A New Perspective on Model Data Fusion for Improving Climate models: Especially clouds

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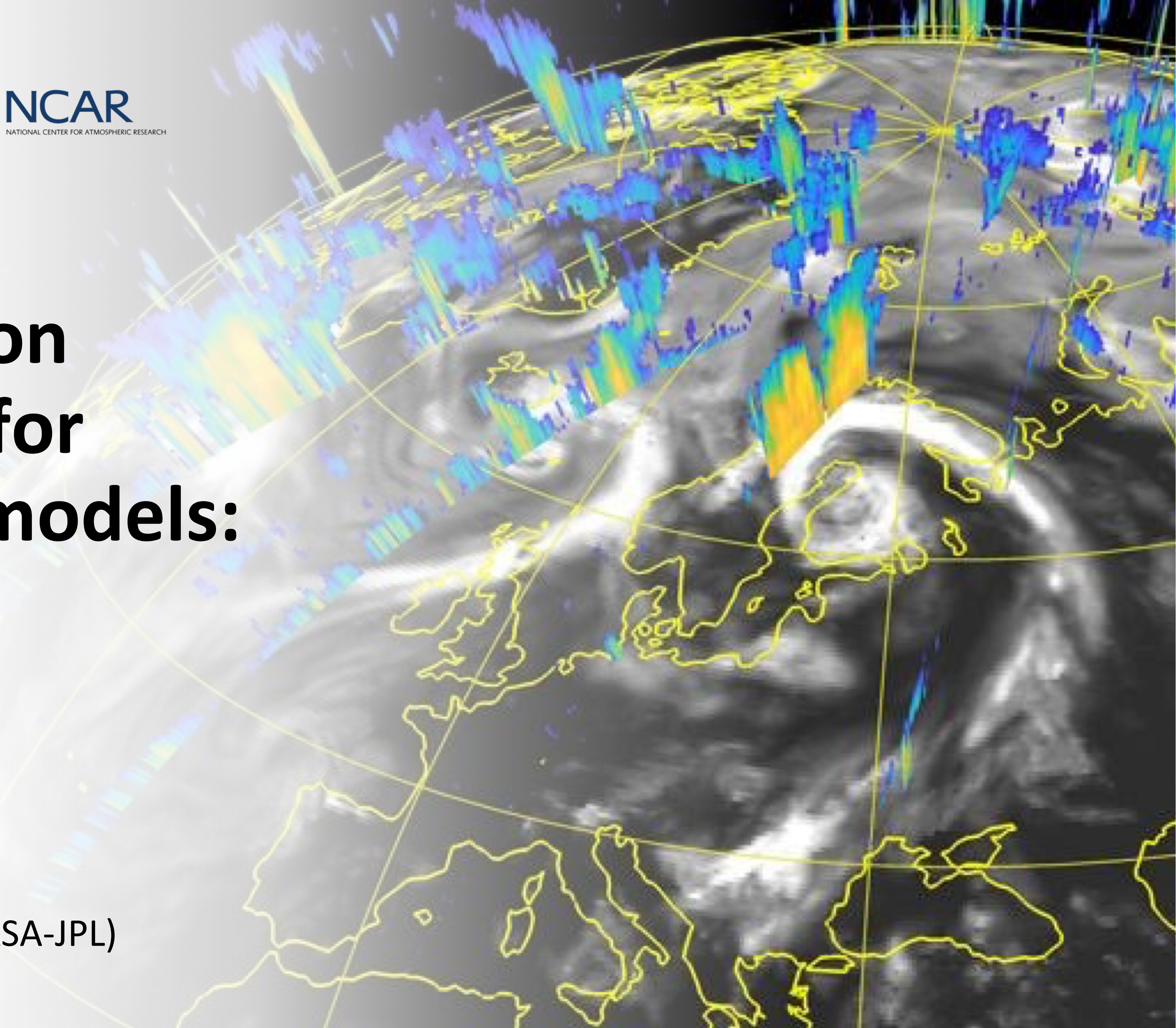
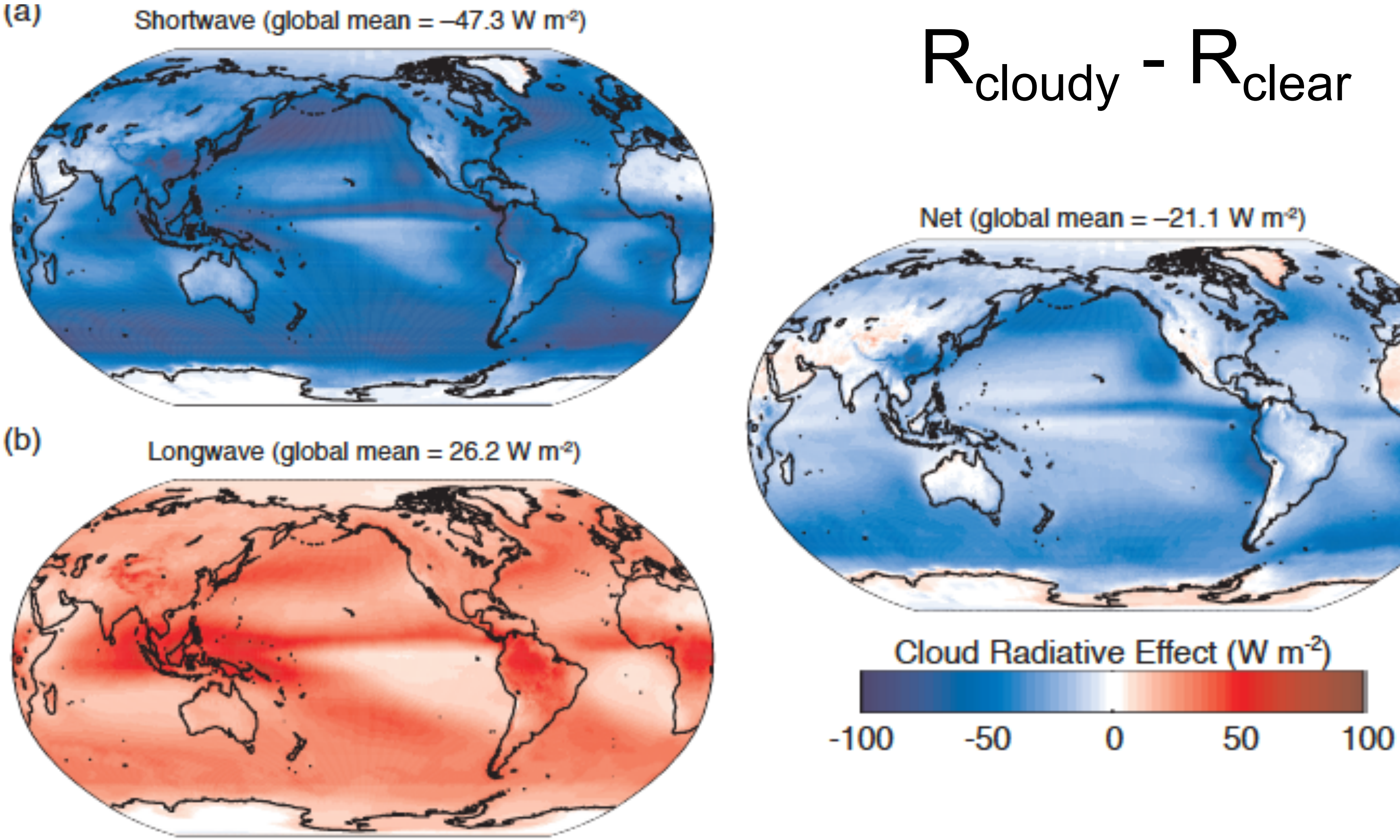


Mark Fielding, ECMWF Newsletter

Climate: Cloud Radiative Effects are Large

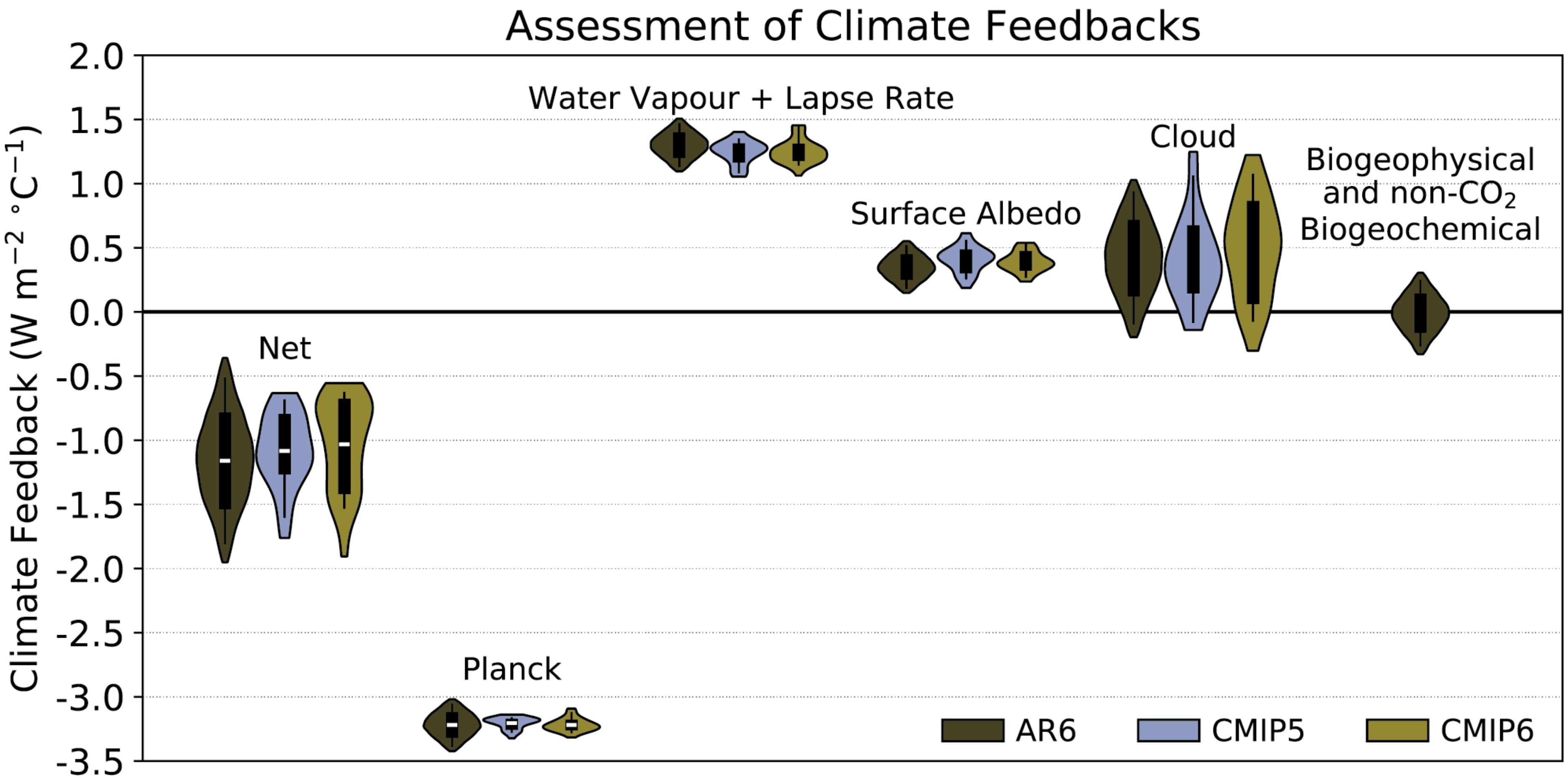
$R_{cloudy} - R_{clear}$



IPCC 2013 (Boucher et al 2013) Fig 7.7

Climate Feedbacks

Climate Sensitivity Uncertainty: *It's all about cloud feedback*



σT^4 $\Delta[H_2O]_v$ ΔAlbedo

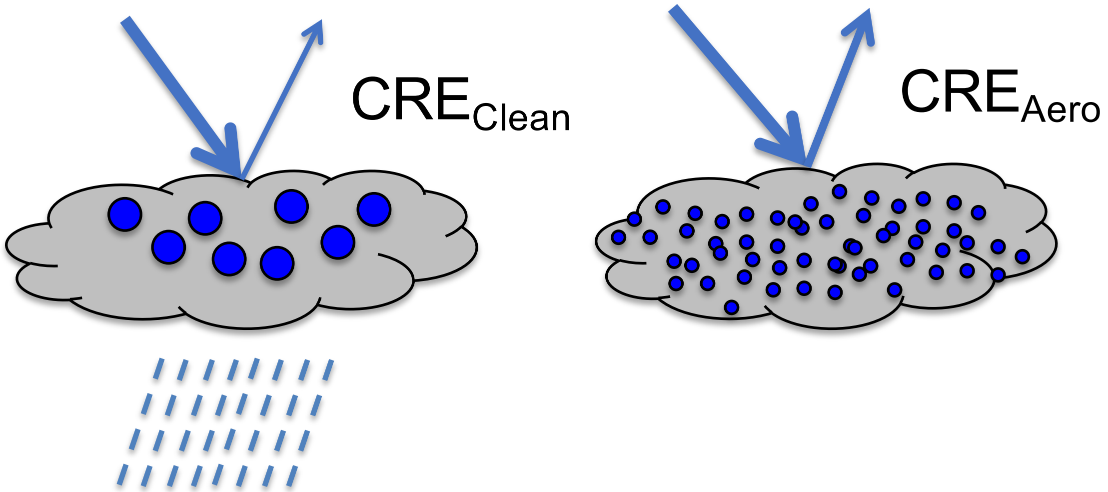
IPCC AR6 Fig 7.10

Aerosol Effects on Clouds: Climate Forcing

Scattering & Absorption = Aerosol-Radiation Interactions

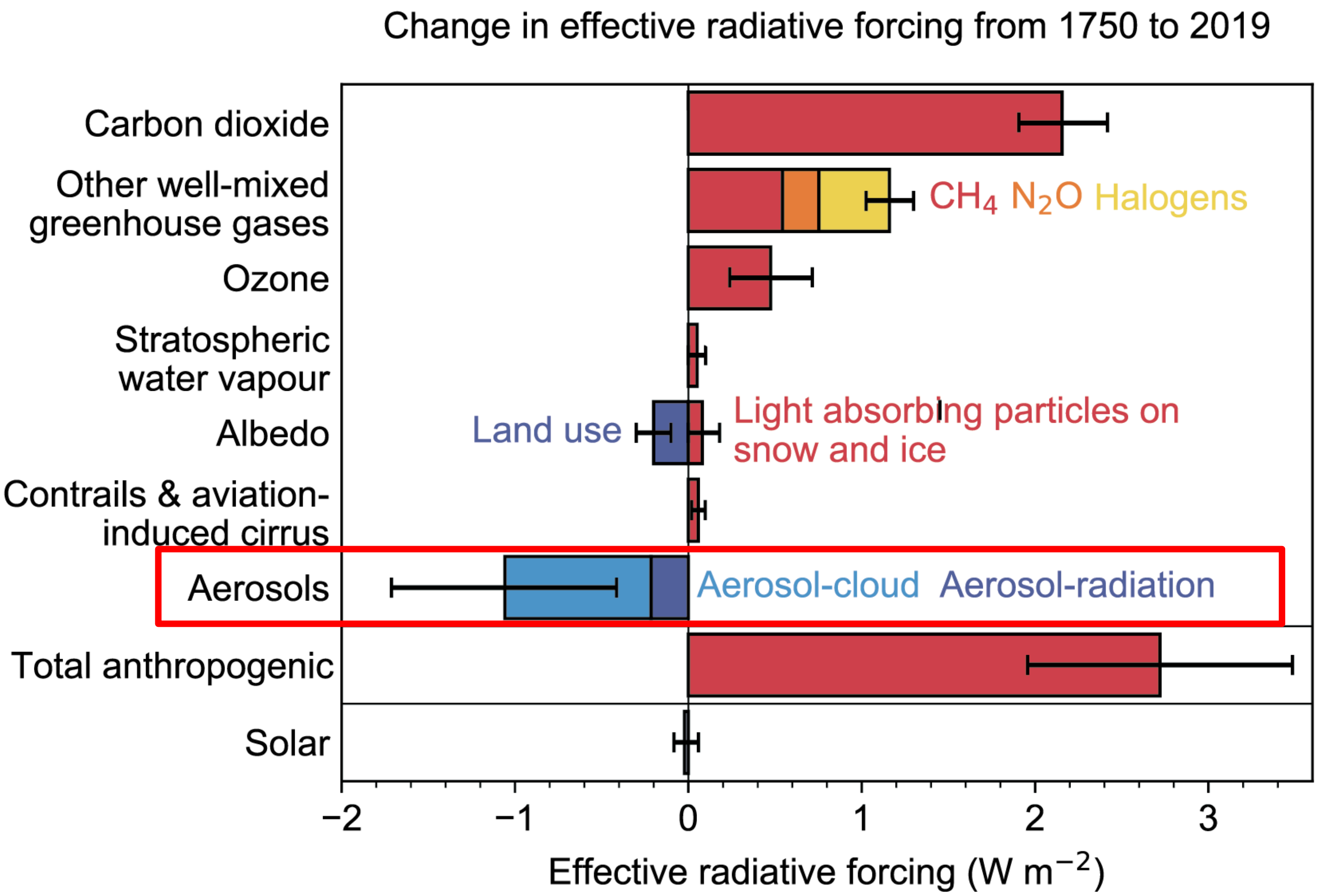
Aerosol – Cloud – Interactions (ACI)

+Aerosols → +CCN → +N_c → ΔCRE



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

Aerosol Largest Uncertainty for Climate Forcing



3.8 Wm^{-2} (2.3→4.5)

-1.1 Wm^{-2} (-1.9→-0.2)

IPCC, 2021, Fig 7.6

Outline

- Motivation: Clouds are Critical for Climate
- ESM Advancements (at any scale)
- Model-Data Comparisons with Simulators (Climate Focus)
- Machine Learning the Rain Processes
- Larger vision: Model-Data Fusion

Improving (weather, climate) predictions requires synergistic use of observations and models

Where are ESMs (GCMs) Going?

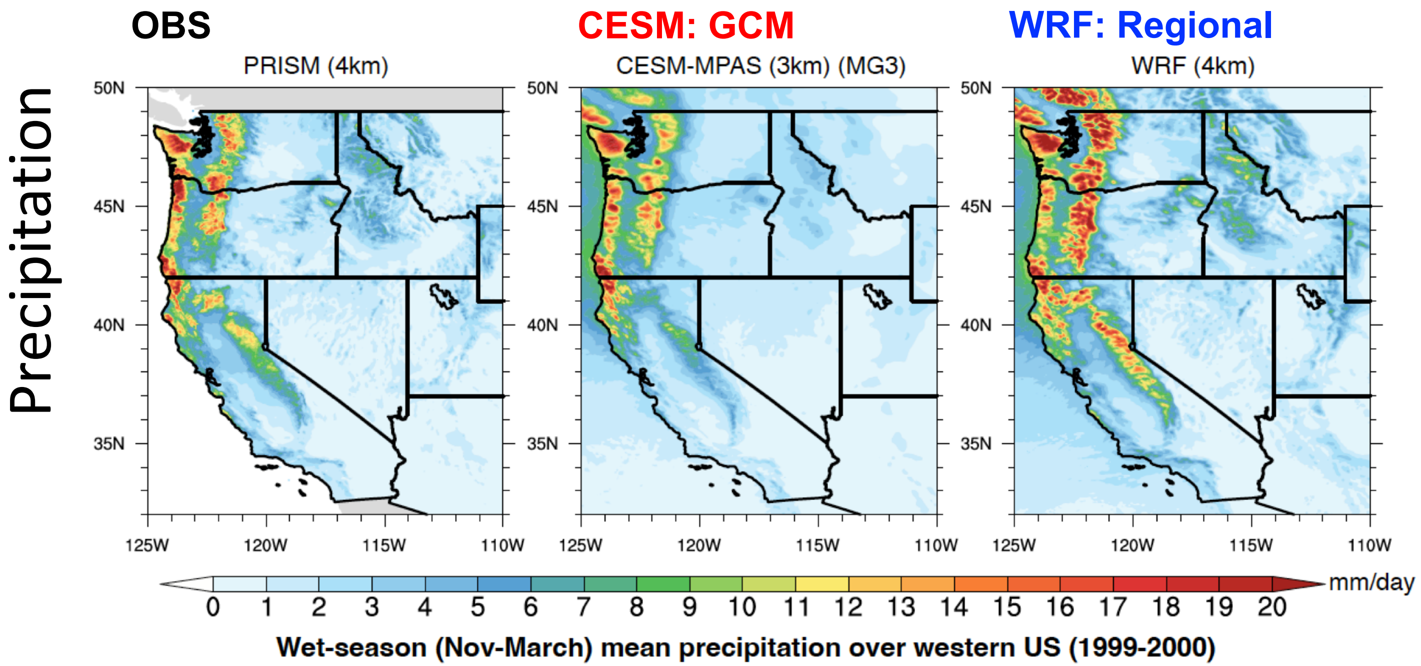
- GSRMs (e.g. uniform high resolution)
- Traceable to lower resolution Global, Regional
  - Merging with mesoscale models (especially cloud processes)
  - Scalable complexity: chemistry, aerosols, cloud processes (e.g. rimed ice)
- New methods
  - Emulators, Machine Learning (new generation of ‘empirical’ parameterizations)
- Better analysis, optimization methods
  - Nudging, Satellite Simulators
  - Data Assimilation for Climate (especially for clouds)

Climate Extremes: Variable-Resolution ESM

- Global Model: CESM-MPAS: 60→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



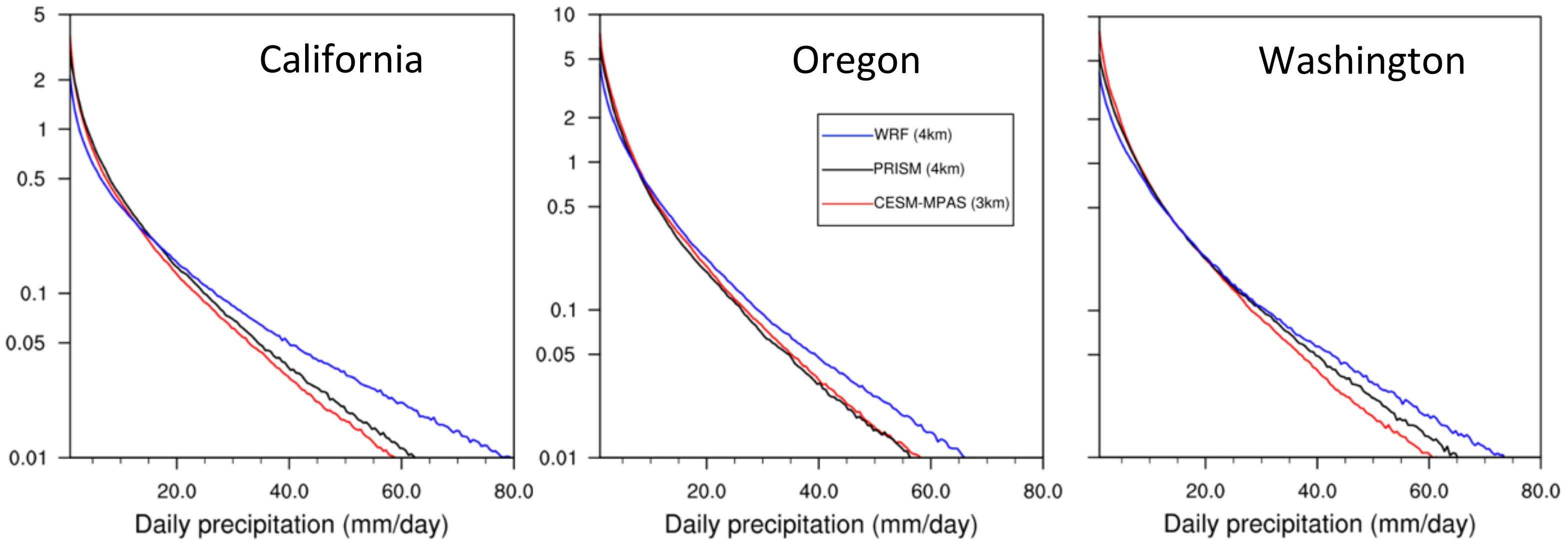
Daily precipitation Intensity PDF

4km Mesoscale Model (WRF)

3km Global Model (CESM)

4km Observations

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



Huang et al, 2022, GMD

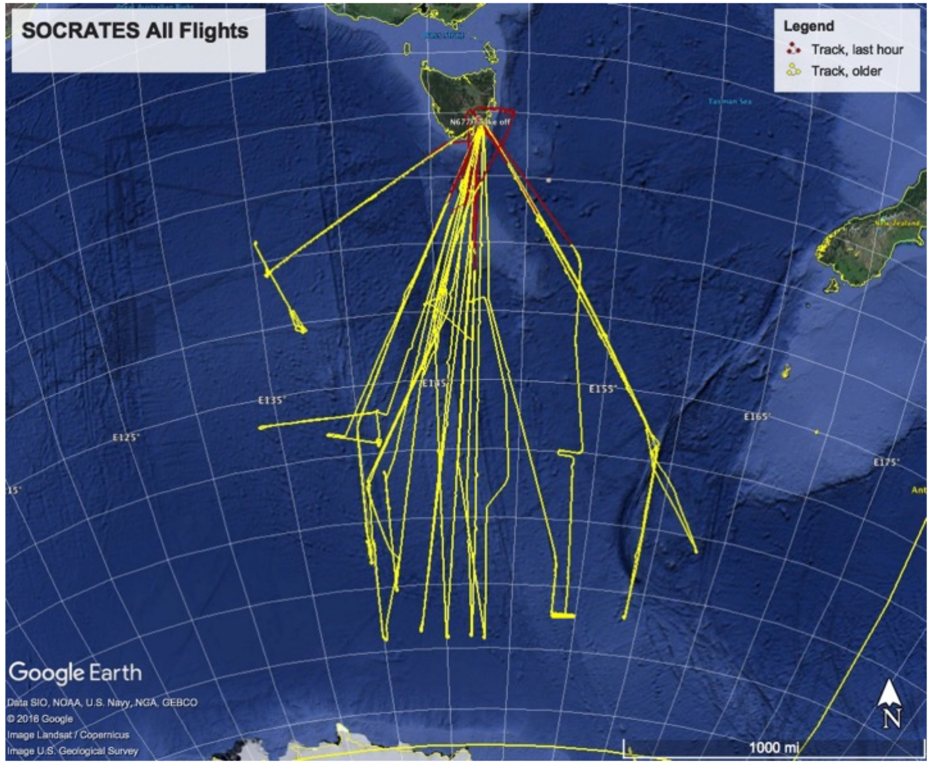
Major Climate Issues for Clouds & Precipitation

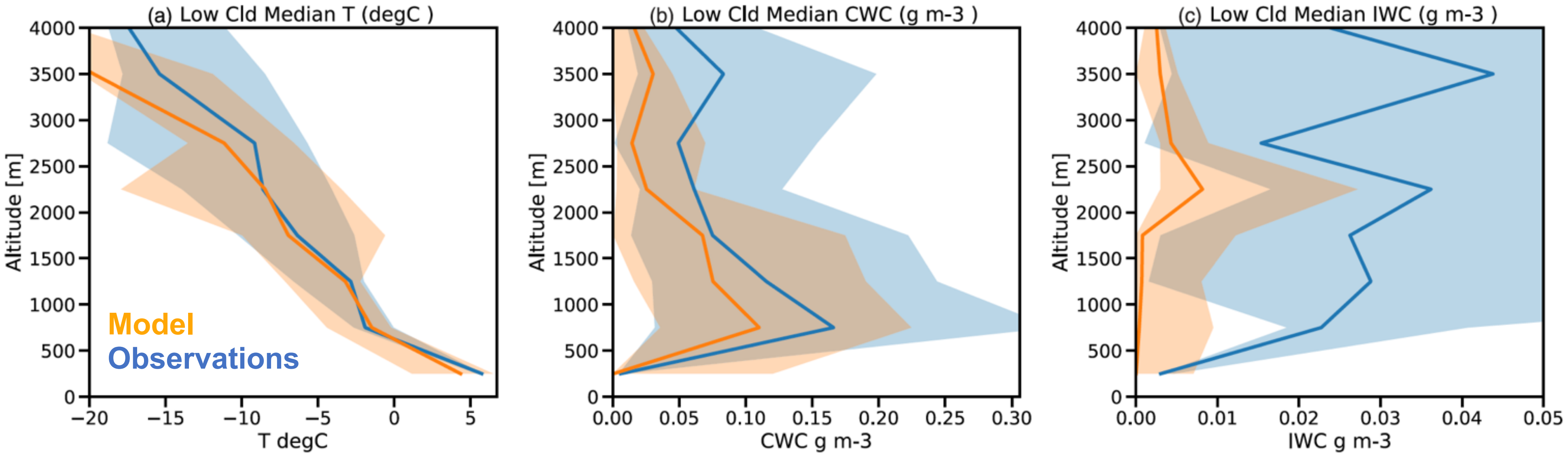
- Cold Cloud Phase:
  - Critical for high latitude radiative effects, cloud feedbacks, weather extremes
- Cloud Microphysics:
  - Size distributions govern process rates
  - Cross scale convective processes
- Dynamics-Microphysics coupling
  - Vertical structure of clouds: cloud base, freezing, entrainment at top
  - Vertical velocity critical for activation (Aerosol-Cloud Interactions)
- Precipitation Formation: Frequency & Intensity
- Convective organization across scales

Cloud Phase

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

CESM2-CAM6: Too little ice. This contributes to high climate sensitivity.



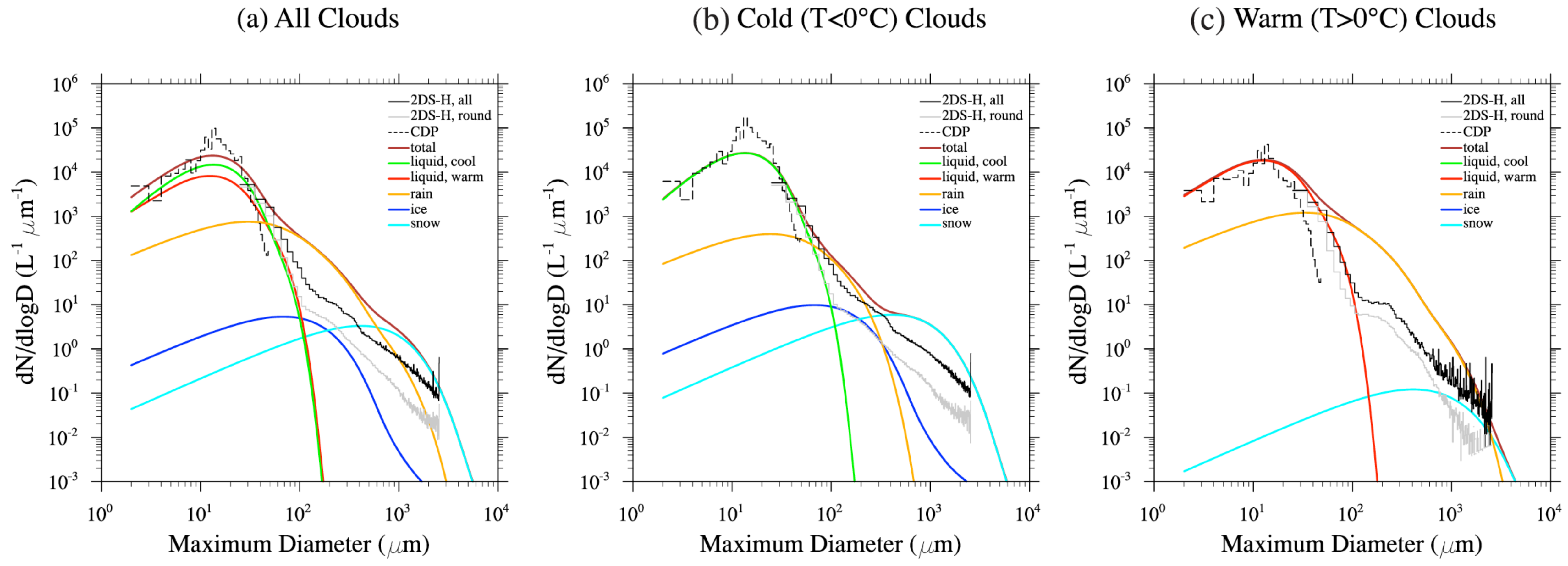


Gettelman et al 2020

Microphysics, Size distributions

- Advanced GCMs/GSRMs can be compared directly to cloud microphysical size distributions
- This is one type of 'instrument simulator'

Comparison of GCM (colors) cloud microphysics along aircraft flight tracks with in-situ data (black)

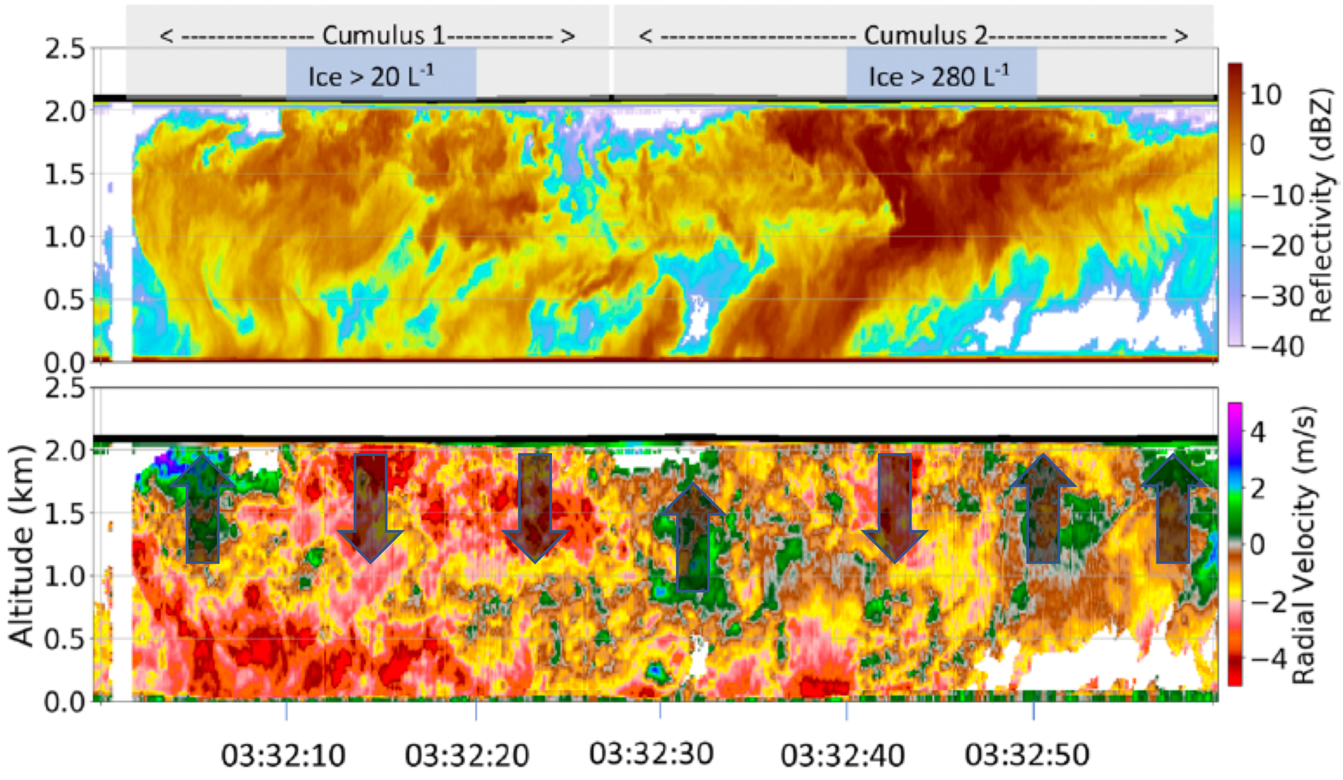


Note potential issue with too large rain sizes

Gettelman et al 2020

Cloud Dynamics & Microphysics

- Cloud dynamics (velocity) influences/controls cloud microphysics & aerosol activation
- Leads to different cloud drop/crystal number, precipitation & radiative effects
- S. Ocean SOCRATES example
- Note: GSRMs are still not ‘resolving’ these interactions

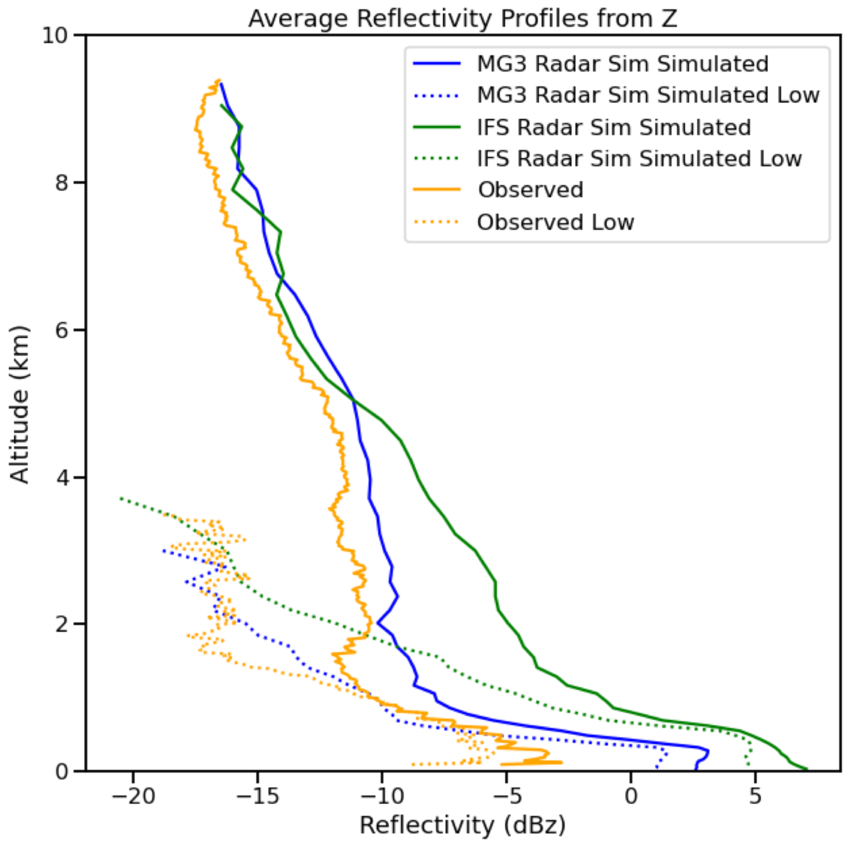


McFarquhar et al 2020

Observation Simulators

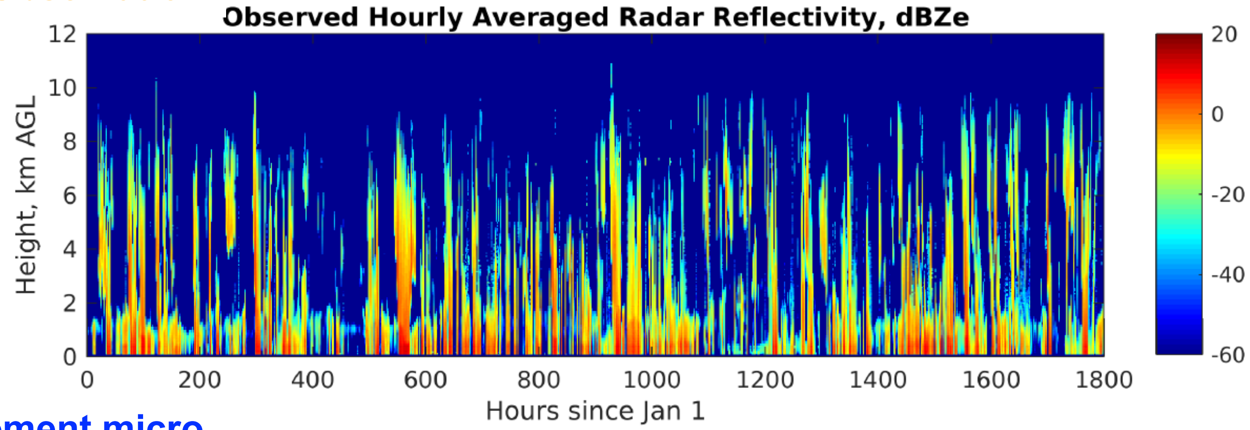
Reflectivity in the IFS-SCM

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.

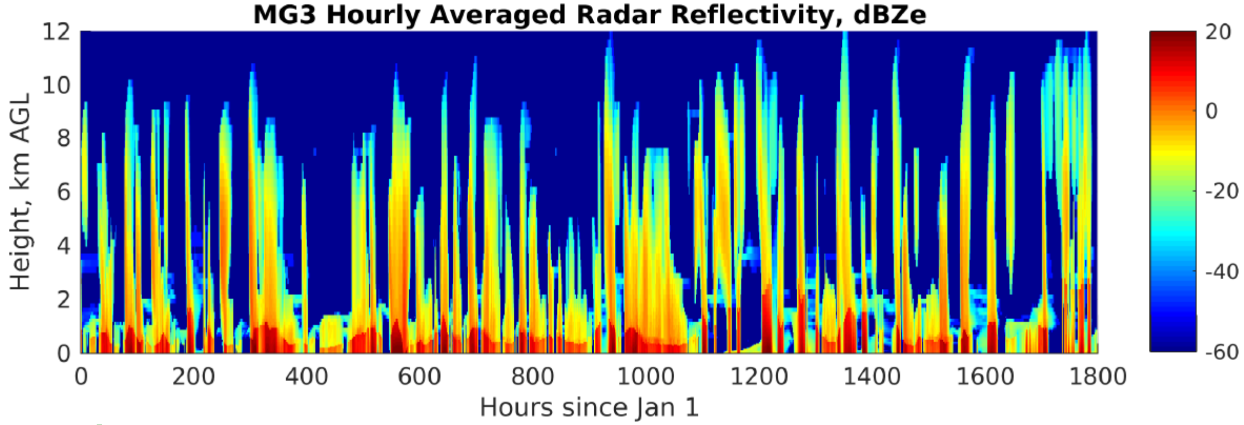


Gettelman, Forbes, Marchand, Fielding, in Prep

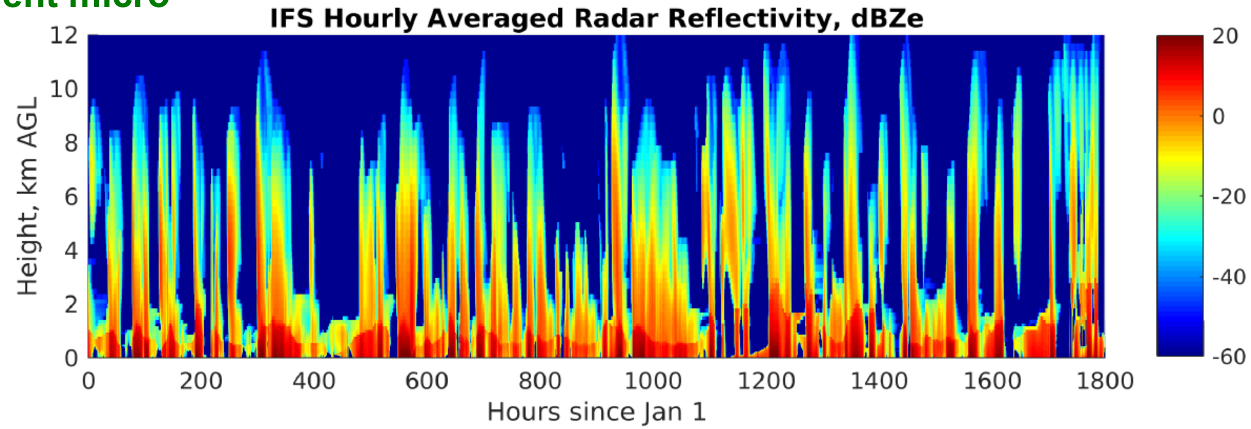
Observation



2-moment micro



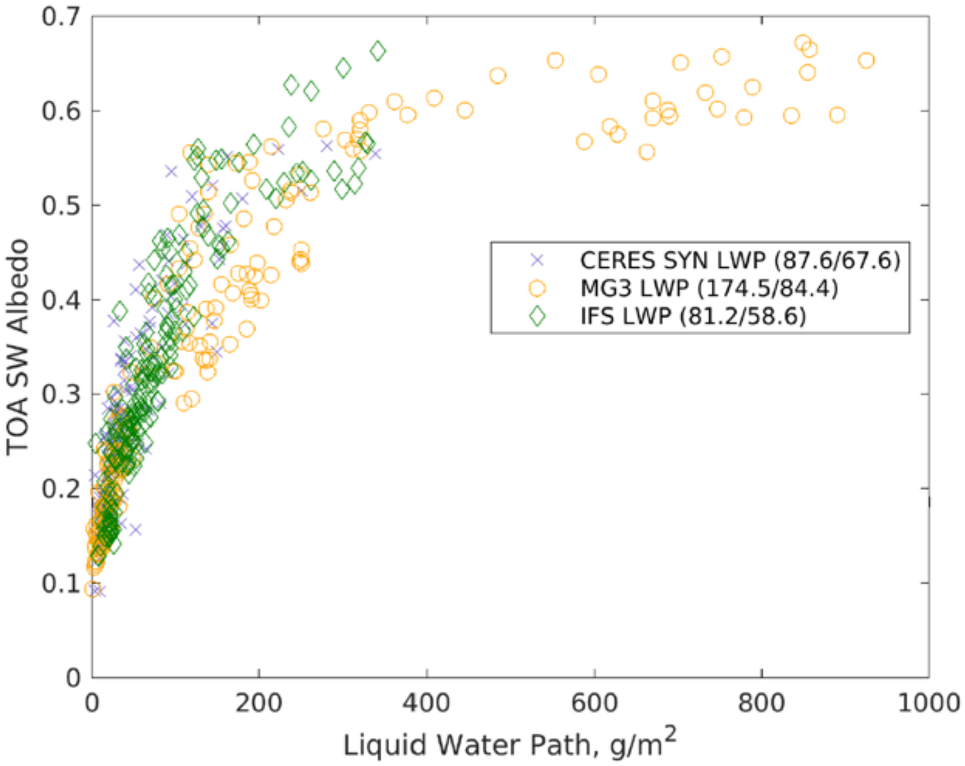
One-moment micro



Radiation Comparisons

MICRE Low Cloud Cases in IFS

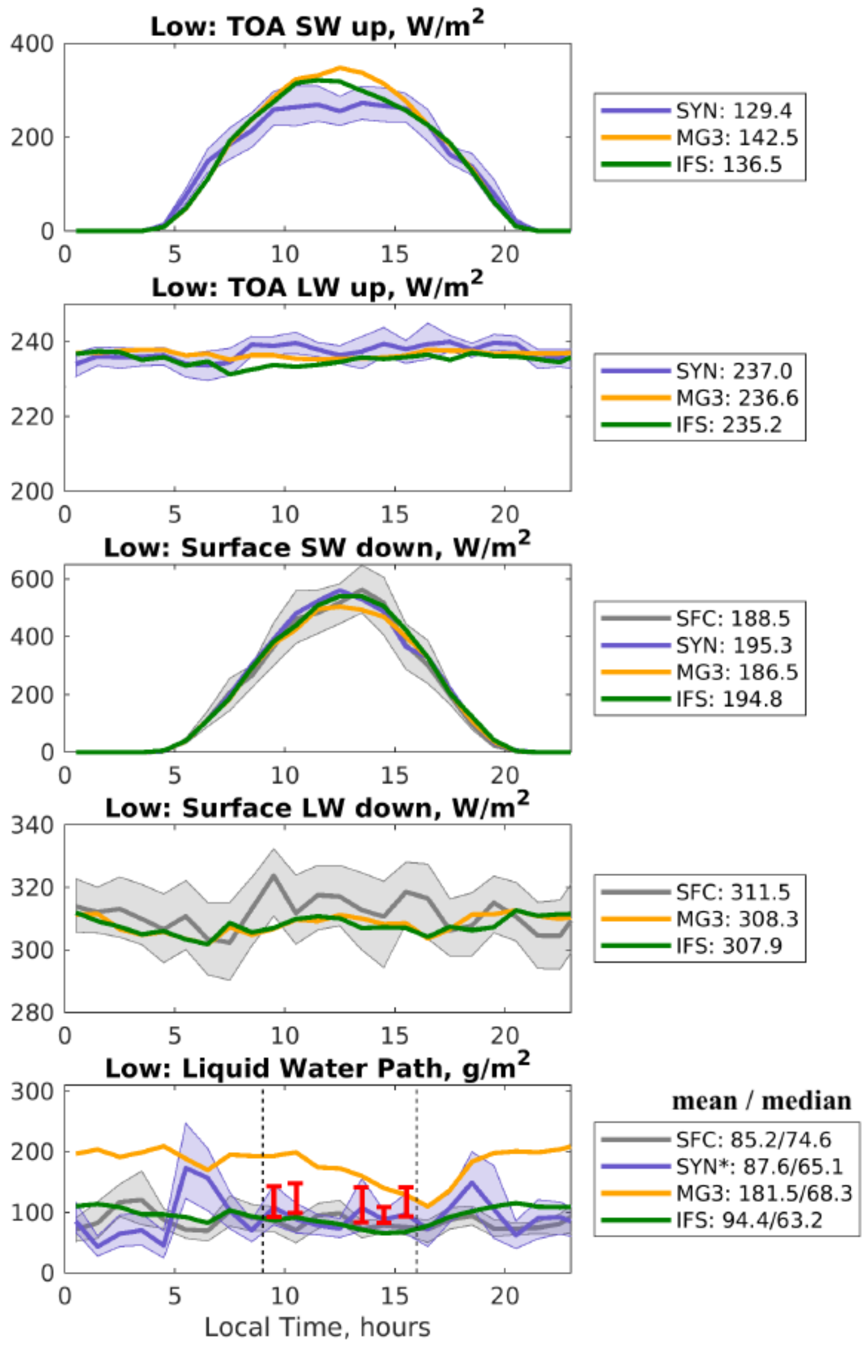
- 2-Moment Microphysics does a good job of reproducing the radiative fluxes
- Low clouds too bright at TOA, okay at surface?
- But large LWP bias!
- LWP v. Albedo saturates



Observation

2-moment micro

One-moment micro



Gettelman, Forbes, Marchand, Fielding, in Prep

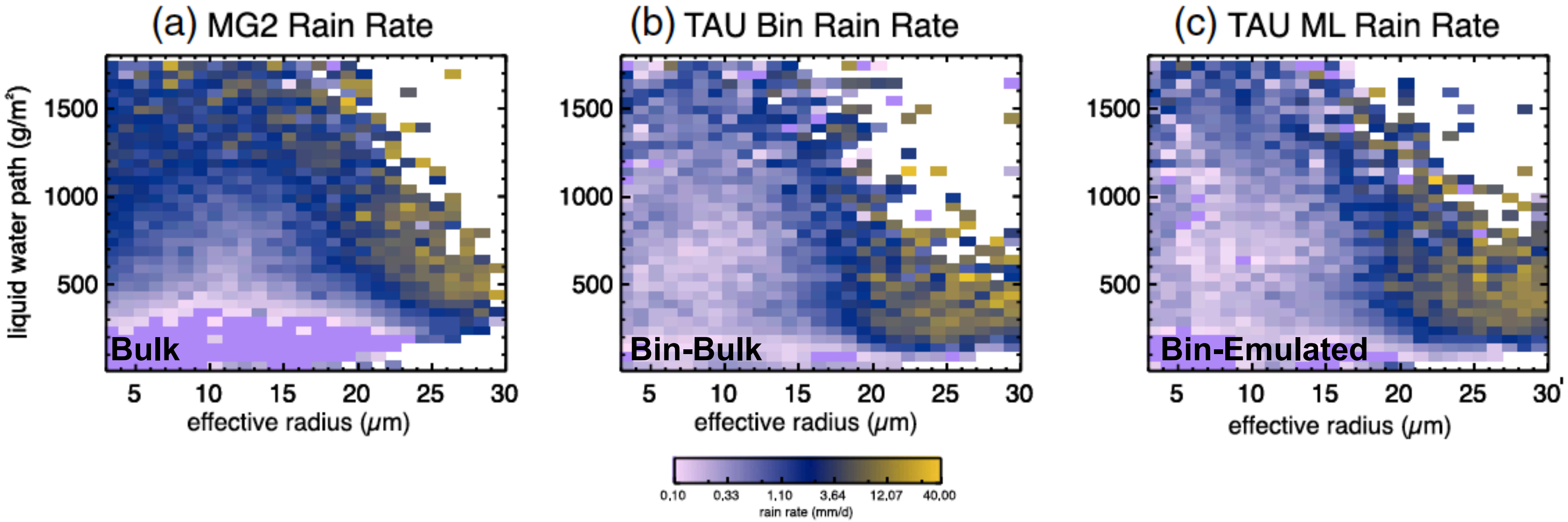
Precipitation Frequency

Improving precipitation formation with emulators

Replace rain formation (autoconversion and accretion) in a bulk cloud microphysics scheme with detailed treatment from a bin scheme (stochastic collection).

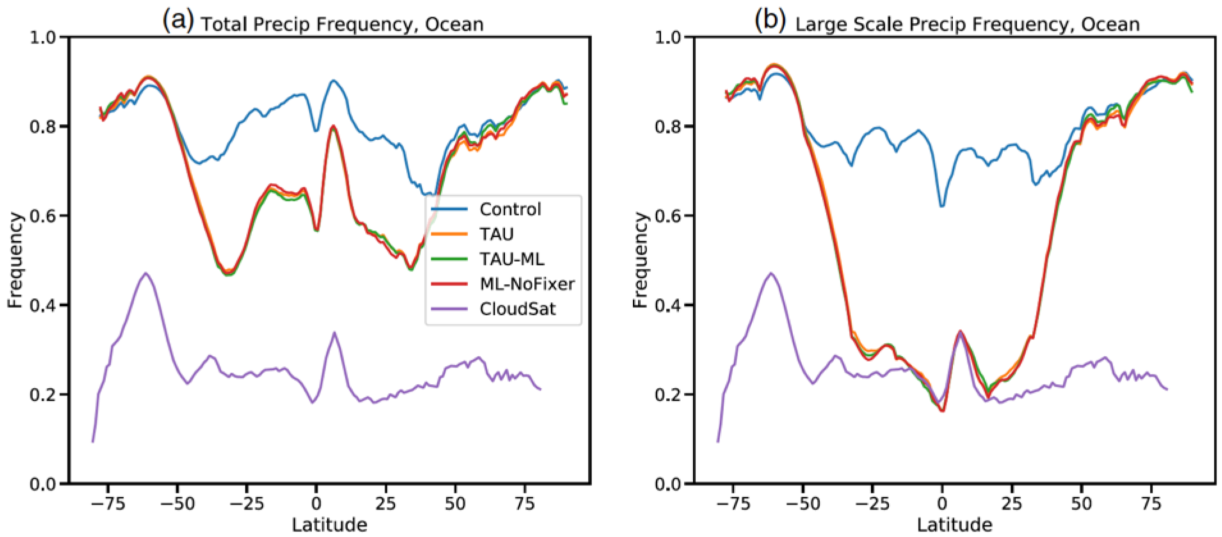
Emulate with a neural network (perfect model experiment)

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

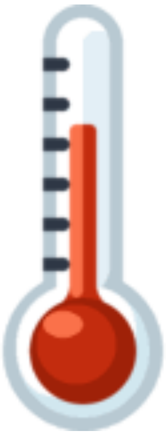


Gettelman et al 2021, JAMES

Gettelman et al 2022, Sci Advances

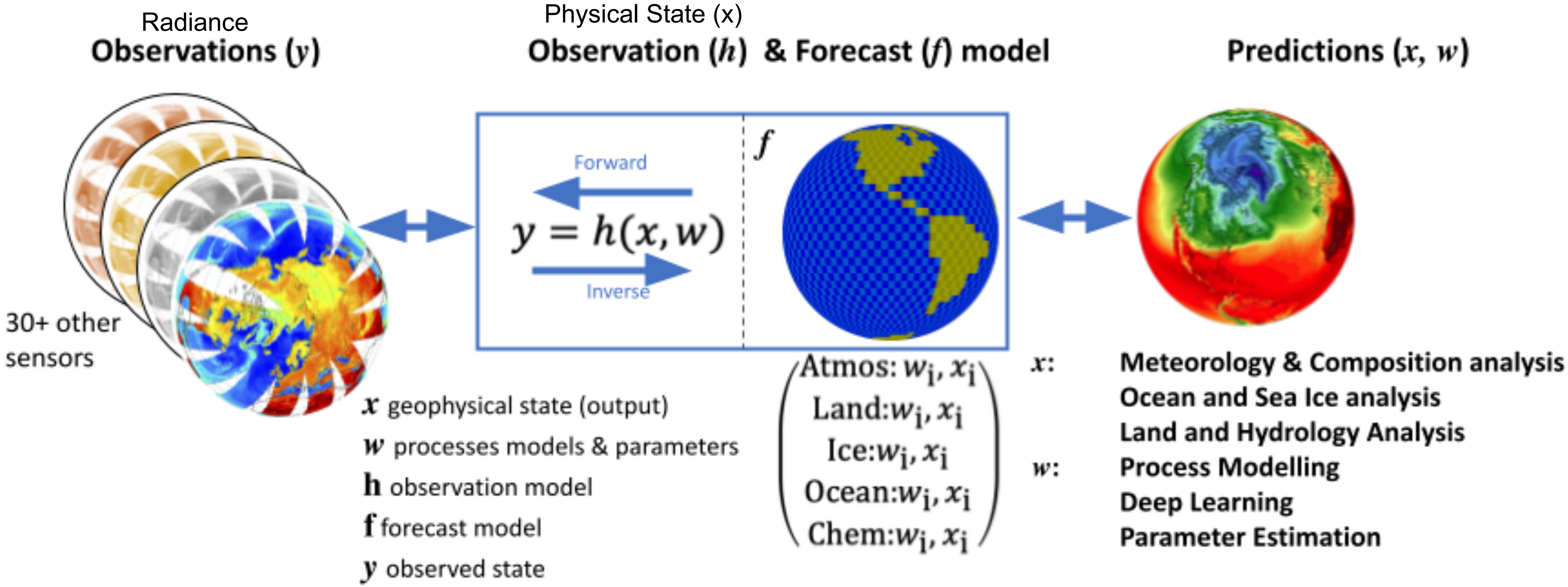
Models and Observations….

T=f(volume)
Is a model



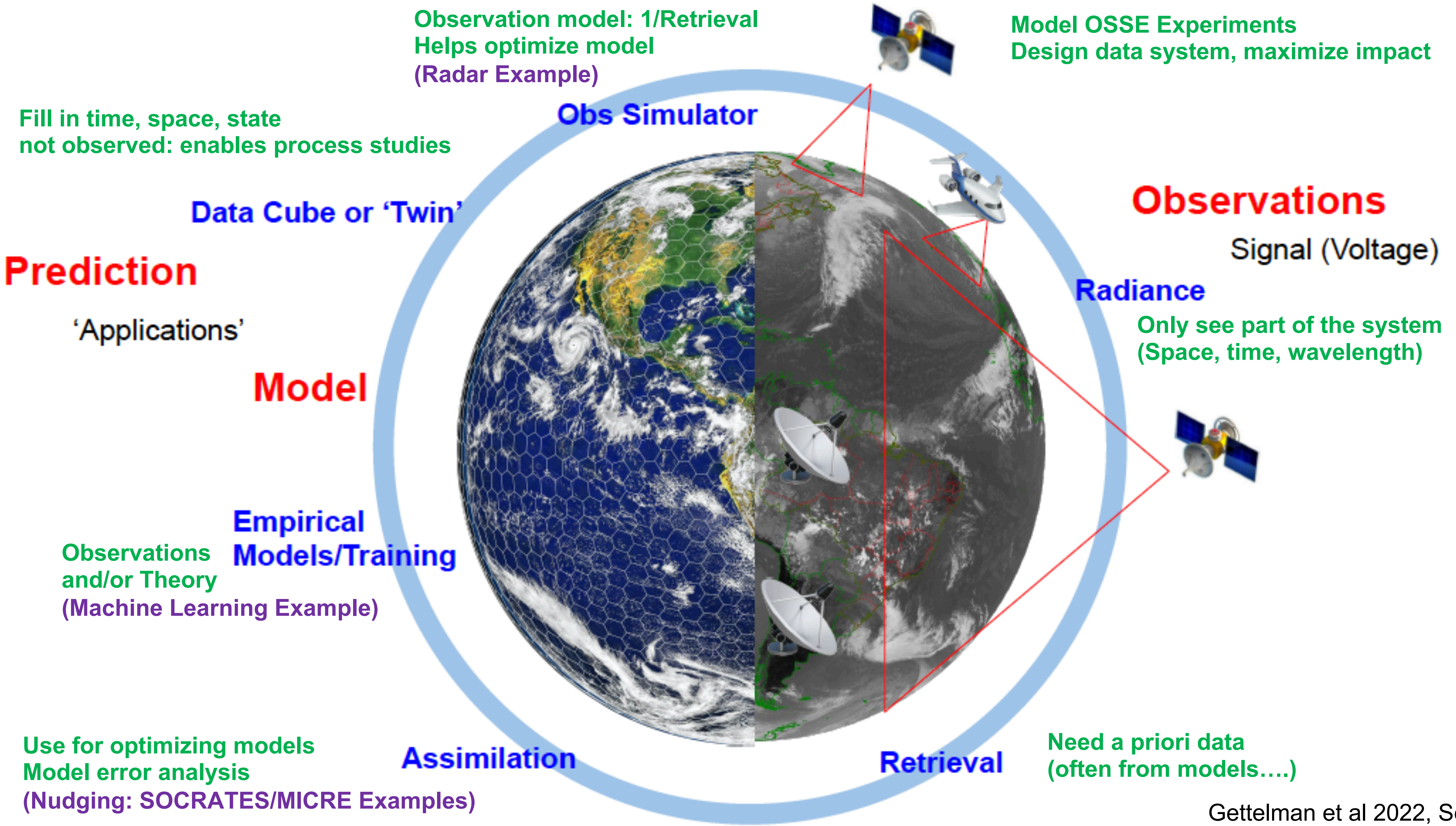
Key points:

- ***All observations have a model in them***
- ***The forward (or observation) model is the inverse of the retrieval (inverse)***



w (processes/parameters): includes traditional methods + machine learning, variational methods

Improving prediction by integrating observations and models



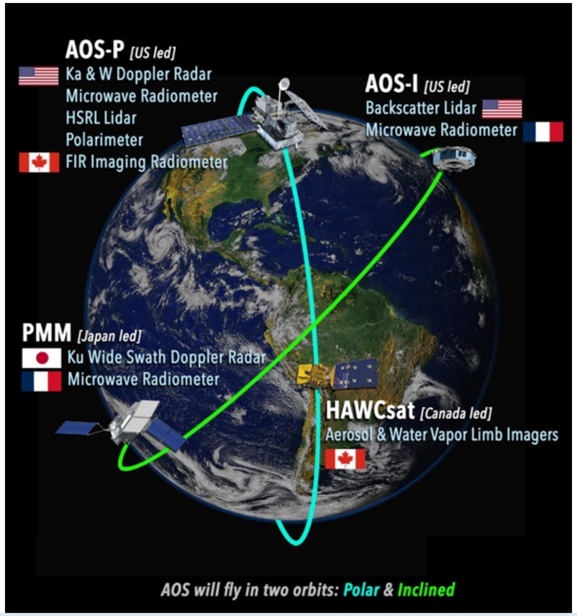
Gettelman et al 2022, Sci Advances

Putting Model-Data Fusion Into Practice

Example: Atmosphere Observing System

https://aos.gsfc.nasa.gov

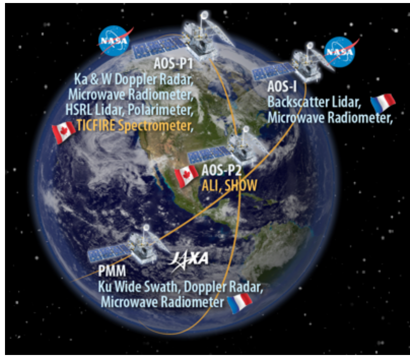
Aerosols, Clouds, Convection, and Precipitation



2 orbit planes, 4 Platforms
11 Sensors
- W+Ka Doppler Radar (Polar)
- HSRL Lidar (Polar)
- Polarimeter, (Polar)
- IR Radiometer (Polar)
- 2 Limb Imagers (Polar)
- 3 Multi-Freq MW Radiometers
- Ku-band Doppler Radar (Inclined)
- Backscatter Lidar (Inclined)

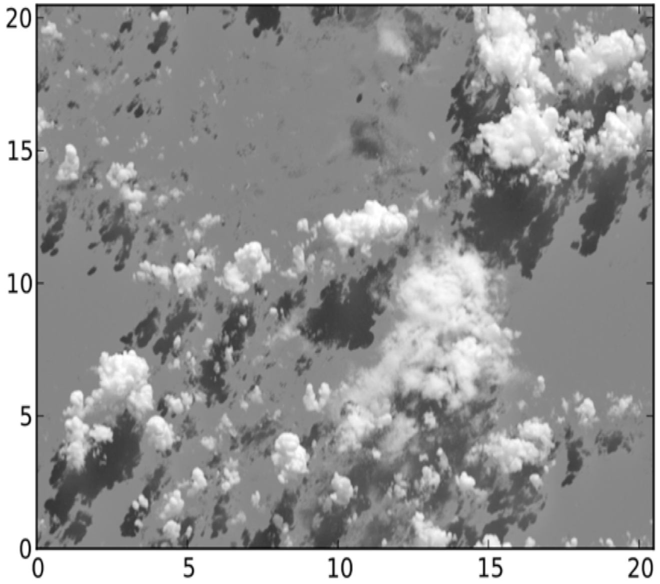
3 International Partners

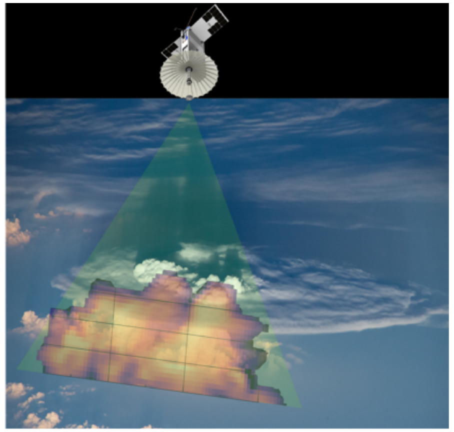
AOS and Model-Data Fusion



Incorporating modeling and DA from the beginning of mission design

1. **Build an open and consistent framework for retrieval and forward operator development**
   - Provide ‘nature’ runs as reference data
   - Integrate forward operators (simulators for models) and retrievals
   - Creating a ‘cloud’ platform for a priori data, simulations, software
2. **Plan for future model-data integration**
   - Production of Level 4 (model + obs integrated) products
   - Model evaluation (e.g., observation simulators for AOS)
   - Data assimilation (observation operators, adjoints)
   - Enable/explore machine learning for faster simulators, inversion of retrievals
3. **Assist in sub-orbital (field campaign) planning**
   - Nature runs + reanalysis + orbit simulators
   - Help to optimize planned deployments





Summary

- Key cloud issues for cliamte:
  - Cloud Phase
  - Cloud dynamics-physics coupling
  - Precipitation
- Improving (weather, climate) predictions requires synergistic use of observations and models
  - New methods for Model-Data Fusion
  - Simulators & Assimilation (adjonts, ML creation of adjoints)
  - Use integrated systems to help predict (and reduce uncertainty)
  - Target observations (Observation System Simulation Experiments)
  - Data driven modeling at different scales (emulators, optimization, assimilation)
- NASA AOS Satellite constellation following a Model-Data Fusion paradigm

‘Digital Earths’
WCRP Lighthouse Activity

Support the design and building of ***integrated interactive digital information systems*** *that provide global and regional information on the past, present, and future of our planet, including both natural and human systems.*

Areas of activity

– **Fully coupled km-scale regional and global models:** Need a global research network in km-scale modeling of the Earth system and individual components

– **Data assimilation for climate:** Establish an active community in data assimilation for climate, expanding on the excising numerical weather prediction and re-analysis efforts

– **Beyond the Physical Earth System:** Include human interactions on and impacts to human systems in ESMs