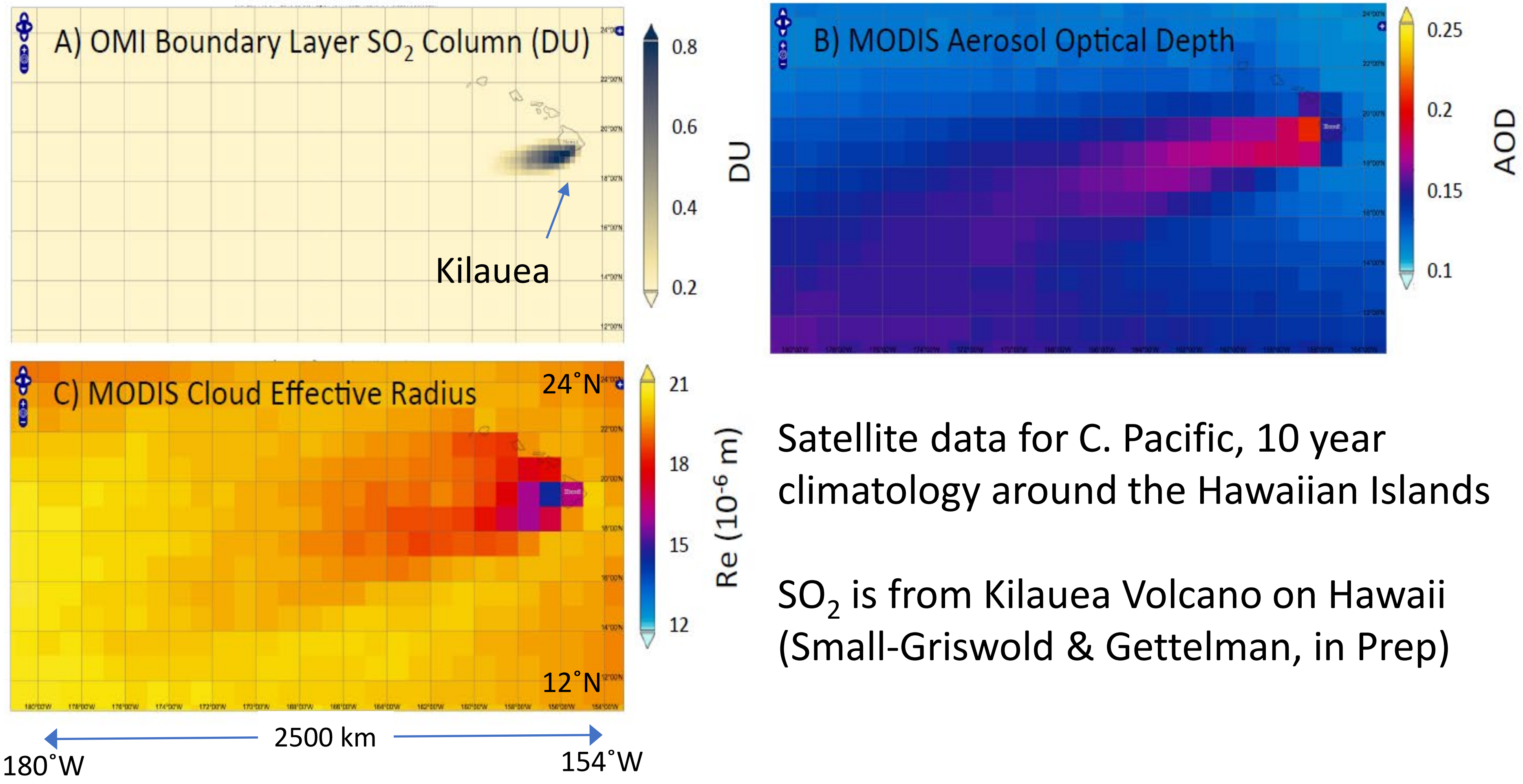
- Scattering & Absorption = Direct effects
- Aerosol – Cloud – Interactions (ACI)

$$+\text{Aerosols} \rightarrow +\text{CCN} \rightarrow +N_c \rightarrow \Delta\text{CRE}$$



Brighter clouds (albedo effect) with smaller drops (S. Twomey 1977)
Also: delay in precipitation (B. Albrecht, 1989). Longer lived Clouds?

‘Volcano Tracks’: Satellite Climatology

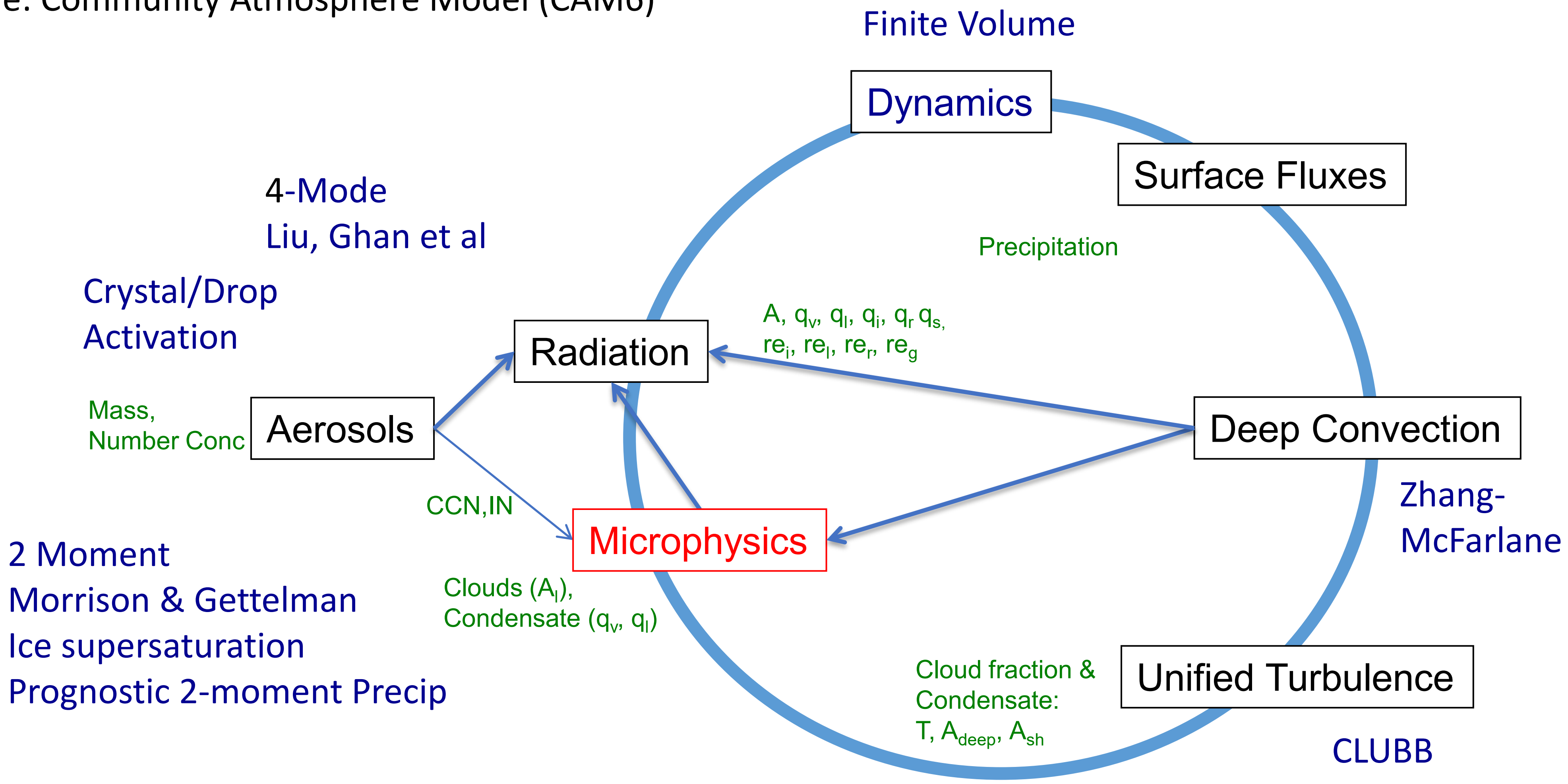


Satellite data for C. Pacific, 10 year climatology around the Hawaiian Islands

SO_2 is from Kilauea Volcano on Hawaii (Small-Griswold & Gettelman, in Prep)

What is Cloud Microphysics?

Example: Community Atmosphere Model (CAM6)

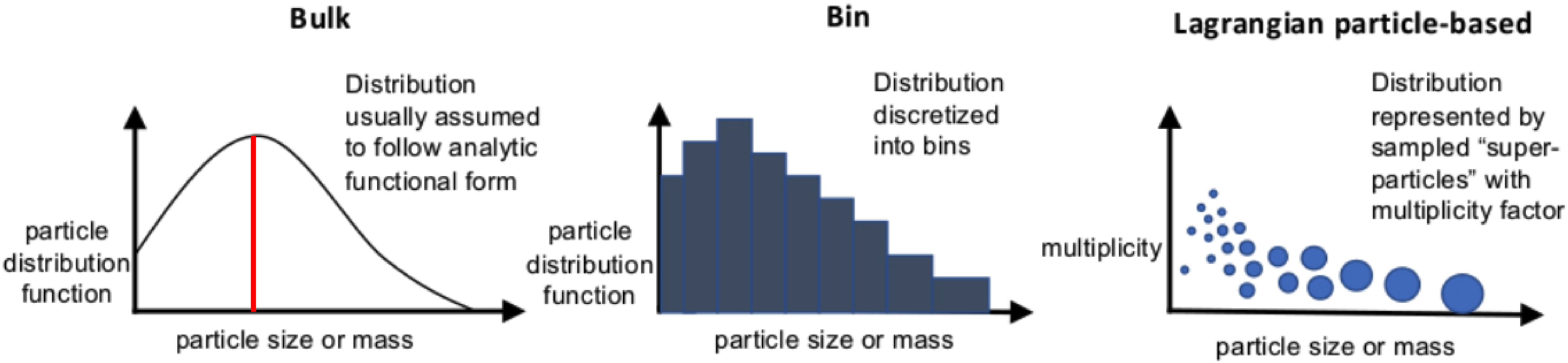


A = cloud fraction, q=H_2O, re=effective radius (size), T=temperature
(i)ce, (l)iquid, (v)apor, (r)ain, (s)now

Types of Microphysical Schemes

Used in models at scales:

Global & Mesoscale models | Mesoscale /Large Eddy Simulations/Parcel | LES/Parcel



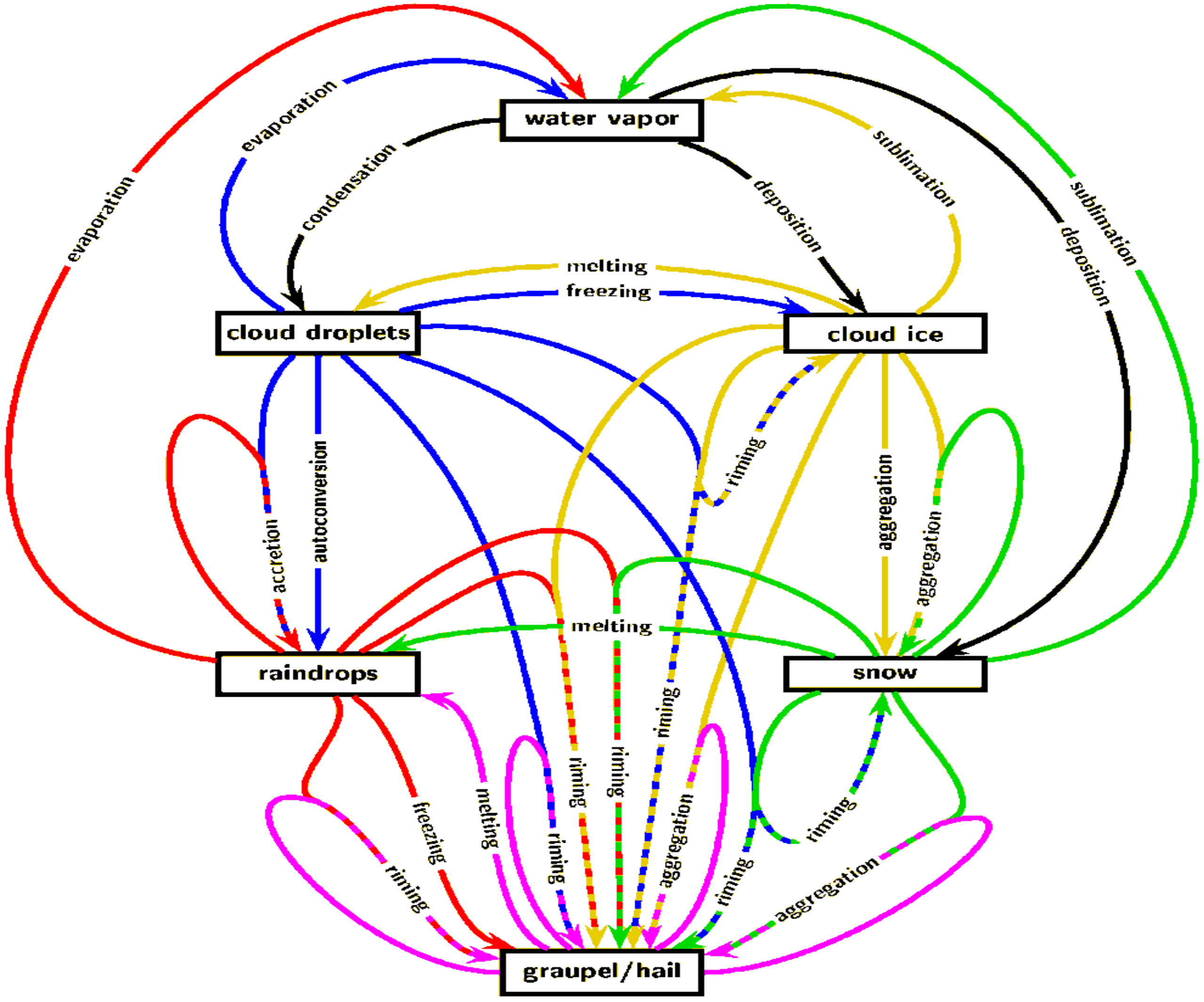
Two Moment = Prognostic Mass and Number

One Moment = Prognostic Mass, Diagnostic Number/Size

Figure: Morrison et al 2020, JAMES

Cloud Microphysical Processes

A. Seifert, Personal Communication

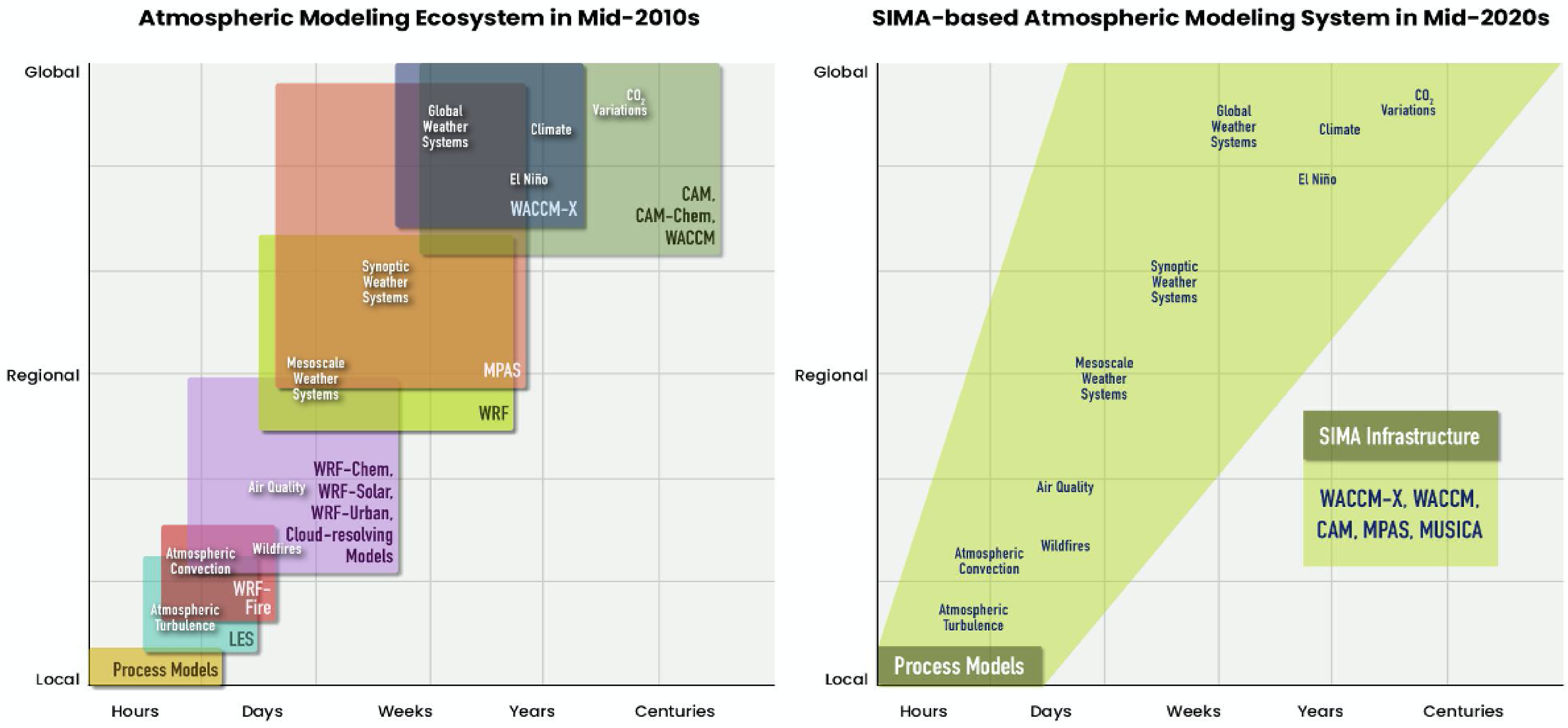


Key processes:

- **Mixed phase** processes important for weather and climate (supercooled liquid meta-stable)
- **Conversion** processes (vapor deposition onto ice, riming snow to graupel)
- **Aggregation** processes grow particles to where they fall fast (rain formation)
- **Ice particle density** and **fall speeds** vary strongly and are important for precipitation

A (not so unique) vision

System for Integrated Modeling of the Atmosphere (SIMA)



Major Issues for Clouds, Precipitation & Aerosols

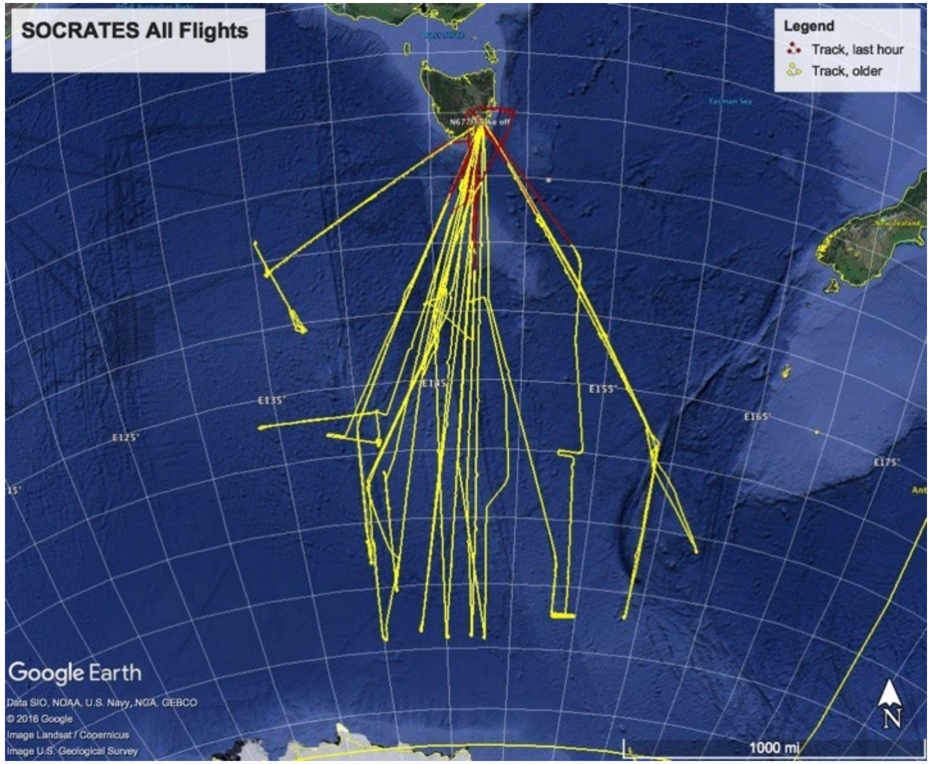
- Aerosol activation (cloud-aerosol interactions)
  - Vertical velocity critical
  - Size distributions govern process rates
  - Ice Nucleation can be highly uncertain
- Cloud Phase
  - Radiative effects at high latitudes AND for cloud feedbacks
  - Also weather impacts: extreme precipitation, riming
- Size Distributions
  - Consistent treatment of process rates and radiation
- Parameter Uncertainty
  - Can we narrow the range of uncertainty in cloud physics / microphysics
- Precipitation Formation: Frequency & Intensity
  - The chronic drizzle problem is a cloud physics problem
- Seamless prediction
  - Can we push across scales: examples from 100km→3km

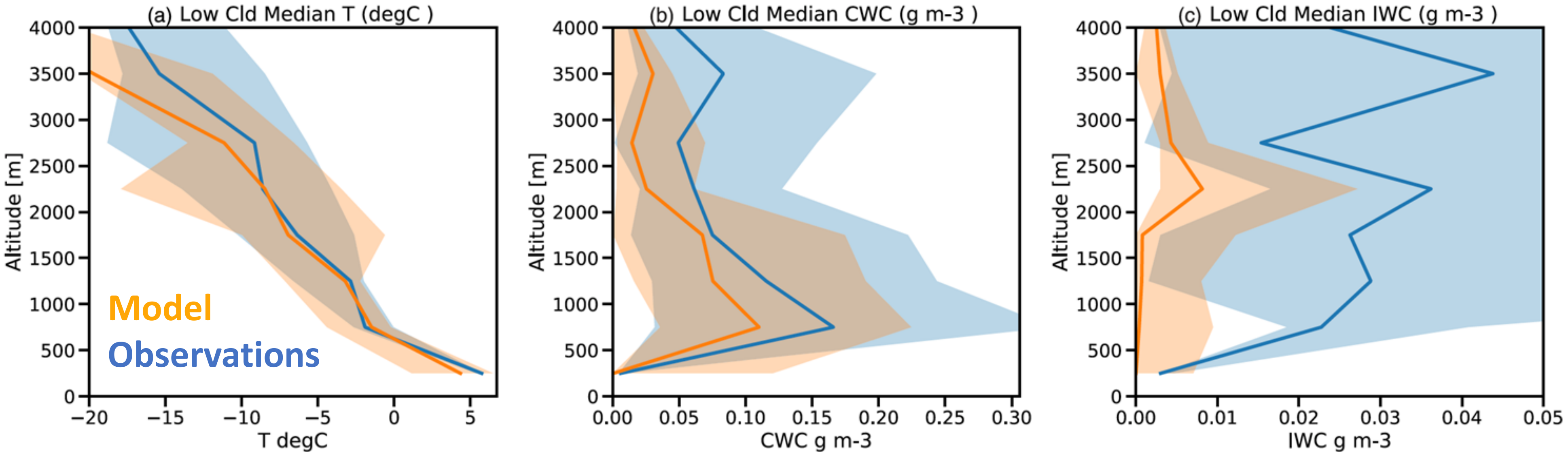
Cloud Phase

SOCRATES in-situ flights over the S. Ocean used to understand & improve models

CAM6: Too little ice. This contributes to high climate sensitivity.

Similar work on importance of cloud phase by Forbes (2014,2015)



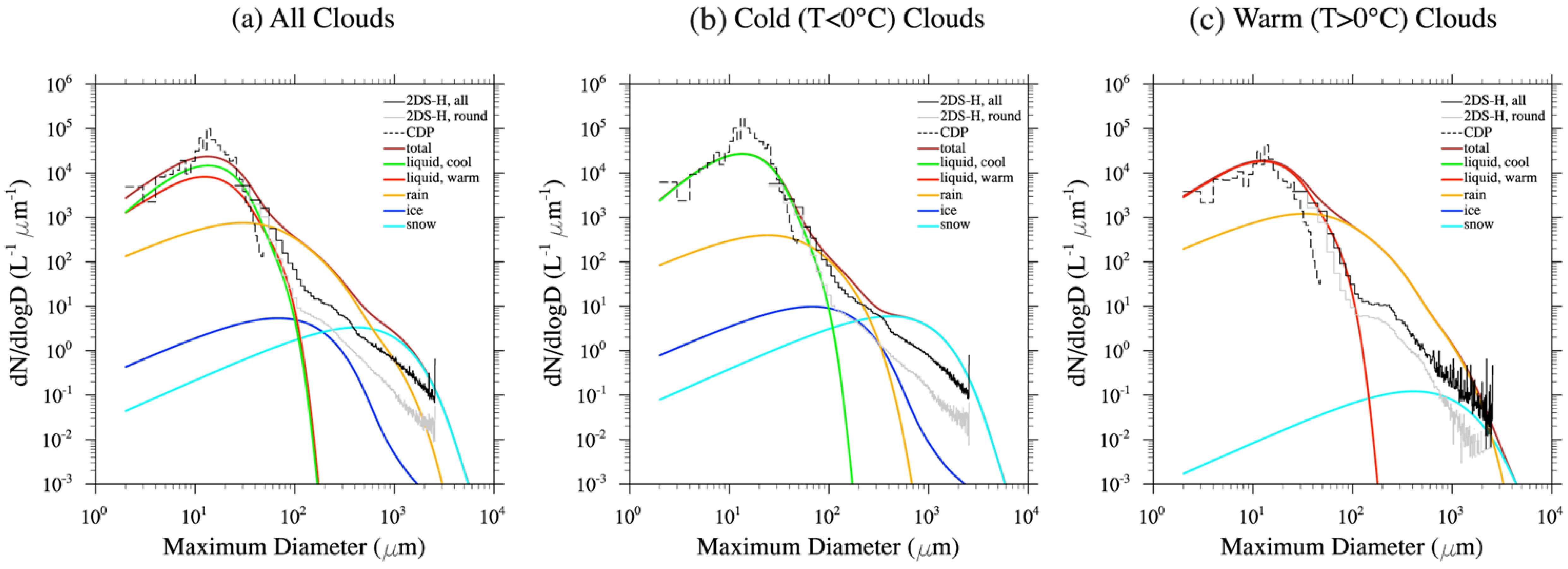


Gettelman et al 2020

Microphysics, Size distributions

Advanced GCMs/GSRMs can be compared directly to cloud microphysical size distributions (here from SOCRATES)

Comparison is GCM cloud microphysics along aircraft flight tracks with in-situ data

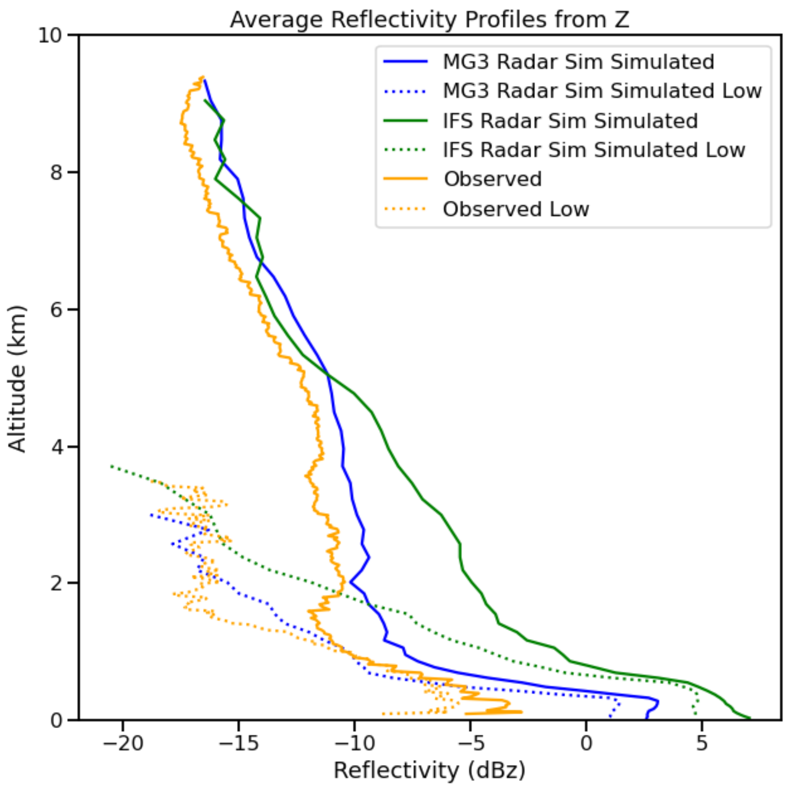


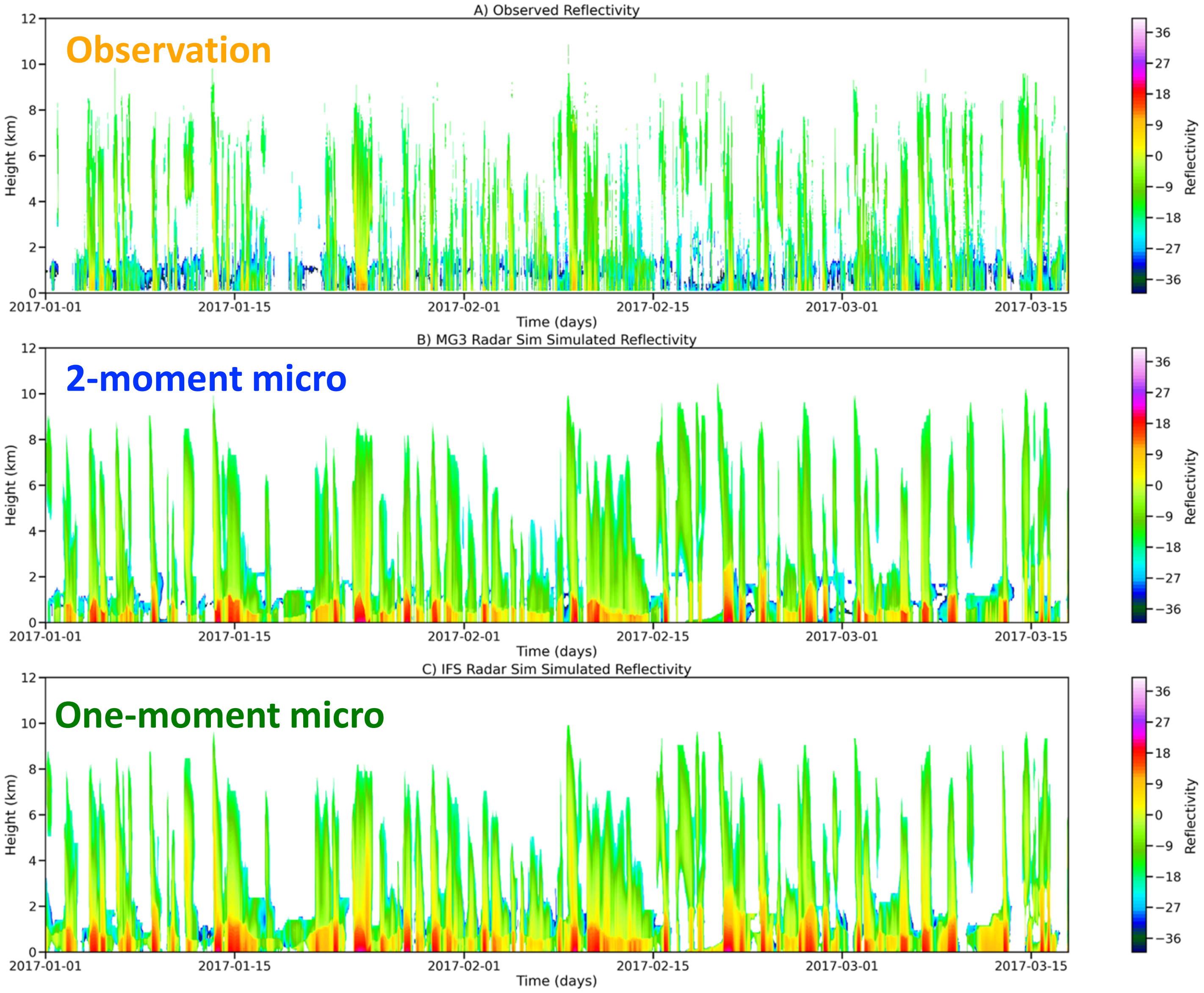
Note potential issue with too large rain sizes

Gettelman et al 2020

Microphysics: Comparing to Reflectivity

Comparisons over Macquarie Island in S. Ocean between a **precipitation radar** and single column simulations with **one-moment** and **2-moment** microphysics in the ECMWF-IFS SCM.





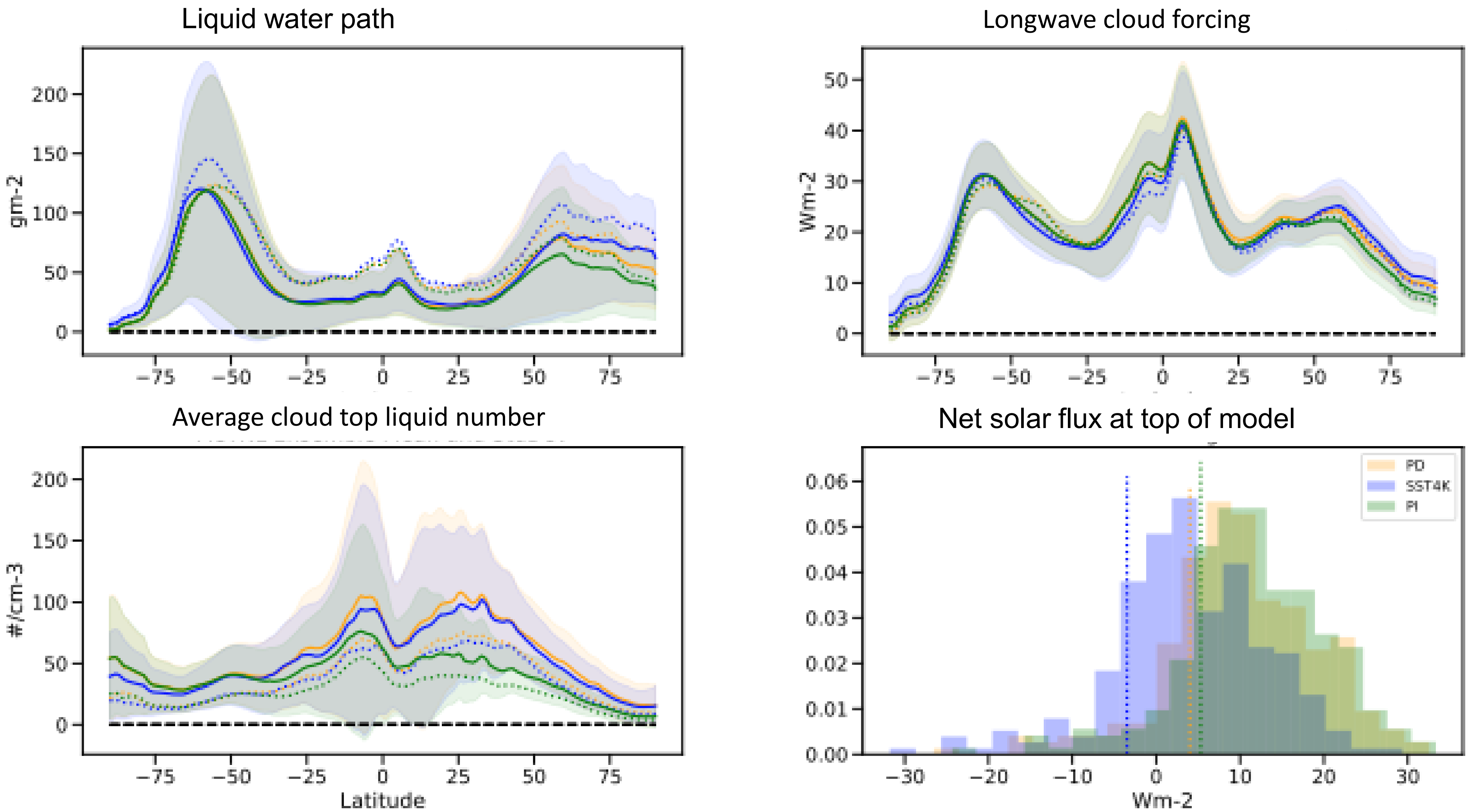
Gettelman, Forbes, Fielding, Marchand, in Prep

Robustness: Parameter Uncertainty

Perturbed Parameter Ensemble (PPE)

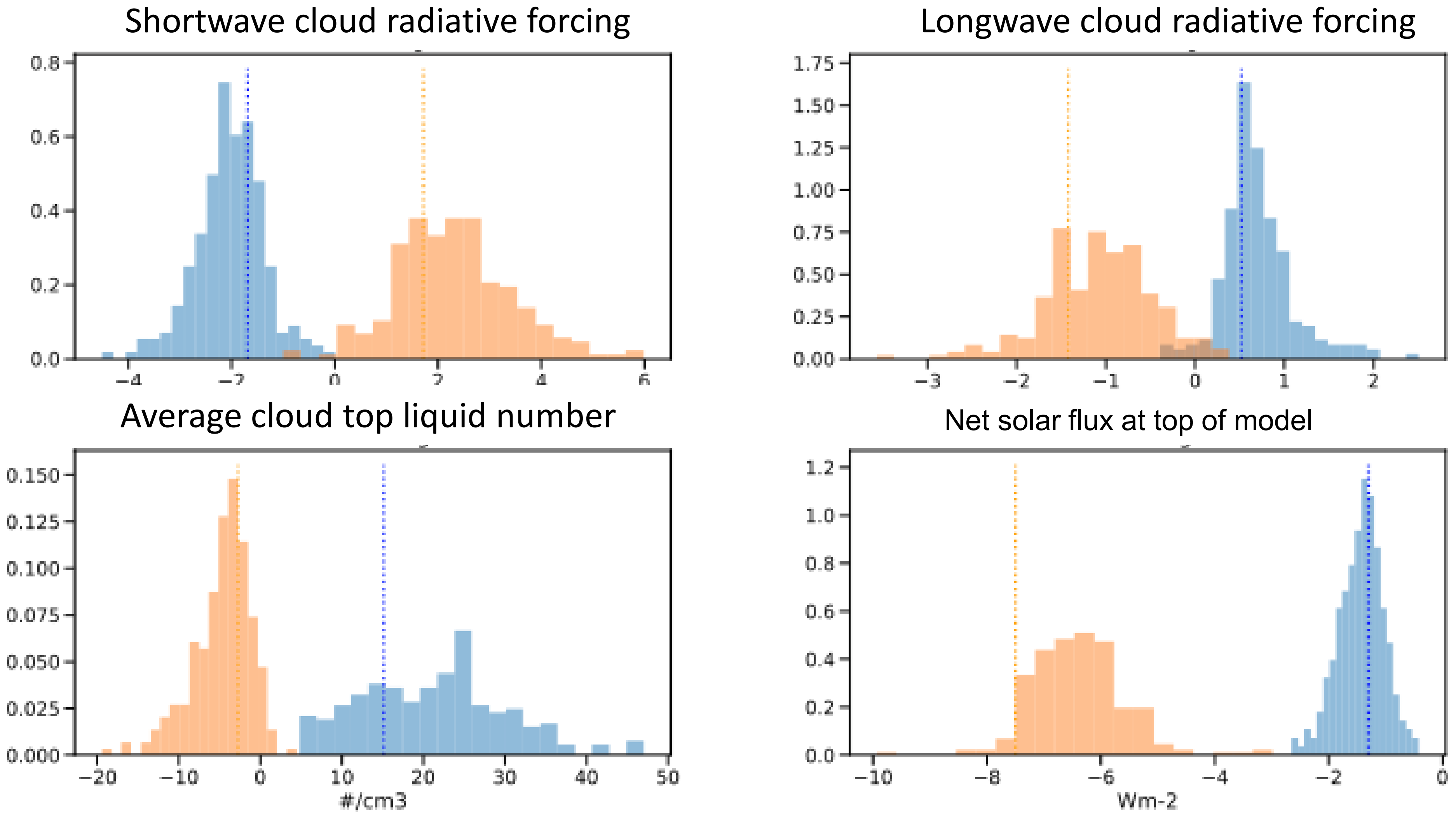
Eidhammer, Gettelman, Thayer-Calder, Duffy

Control run (Baseline CAM6 parameters)
Mean over all 250 simulations



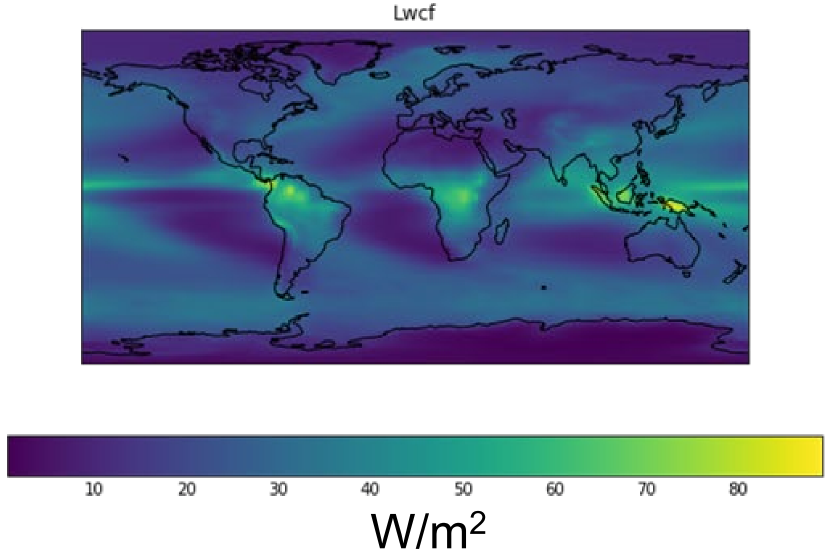
Forcing and Feedback

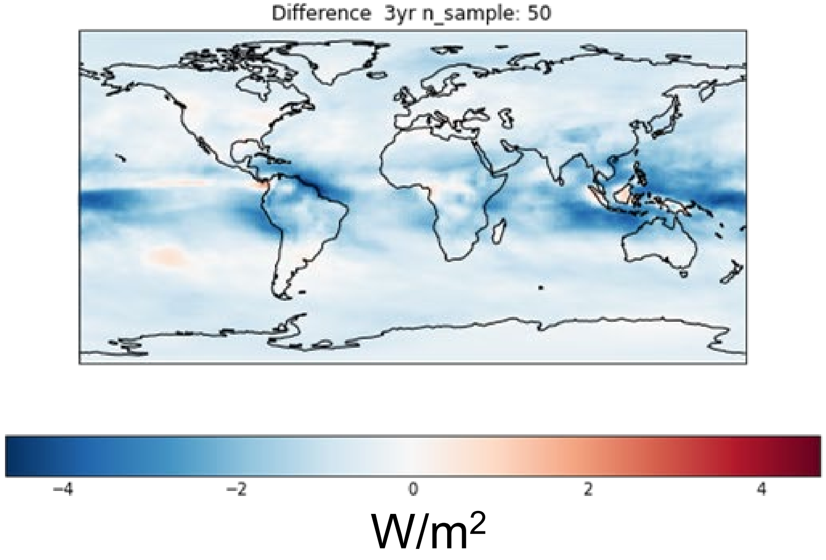
Forcing: Present day (PD) - Pre-industrial (PI) aerosol
Feedback: 4K SST - Present day (PD)

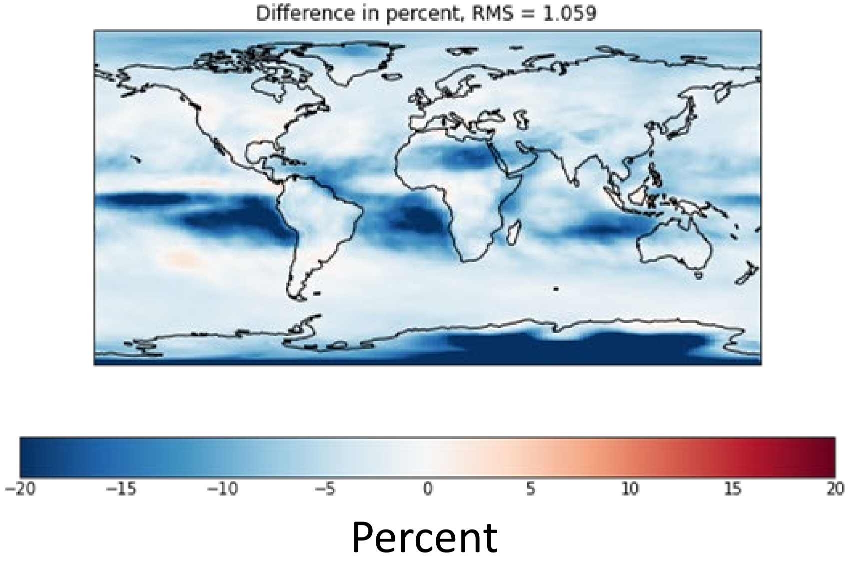


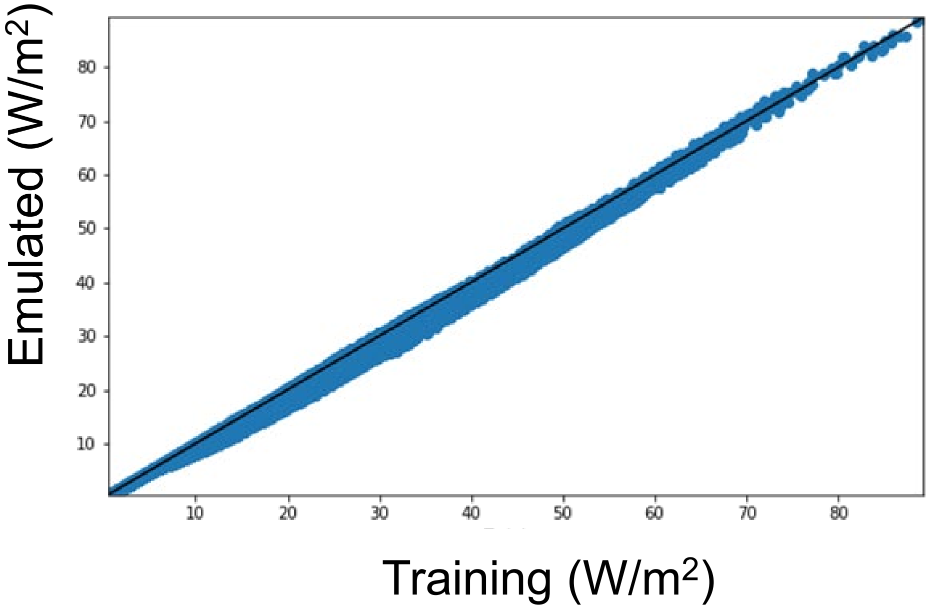
Emulating Longwave Cloud Radiative Forcing
Gaussian Process Emulator (*University of Oxford*)

Emulate LW Cloud Radiative Effect (LWCRE)

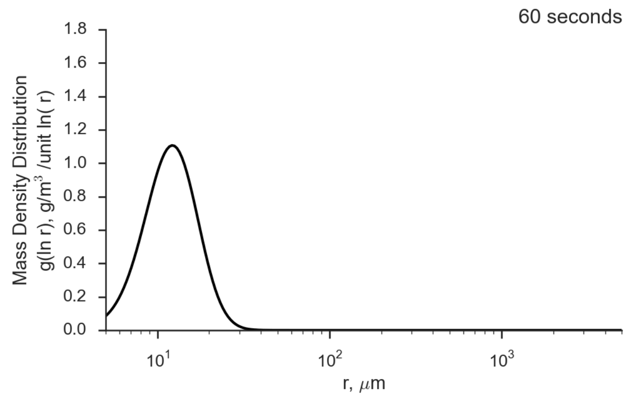








Machine Learning the Warm Rain Process



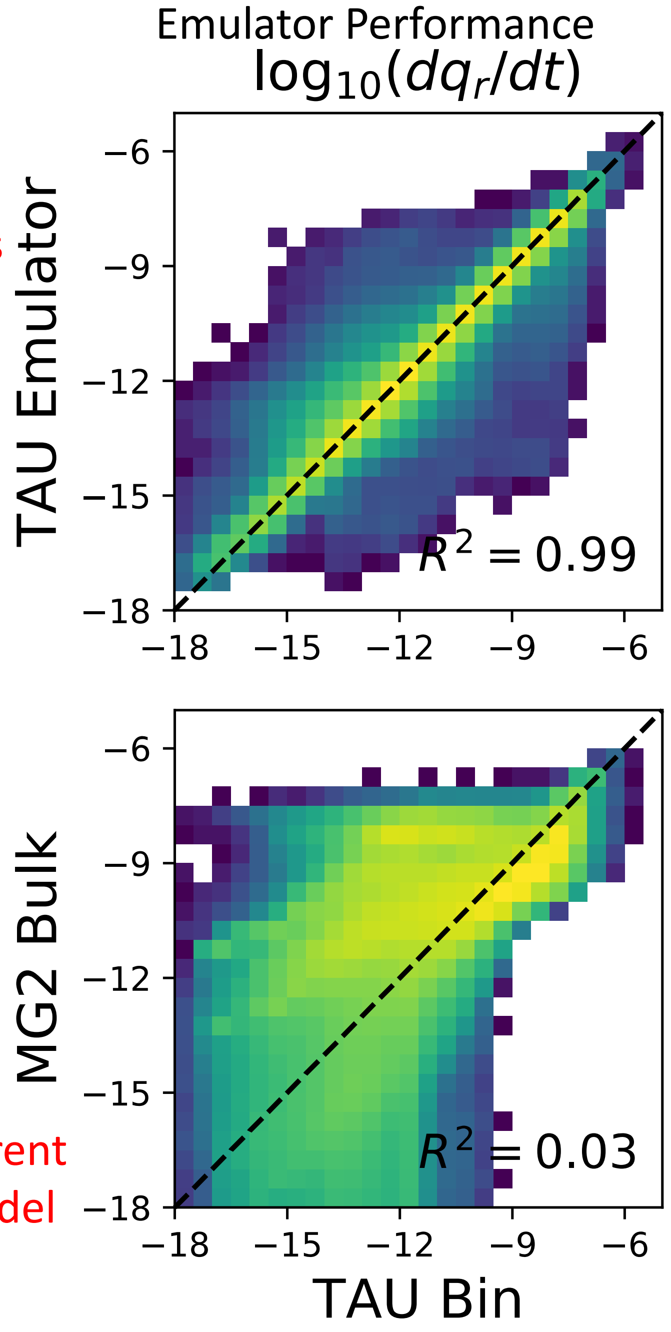
Replace traditional GCM bulk rain formation with a bin model formulation for stochastic collection. This is too expensive for climate use. So emulate it with a neural network.

Results:

- We can change the answer in the model with the bin code.
- Very slow when using full treatment
- Recover speed and recover results with a neural network emulator (it works)
- Embedded NN in the microphysics: maintains conservation with series of checks

NN Emulator reproduces detailed code

Bin code is Different than original model

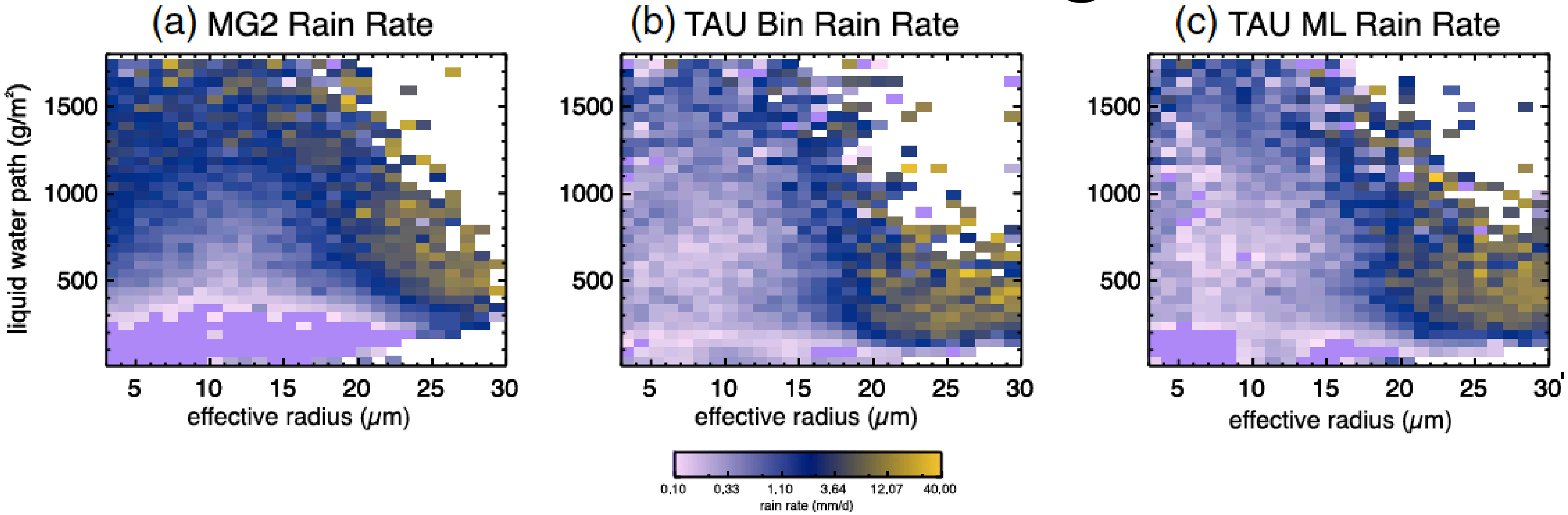


Gettelman et al 2021, JAMES

Improving results with Machine Learning

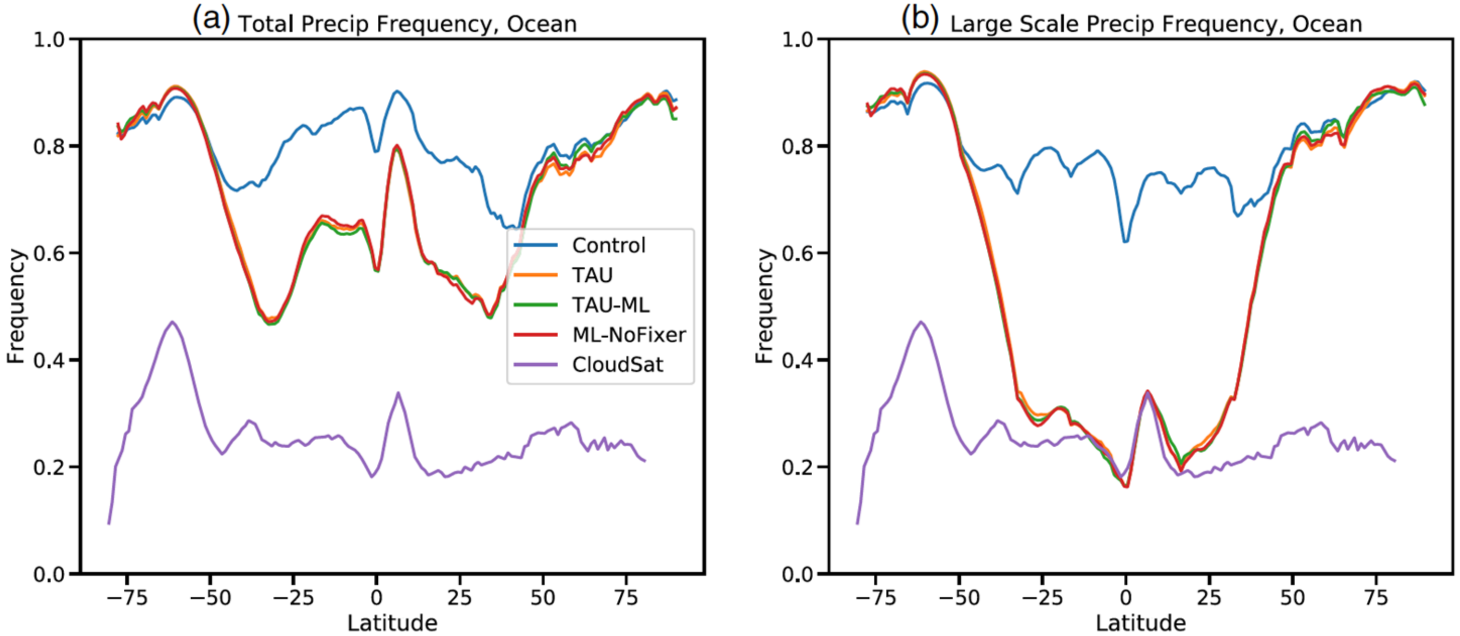
Replace autoconversion and accretion in a bulk scheme with stochastic collection with a bin scheme. Then emulate that with a neural network.

Reduces rain rate for small drop sizes but large LWP



Precipitation Frequency

Control v. **Observations** and
Bin precipitation and **ML Emulator.**
Using stochastic collection from a bin scheme improves large scale precipitation frequency in shallow clouds



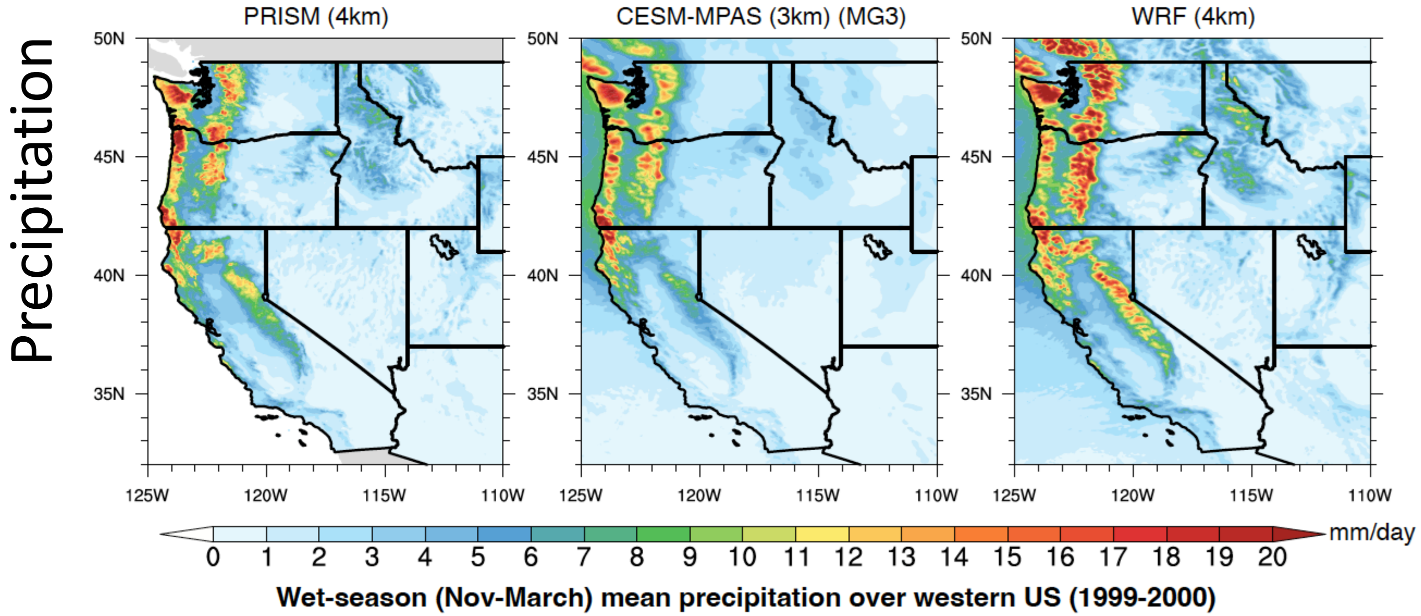
Gettelman et al 2021, JAMES

Climate Extremes: Variable-Resolution (60→3 km)

- Global Model: CESM-MPAS: 3km regional, non-hydrostatic dynamics.
- Regional climate model: WRF (CONUS) 4km (Rasmussen et al., 2021)

W. USA Wet-season (Nov-Mar) precip (5yrs)

- CESM-MPAS results compare well to obs
- Smaller biases than WRF mesoscale model



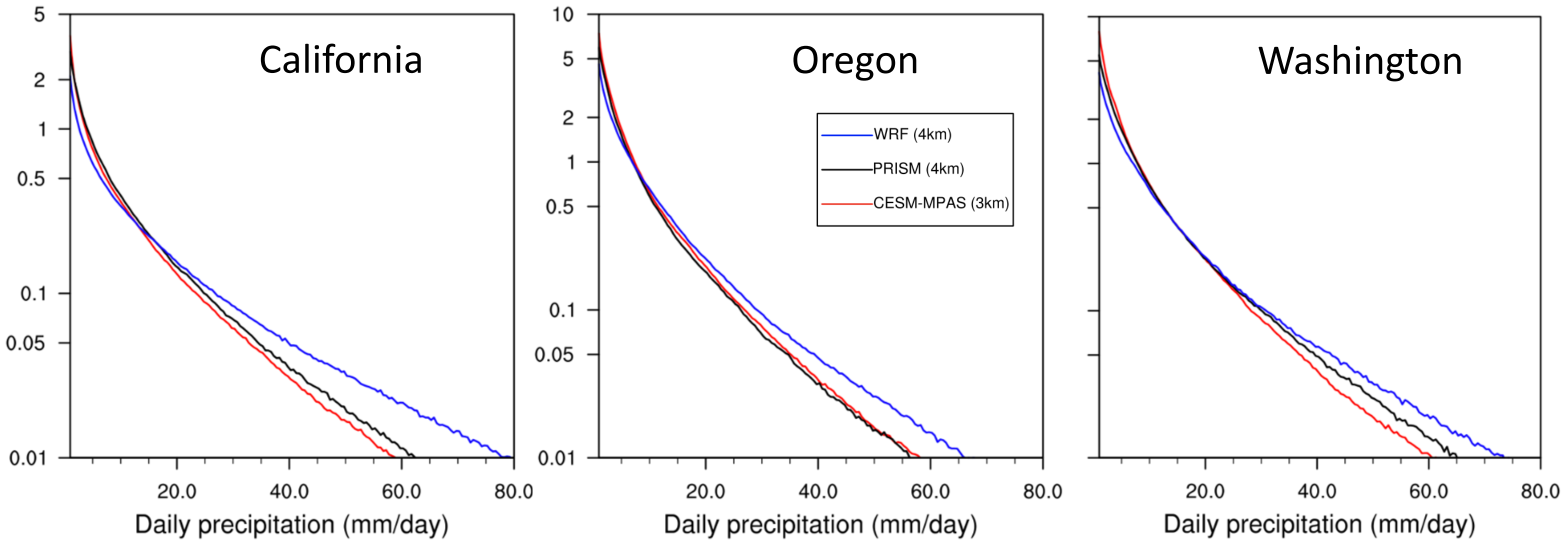
Daily precipitation Intensity PDF

4km Mesoscale Model (WRF)

3km Global Model (CESM)

4km Observations

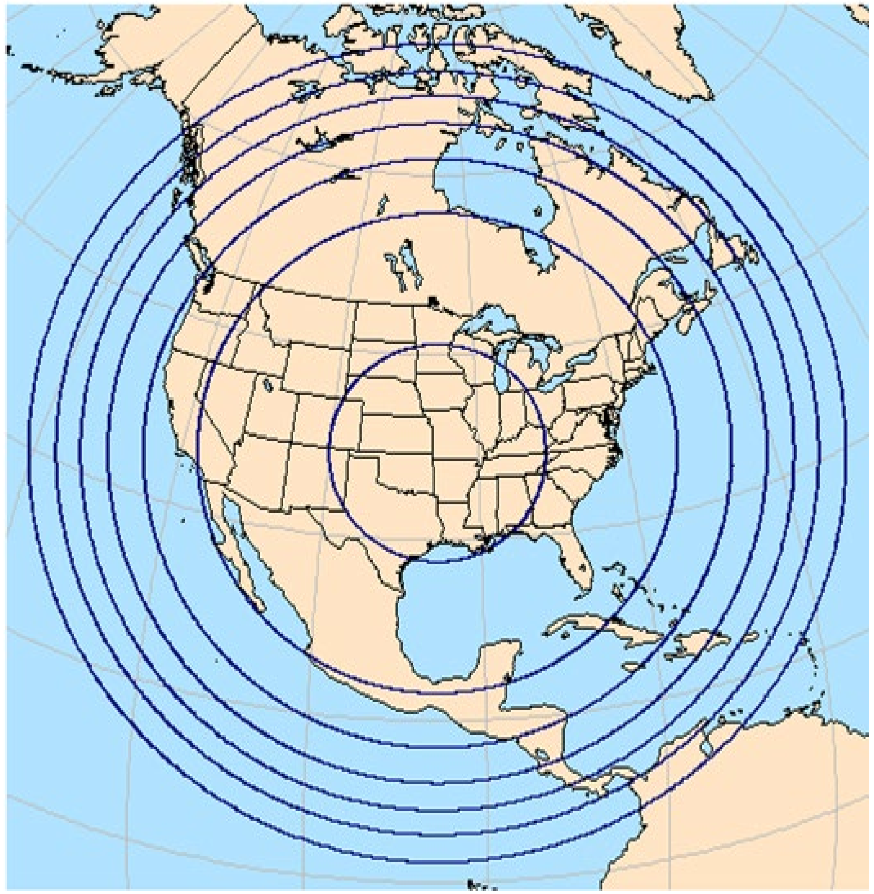
CESM captures **observed PDF** better than **WRF**, especially for extreme precipitation

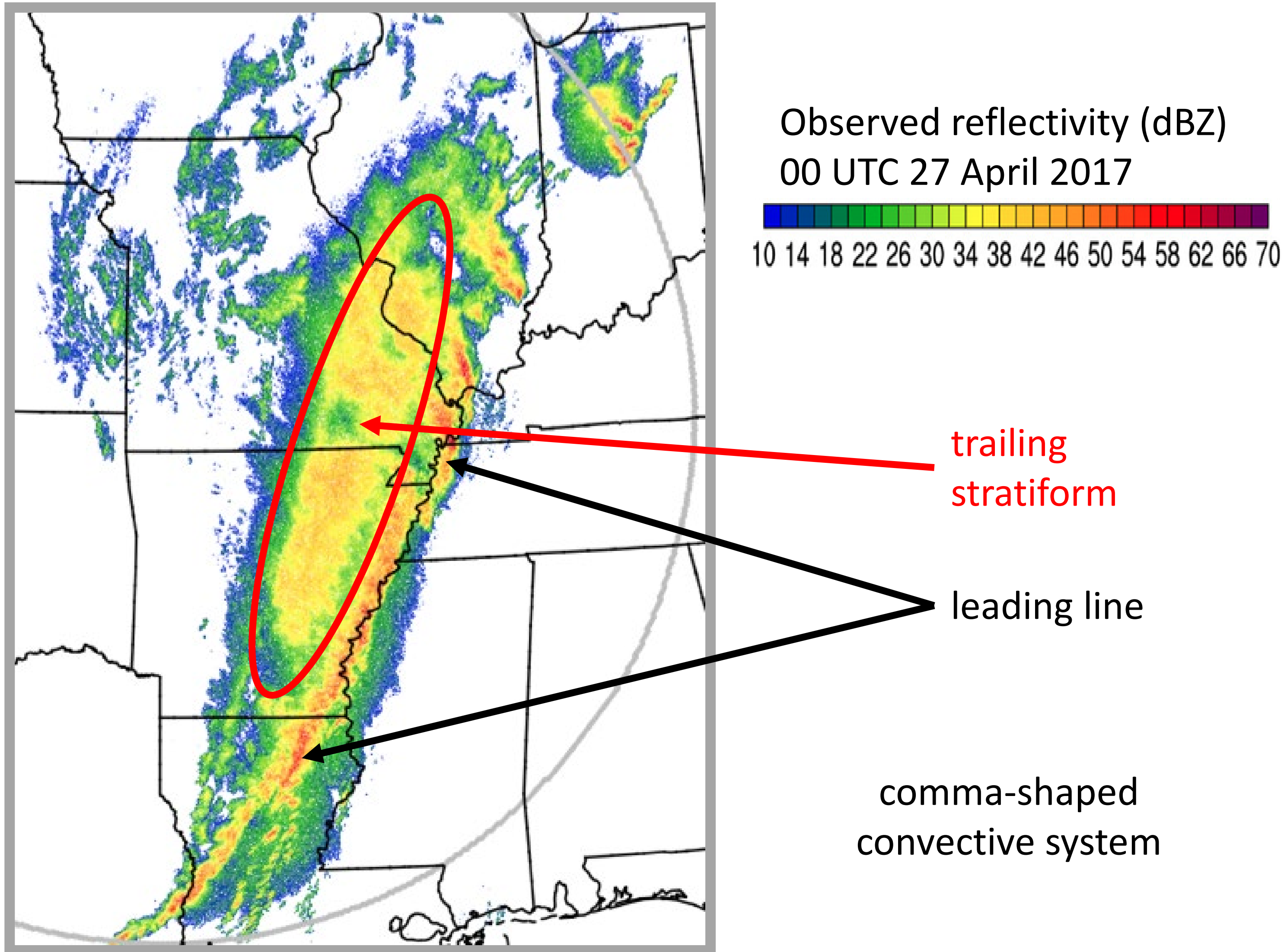


X. Huang, NCAR

Atmosphere Testing
MPAS - CAM6 physics at convection-permitting scales
Central US spring test case, 24 hour forecast

0 UTC 26 April 2017 initialization
60-3 km variable-resolution mesh



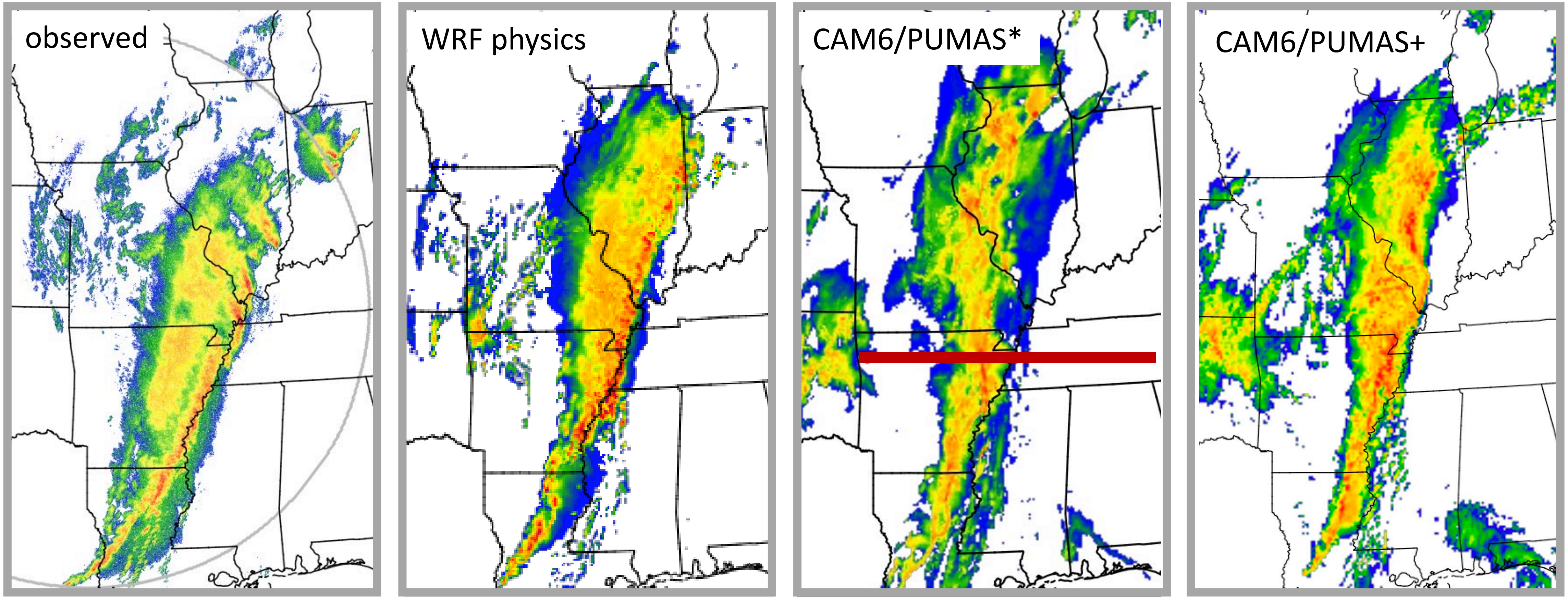


comma-shaped convective system

Central US: initial results

- Central US Summertime squall line. 24 hour forecast valid 0 UTC 27 April 2017
- Mesoscale model v. Climate Model

(* Computed using single-moment reflectivity diagnostic)



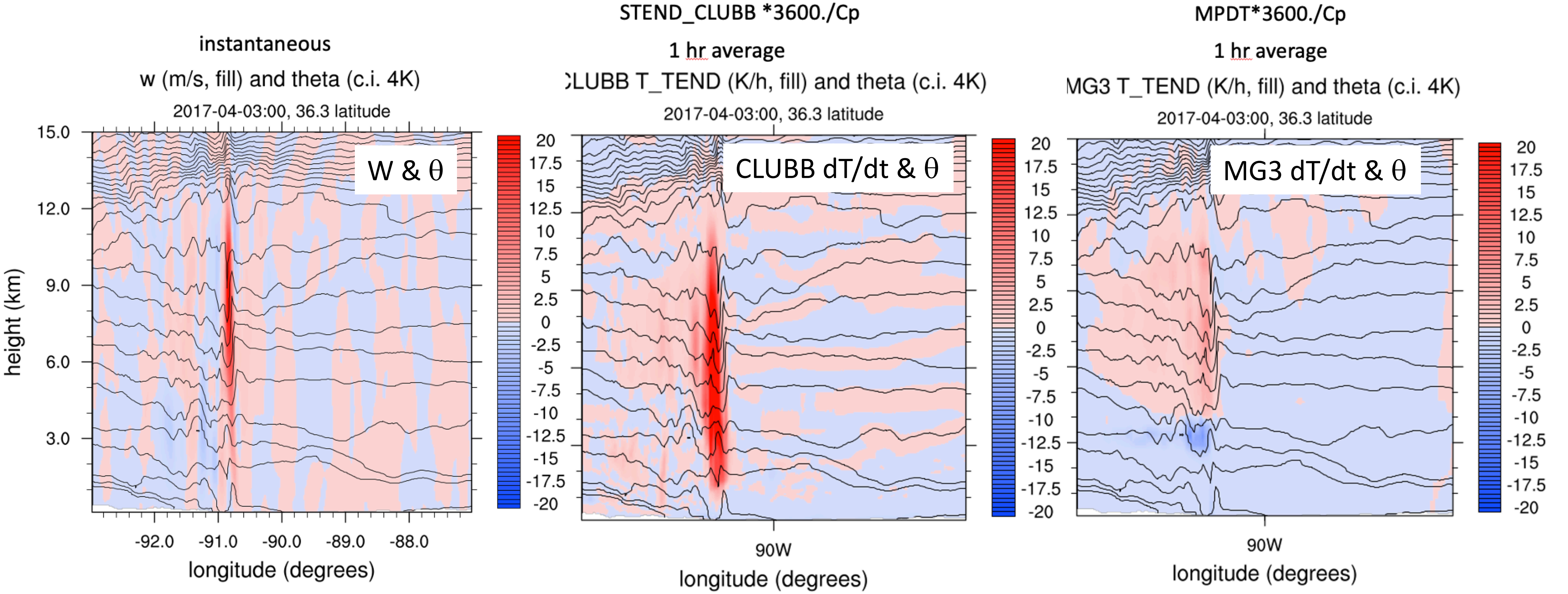
Reflectivity (dBZ) 10 14 18 22 26 30 34 38 42 46 50 54 58 62 66 70

CAM6+Graupel

Collapsed PDFs in CLUBB's saturation adjustment

M. Chen, W. Skamarock, X. Huang, NCAR

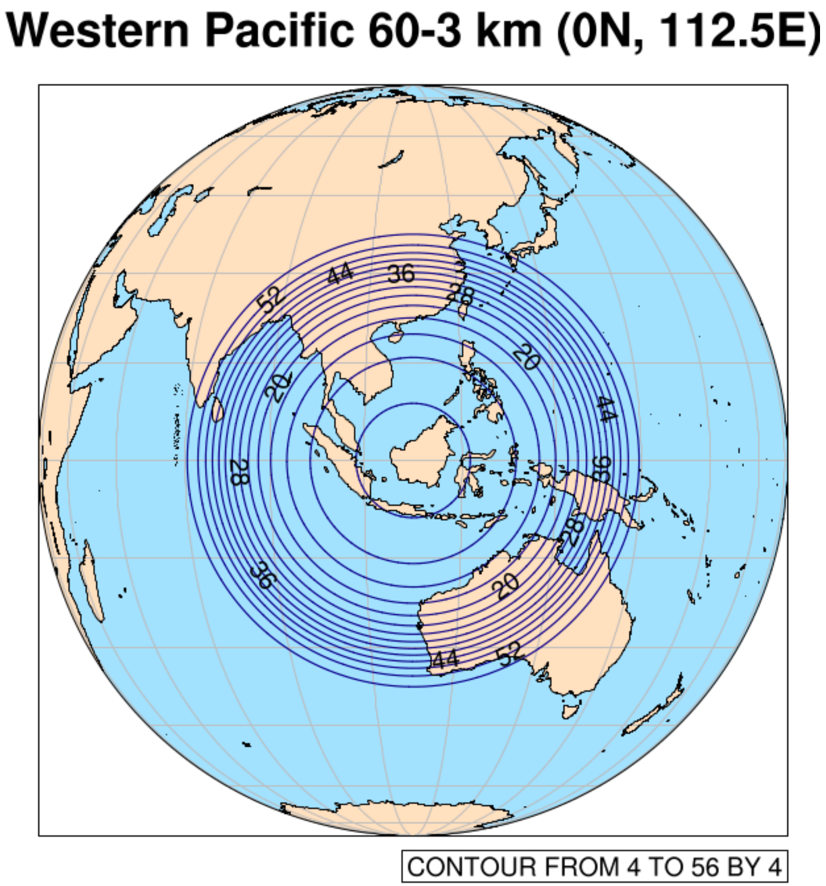
Instantaneous outputs across squall line

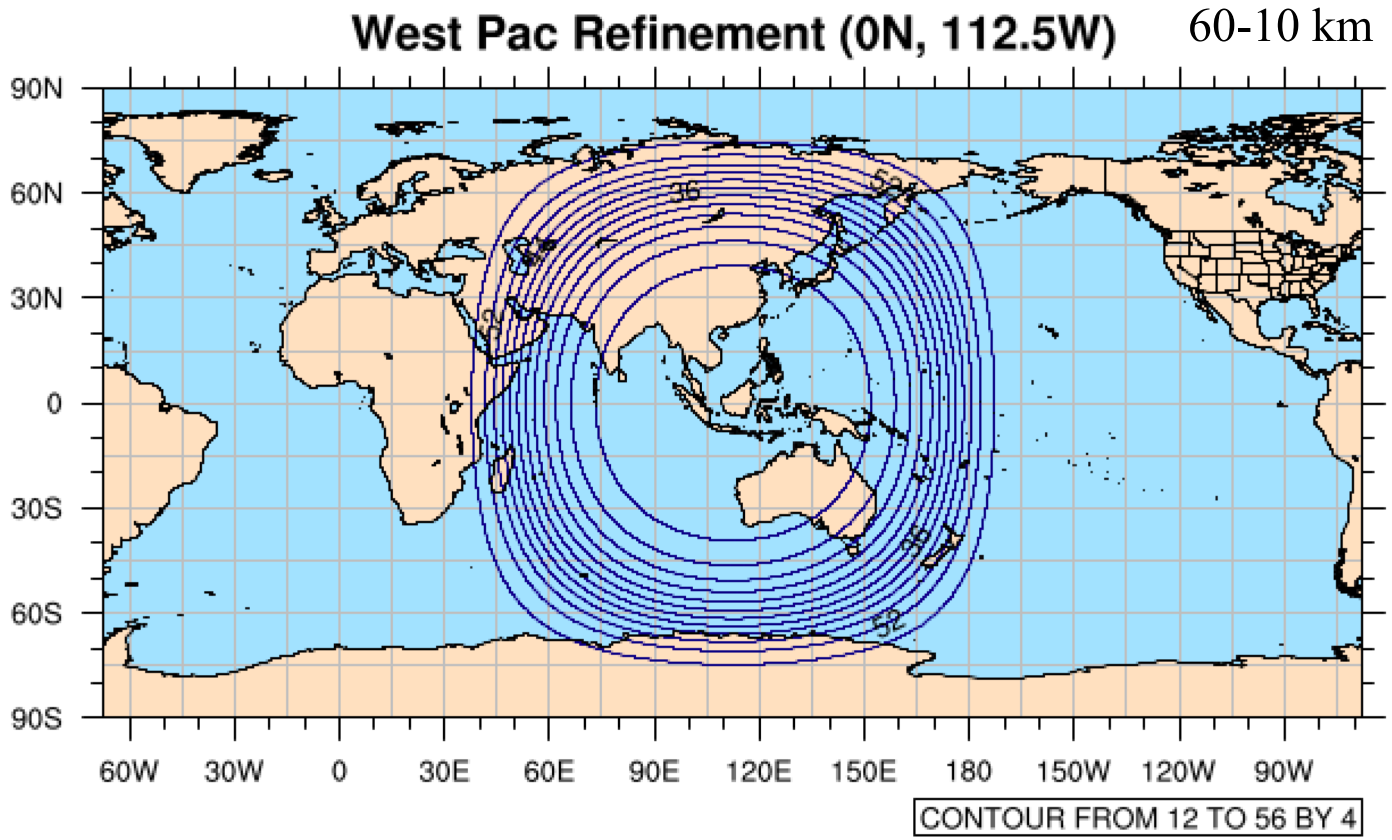


Issue: CLUBB seems to be doing a lot here.

After some discussion: remove ‘partial cloudiness’ (collapse PDF) in CLUBB saturation adjustment calculation

Western Pacific Cases





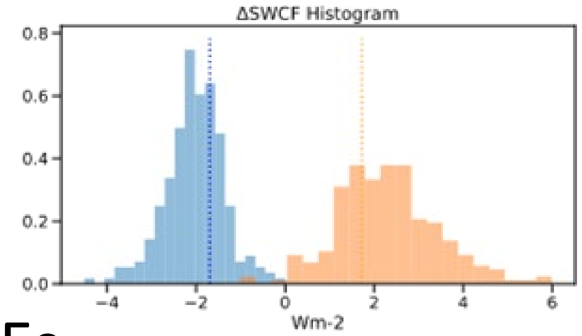
Western Pacific Movies…

- Looking at scales of variability
- Eastward propagating cells
- Diurnal cycles over Indonesia
- Tropical Cyclones
- Larger scale organization

Next Steps: Paths forward

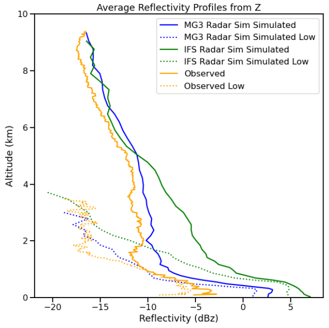
- For cloud microphysics: we can do ‘seamless’ (100km→3km)
  - Requires some complexity (rimed ice)
  - Working on modifications to physics
  - Exploring regime by regime in refined (regional) simulations
- Rain formation is critical, we need to do it better
  - Frequency, Intensity of precipitation
  - Aerosol forcing/response
  - May want to ‘emulate’ detailed models: microphysics is a good candidate
- ‘Simplify’ schemes
  - Unified ice/snow desirable
  - Think about also learning model structure (size distributions, process rates)
  - Emulators to help constrain process rates (objective adjustments)
- Cloud Phase still important
  - Requires improved knowledge of aerosols
- Couple the physics and dynamics
  - May be necessary at large scales. Where is microphysics gray zone?
  - Gray zone for activation, evaporation, coupling with turbulence

Future Work: Where does it all go?

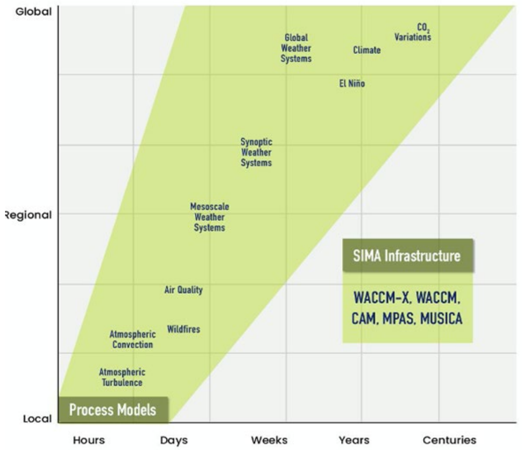


- Better uncertainty quantification (parameters, processes): PPEs

- Model-data fusion, using observations

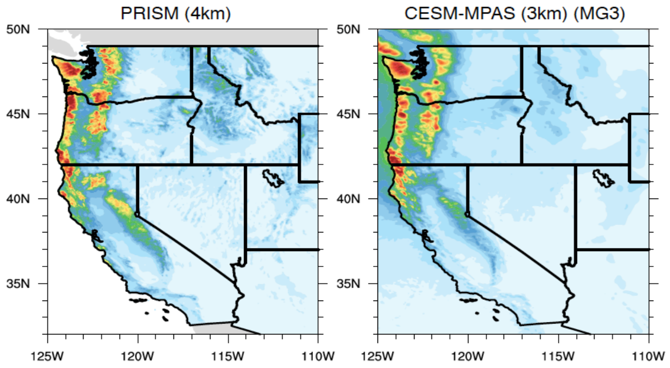


- Crossing scales (LES--> Global)

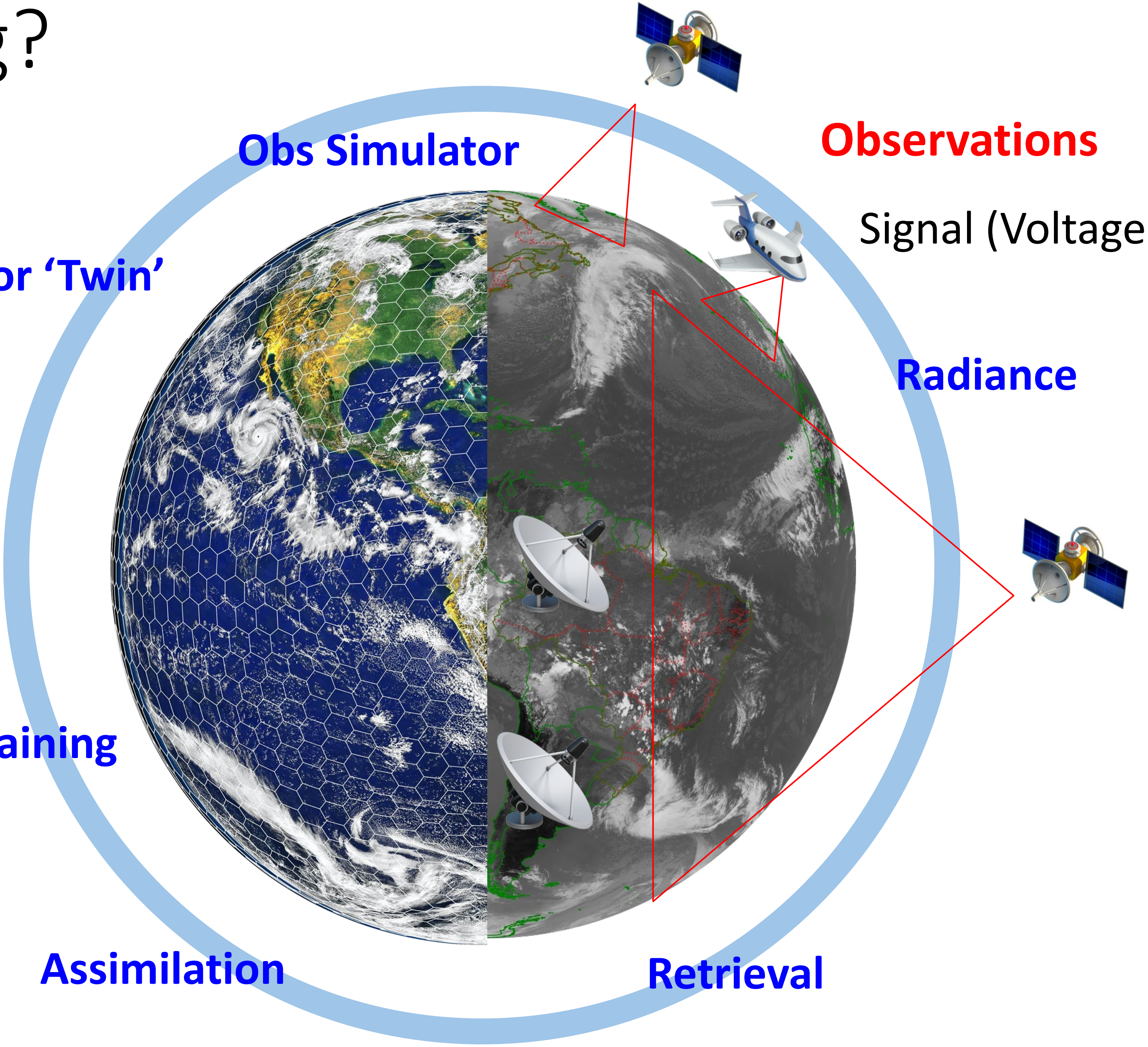


- New modeling capabilities with refined ESMs and with global km scale models

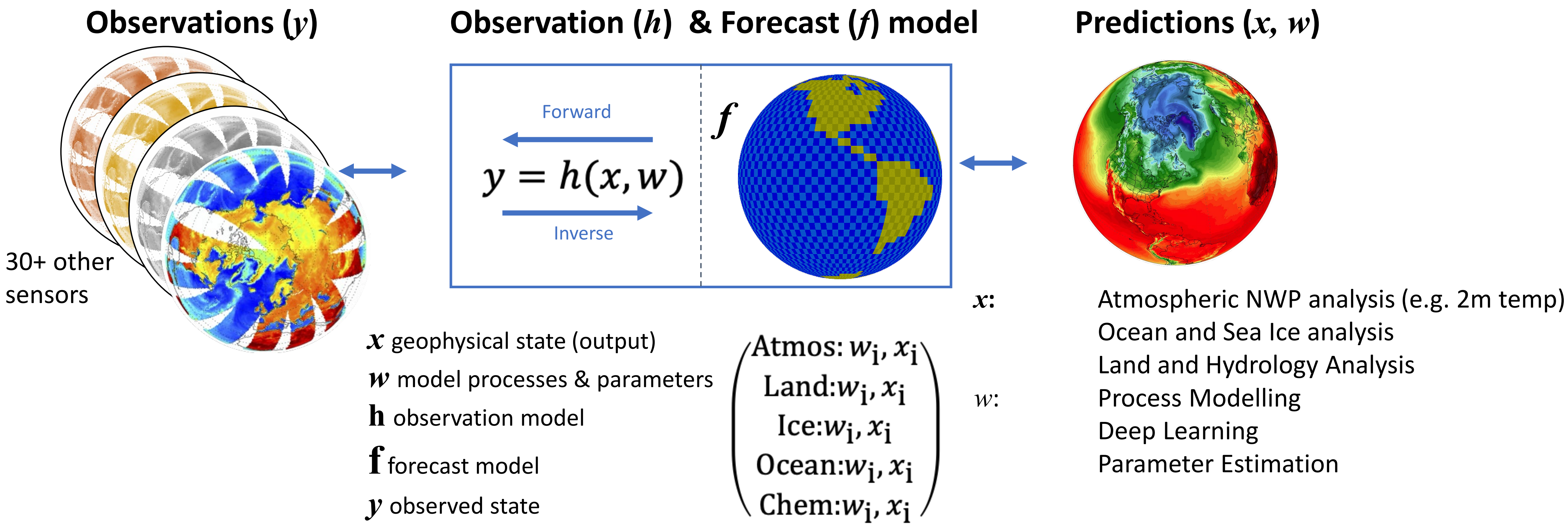
- Machine learning/emulators:
New tools, but still need understanding



Where is it all going?
Model-Data Fusion



Gettelman et al 2022, Science Advances
(With Forbes, Geer et al)



Observations (y)
Observation (h) & Forecast (f) model
Predictions (x, w)
30+ other sensors
Forward
$y = h(x, w)$
Inverse
f
x geophysical state (output)
w model processes & parameters
h observation model
f forecast model
y observed state
Atmos: w_i, x_i
Land: w_i, x_i
Ice: w_i, x_i
Ocean: w_i, x_i
Chem: w_i, x_i
x:
w:
Atmospheric NWP analysis (e.g. 2m temp)
Ocean and Sea Ice analysis
Land and Hydrology Analysis
Process Modelling
Deep Learning
Parameter Estimation