Beyond bulk cloud top quantities: A climate perspective on Satellite Cloud Observations

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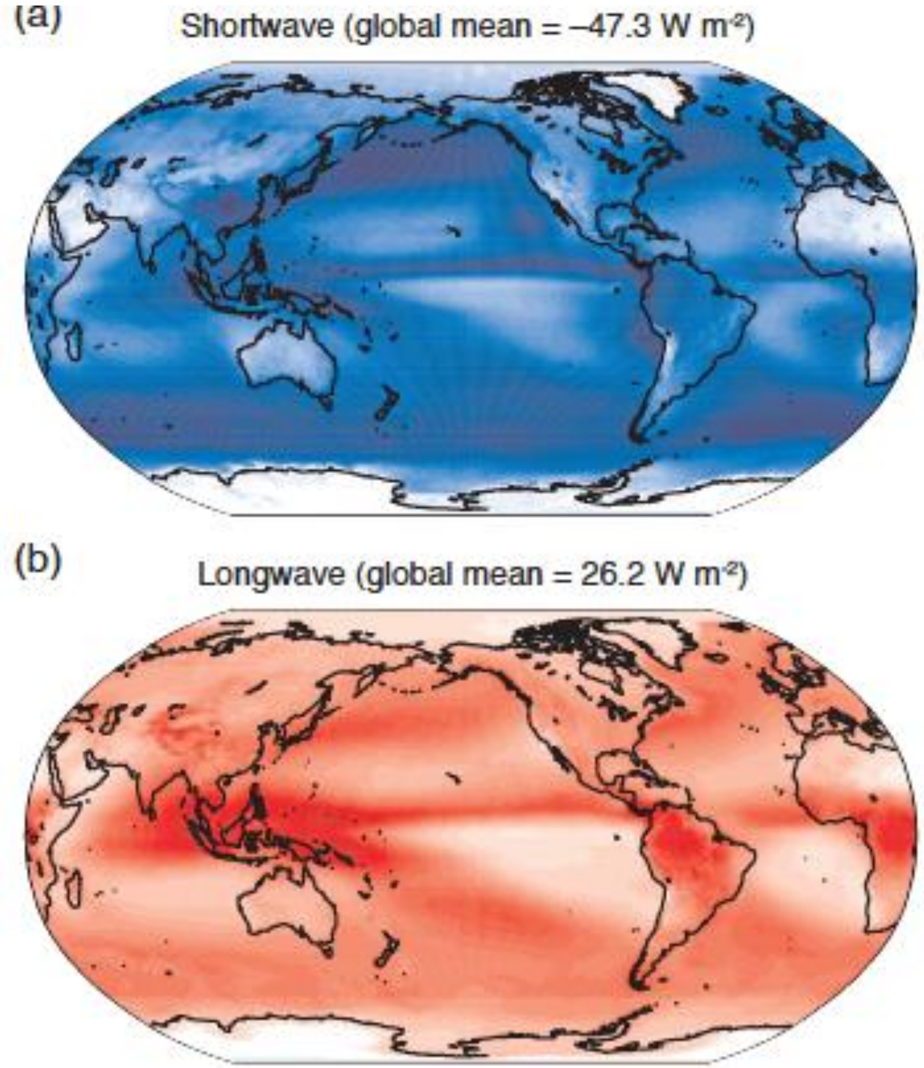
(also Oxford, ECMWF)

Key Problems in Climate Prediction

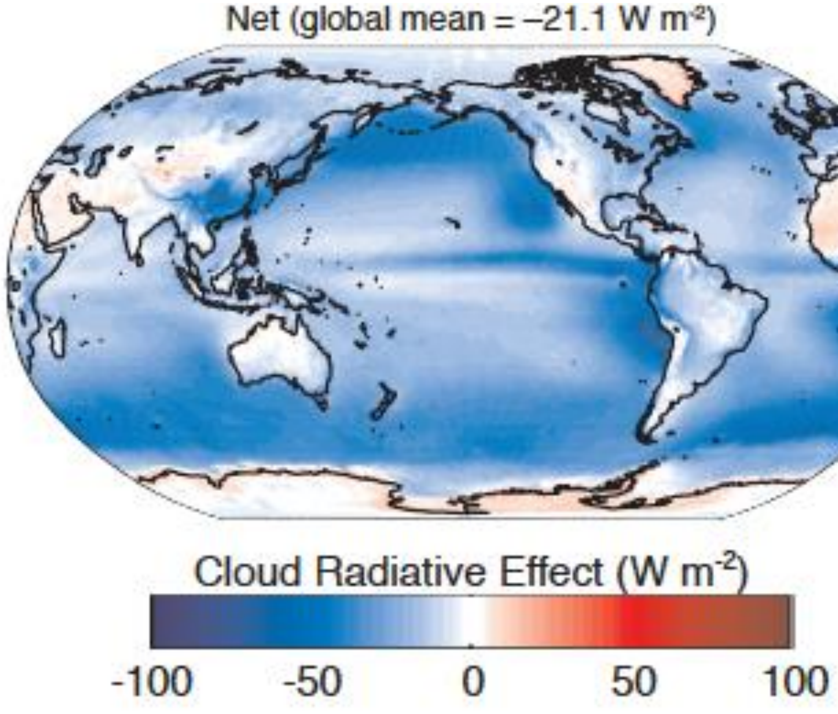
- Cloud Feedbacks (Climate sensitivity)
- Climate Forcing (Aerosols)
- Impacts and the hydrologic cycle (extreme precipitation)
- These all run through clouds
- Many run through cloud microphysics
- Critical processes are small scale, fast, observable
  - Uncertainty in how long term effects emerge from small scale
  - Cannot ‘verify’ a climate forecast
  - Can only constrain based on current and past (weak analog for future)

That’s why I am here….

Cloud Radiative Effects are Large

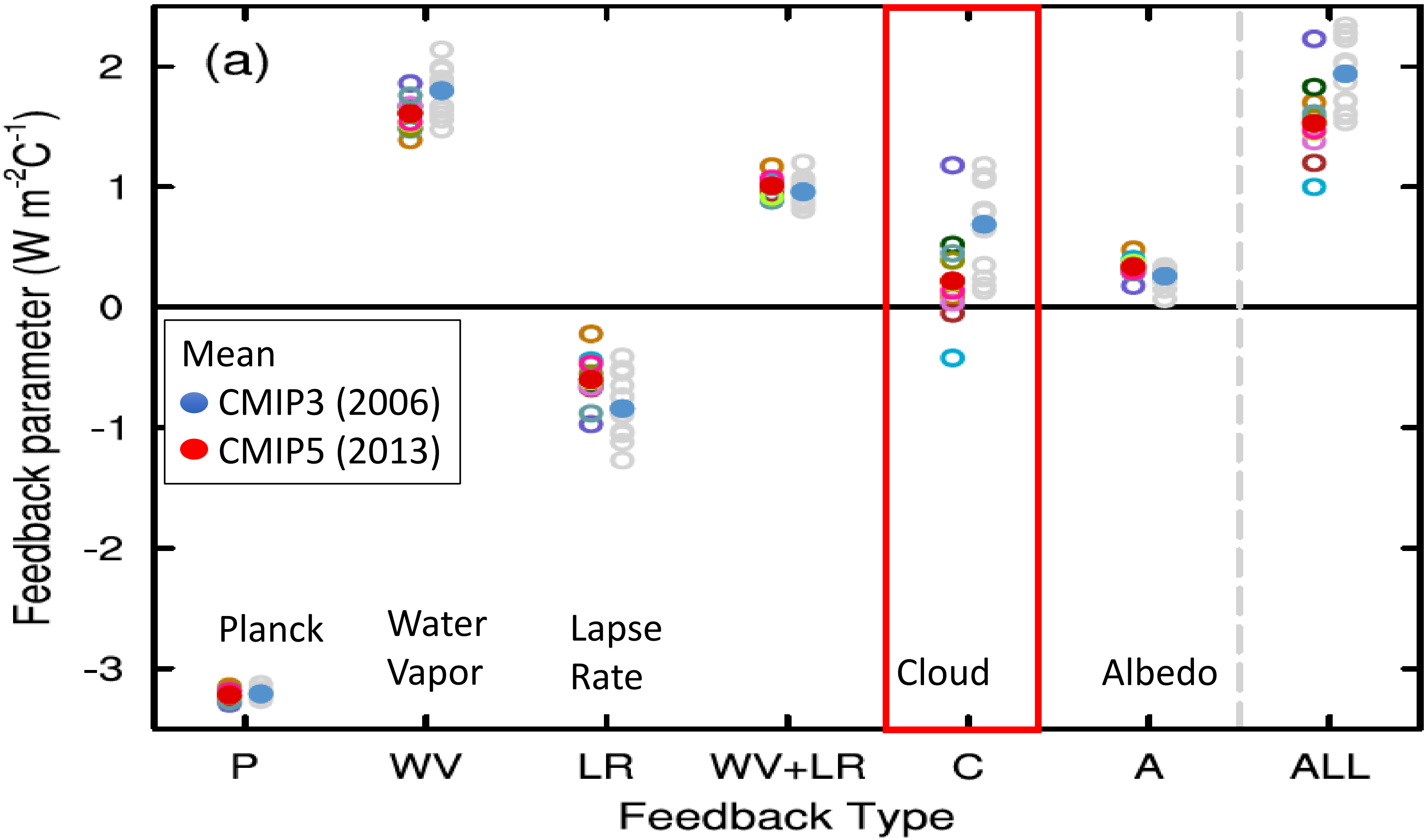


$R_{cloudy} - R_{clear}$



IPCC 2013 (Boucher et al 2013) Fig 7.7

Clouds = Largest Uncertainty in Climate Feedbacks



Planck $\varepsilon = \sigma T^4$ (-)

Water Vapor
+T & RH=C → +H2O (+)

Lapse Rate (-

Albedo (snow, ice)
+T → less snow, ice
-T → more snow, ice (+)

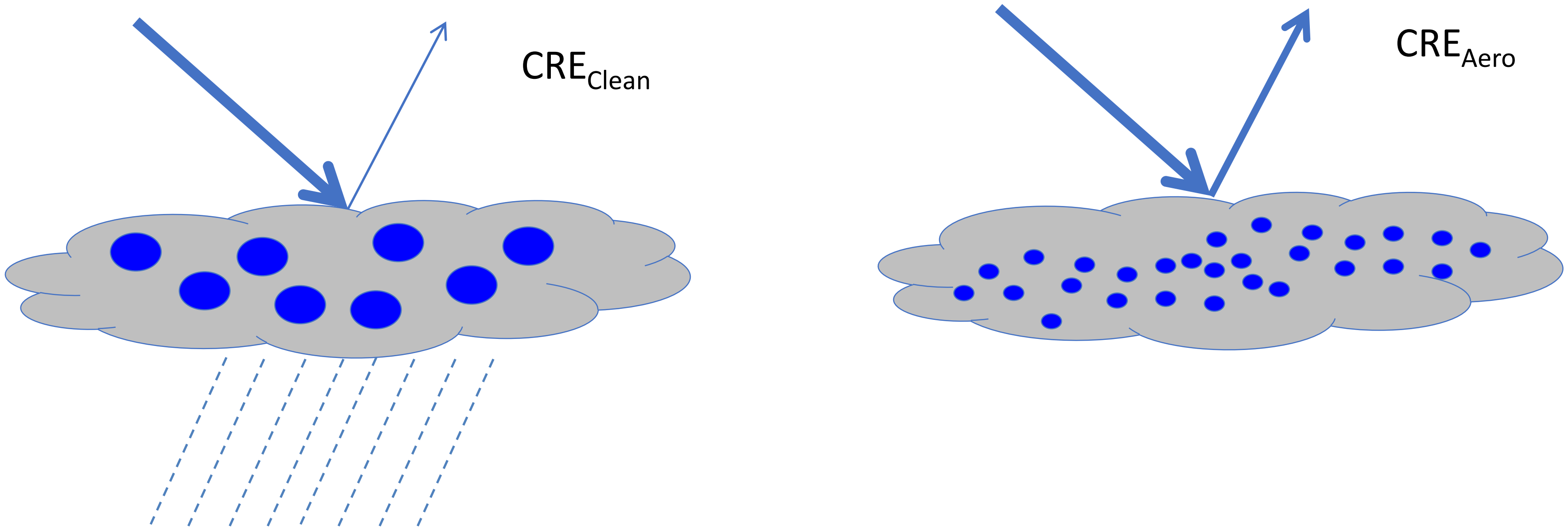
Clouds: Complicated (+)

IPCC, 2013 (Ch 9, Hartmann et al 2013) Fig 9.43

Aerosol Effects on Clouds

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

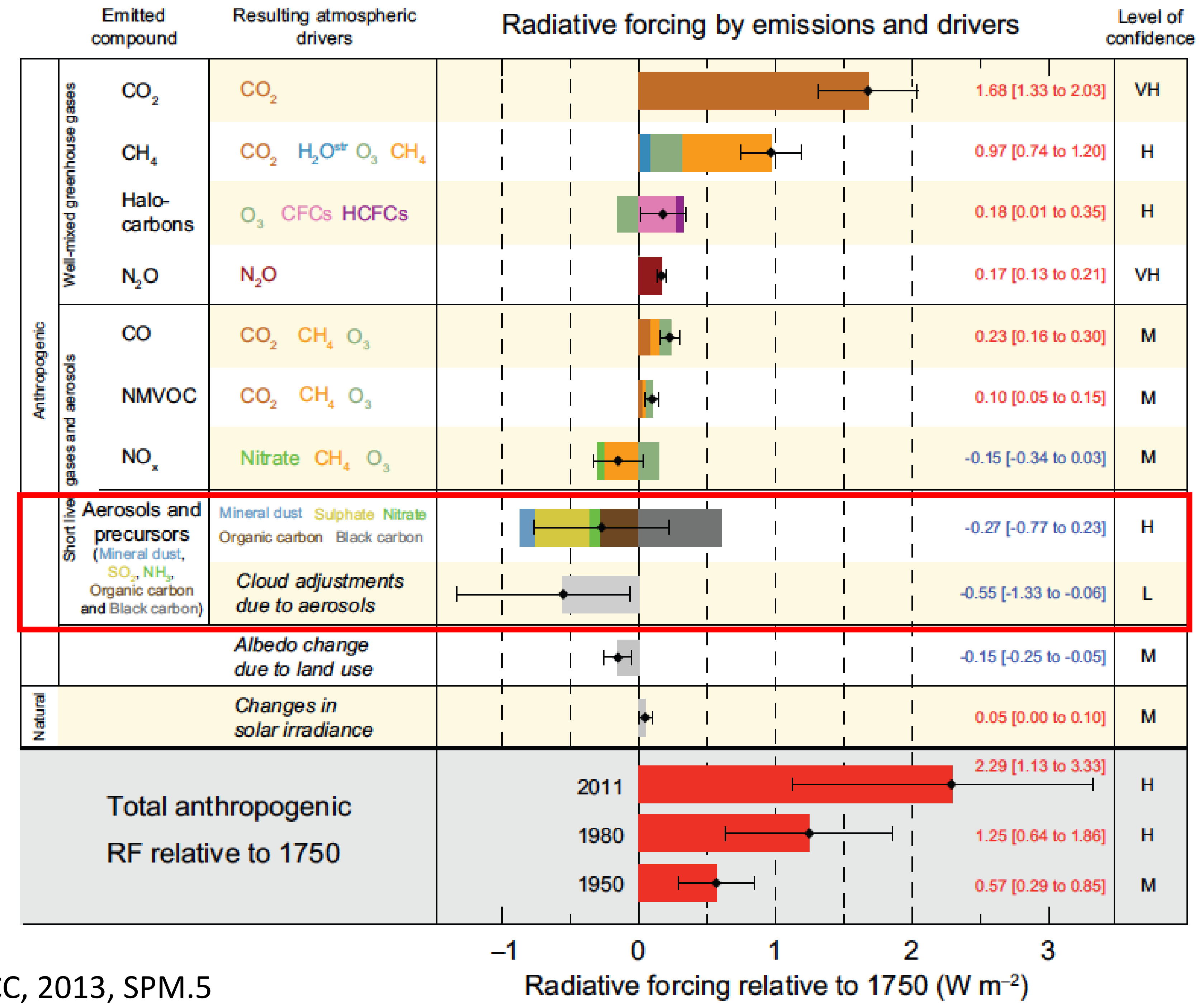
$$+\text{Aerosols} \rightarrow +\text{CCN} \rightarrow +N_c \rightarrow \Delta\text{CRE}$$



Net Cooling Effect: brighter clouds
Also: delay in precipitation. Longer lived Clouds?

Climate Forcing

Aerosol Cloud interactions are the largest uncertainty in Climate forcing



IPCC, 2013, SPM.5

Clouds and Weather

- Clouds are responsible for most severe weather
  - Tornadoes, Thunderstorms, Hail, Tropical Cyclones
- Critical processes depend on cloud microphysics (Thunderstorms, Hail, even Tornadoes)
- Question: how will severe weather change under climate change?
  - Necessary but not sufficient condition: get severe weather right now

Cloud Interactions with Radiation: Liquid

Cloud Radiative Effects related to Albedo

$$A = C\frac{\tau}{\beta + \tau} + (1 - C)A_b,$$

Albedo depends on optical depth (τ) & cloud fraction (C). β = constant

τ a non-unique function of size and mass

$$\tau = \alpha N_c^{1/3} L_c^{5/6}, \qquad \alpha = 0.19.$$

Seifert et al 2015, JGR

Droplets well constrained (e.g. self-consistent treatment from PSD)

Note: significant implications for OBSERVING cloud microphyiscs

Observing cloud physics

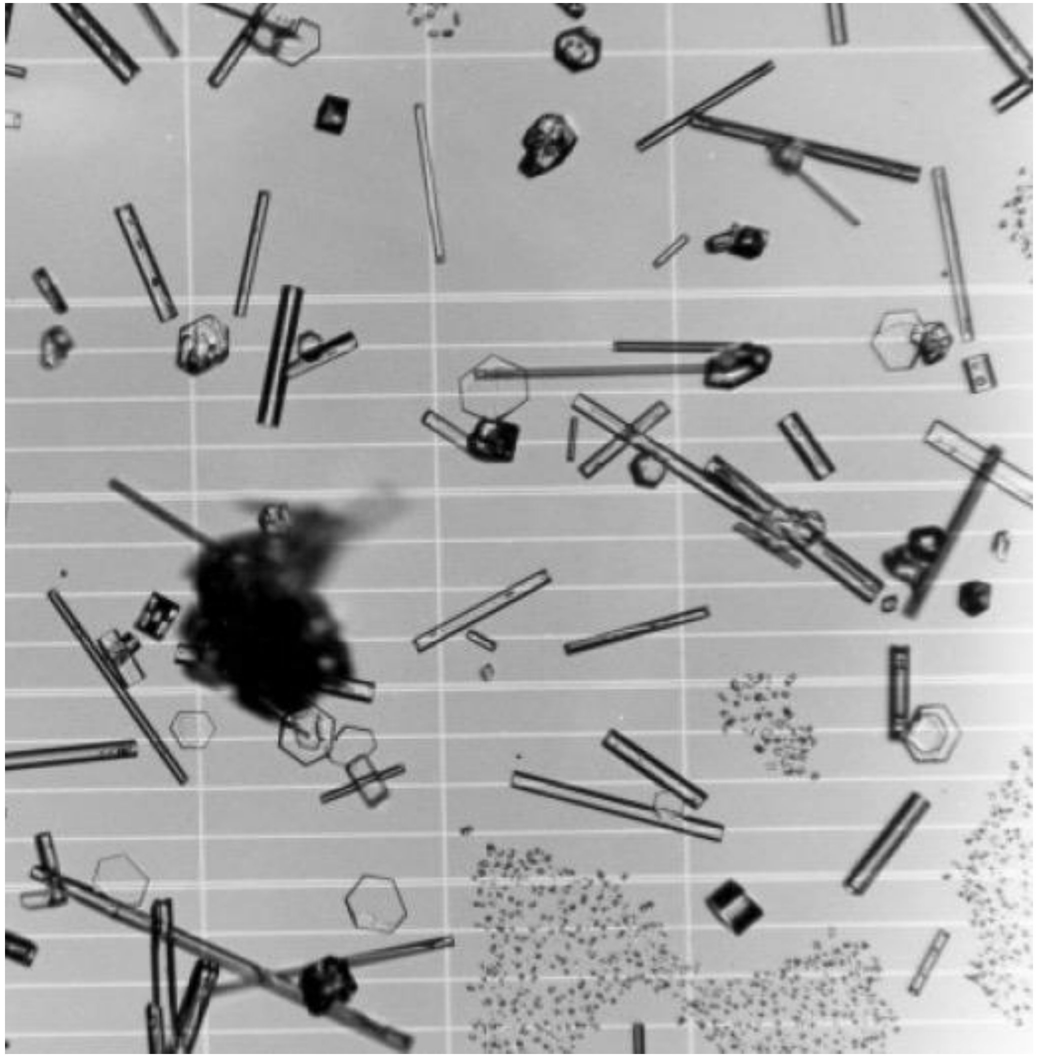
- Satellites observe τ in some wavelength (even active sensors)
- τ is a non-unique function of N, LWP

$$\tau = \alpha N_c^{1/3} L_c^{5/6}$$

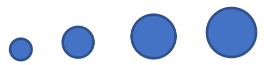
- To determine cloud microphyiscs (N, LWP), need to make an assumption
- Better: IR more sensitive to N, microwave more sensitive to LWP
- Still large uncertainties (even for liquid)

Cloud Interactions with Radiation: Ice

- Ice is more complicated
- It’s not spherical: different ‘habits’ have different optical properties
- Ice clouds are typically a collection of habits
- Impacts optics (absorption, scattering), also sedimentation (loss process)

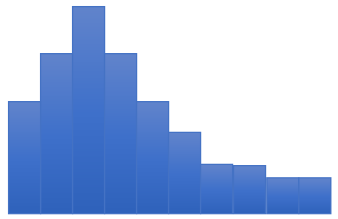


Types of Microphysical Schemes



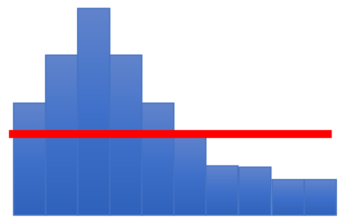
- Lagrangian 'Superdroplet' Microphysics
  - Represent interactions among individual drops
  - 'Explicit', mostly done for warm processes

Idealized,
Turbulence Models



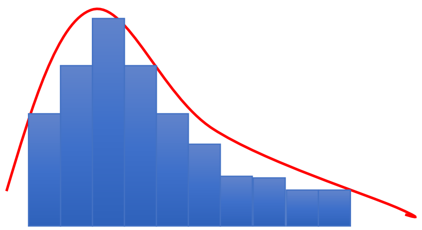
- Bin Microphysics
  - Represent the number of particles in each size 'bin'
  - One species(number) for each mass bin
  - Computationally expensive, but 'direct'

Some Mesoscale,
LES models



- Bulk Microphysics
  - Represent the total mass and number
  - Computationally efficient
  - Approximate processes

Most Global Models



- Bulk Moment based microphysics
  - Represent the size distribution with a function
  - Distribution for different 'Classes' (Liquid, Ice, Mixed Phase)
  - Hybrid: functional form makes complexity possible

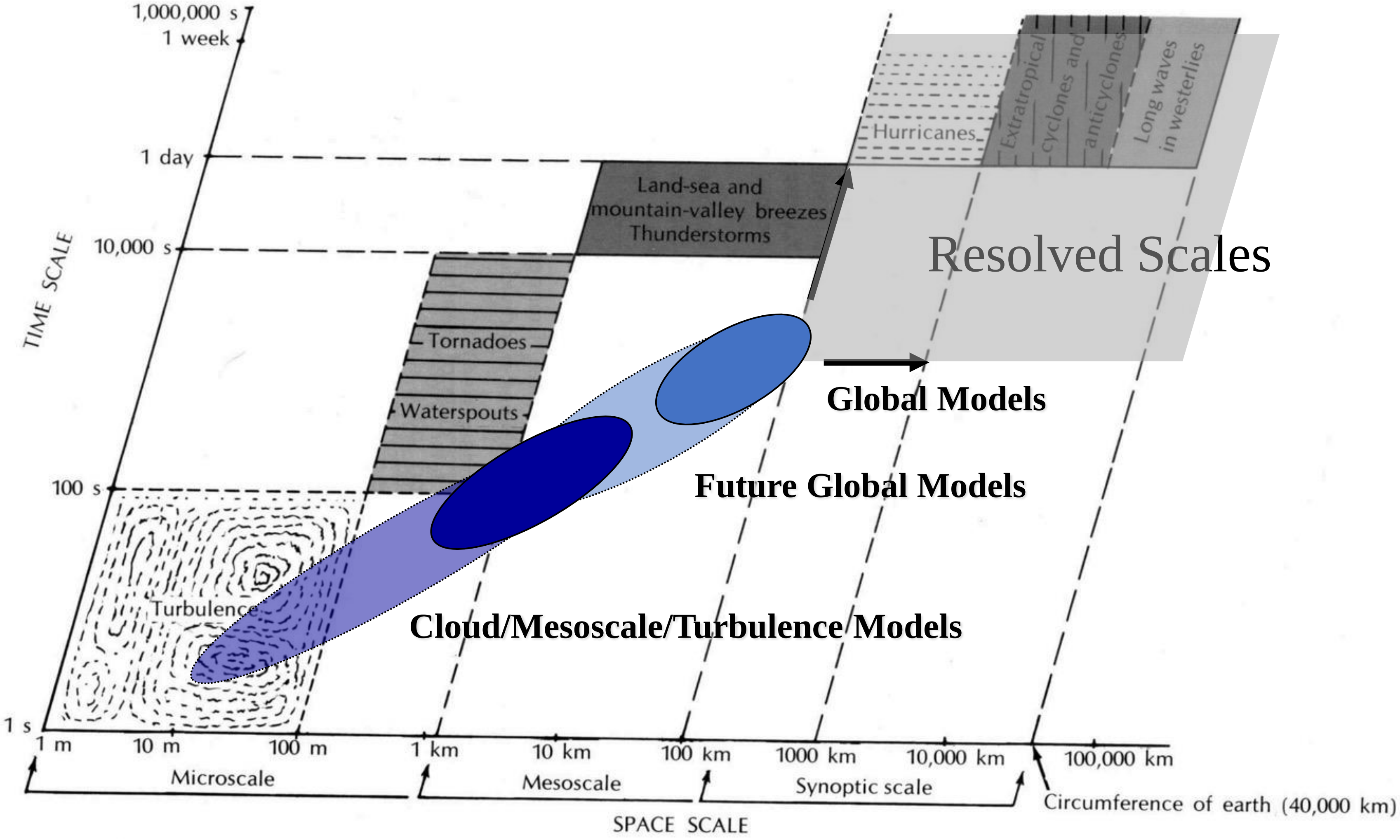
Some Global,
Mesoscale Models

Modeling Clouds for Weather & Climate
What is important?

- Weather
  - Precipitation is critical (duration, intensity, phase)
  - Supercooled liquid
  - Extremes
  - Clouds over land
- Climate
  - Radiative fluxes (TOA)
  - Shallow Clouds over oceans (Tropical & Subtropical)
  - Arctic clouds and Surface Radiative Fluxes
  - Mean precipitation

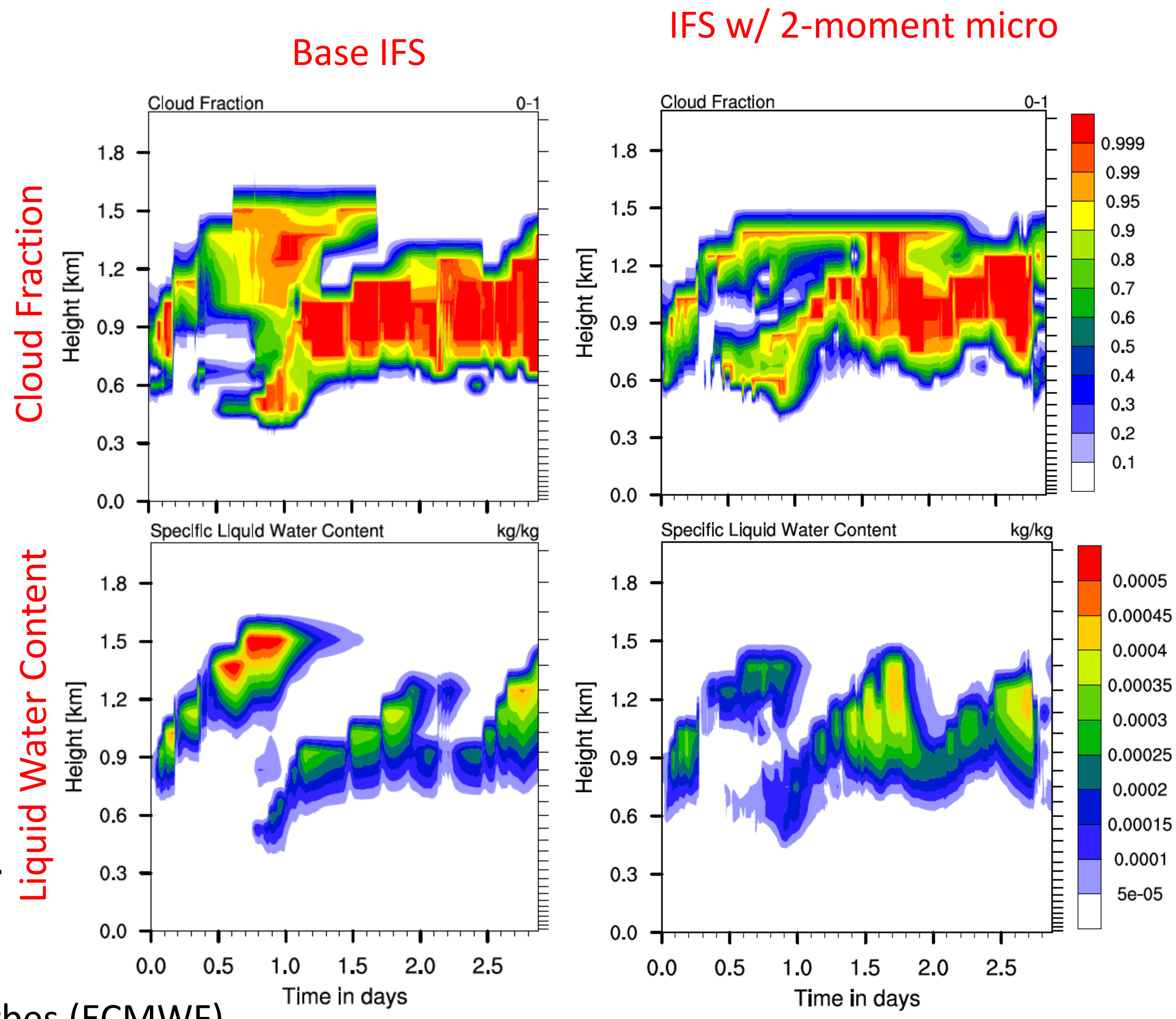
Where are Global Models Going?

Weather & Climate



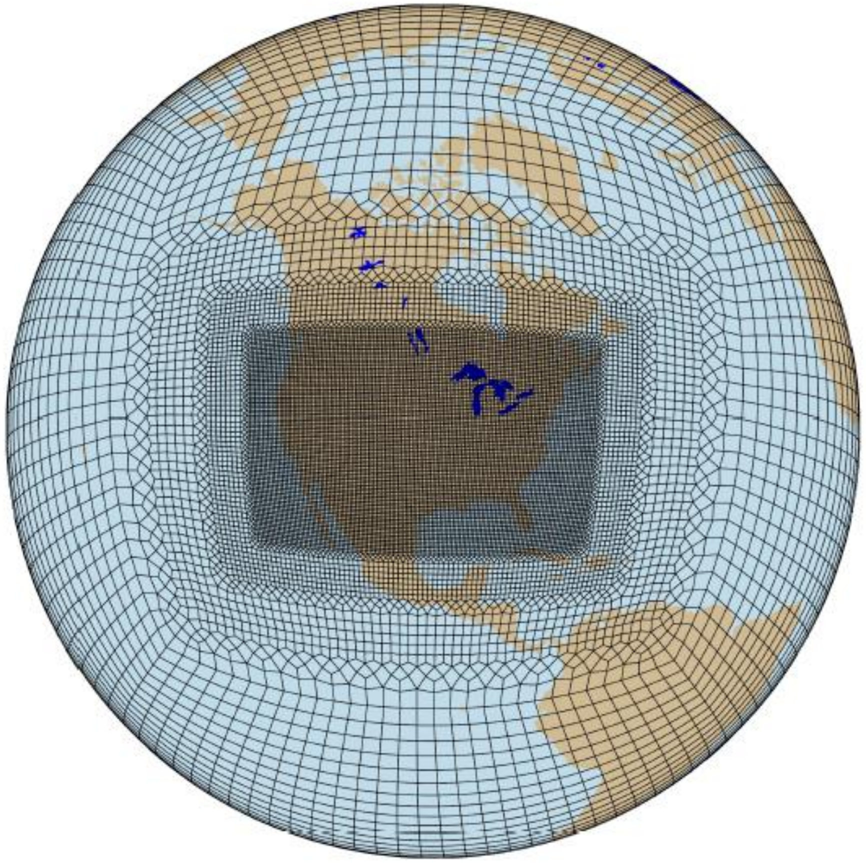
Convergence for Weather and Climate

- Weather and climate models are converging in scale & methods
  - Weather: running coupled, long-range to seasonal forecasting, air quality
  - Climate: smaller scales, resolve sub-synoptic extreme events
- E.g.: Now running a bulk 2-moment scheme (MG3) in the IFS
  - Example: Arctic mixed phase cloud case
  - Does detailed microphysics matter for weather?



Thanks to J. Chen (NCAR), R. Forbes (ECMWF)

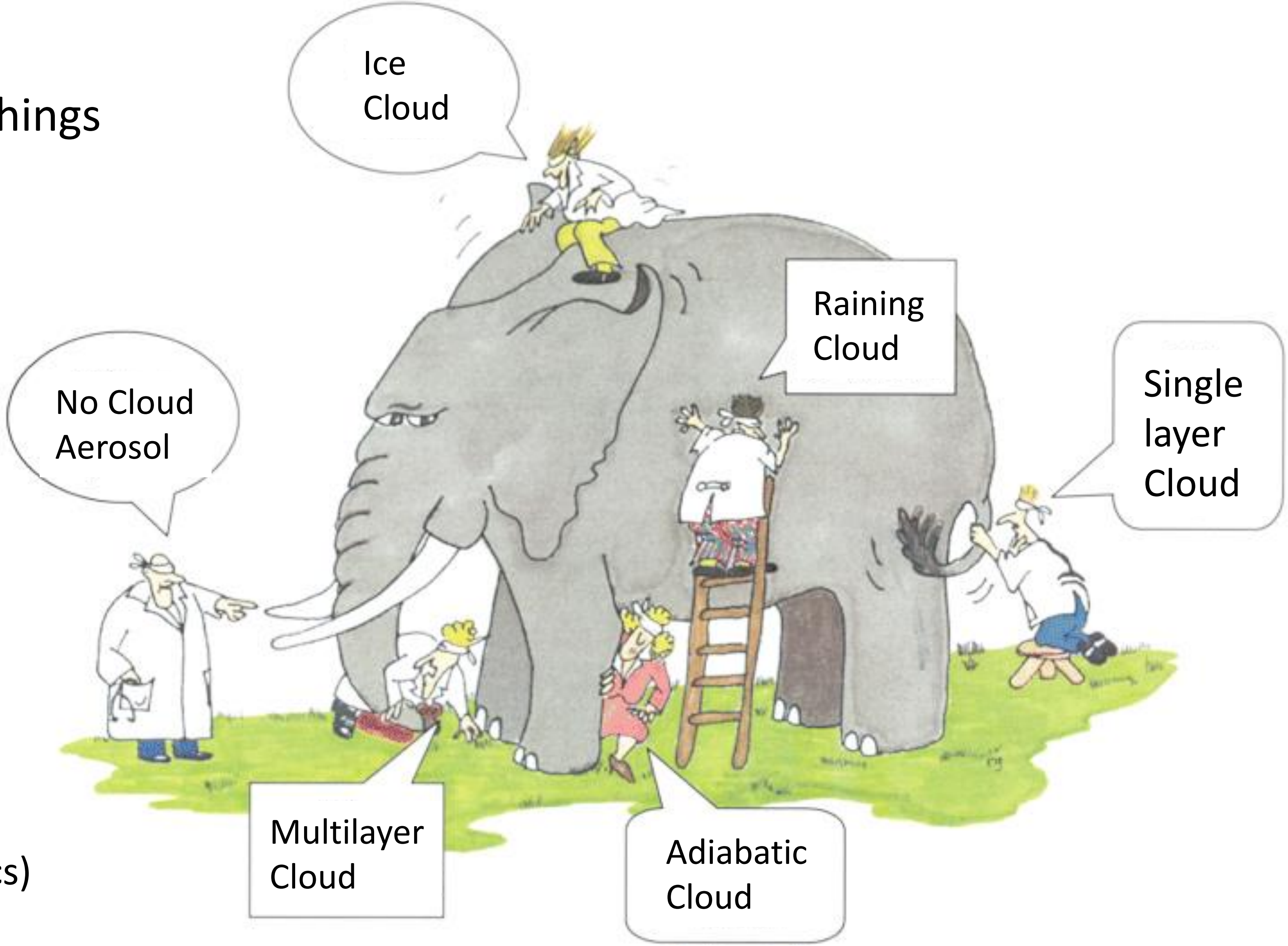
Cloud Physics: Future Directions
Large Scale/Global Modeling (Weather and Climate)



- High horizontal resolution: unified or refined mesh dynamical cores
- Representation of hydrometeor size distributions
  - Ice crystal habits and shape
- Better cloud phase (including riming)
- Sub-grid distributions of cloud properties
  - Beyond cloud fraction: size, variable LWP
- Unified Shallow Turbulence
  - boundary layer, stratiform cloud, shallow convection
  - ‘Higher Order Closure’
  - Predict sub-grid correlations (Q,W)

Using observations to evaluate clouds

Different sensors see different things
- Passive (IR, Visible, MW)
- Active (Lidar, Radar)
- Stereo, Multi-angle



Key question:
What can we 'assimilate' reliably
(limited bias, good error characteristics)

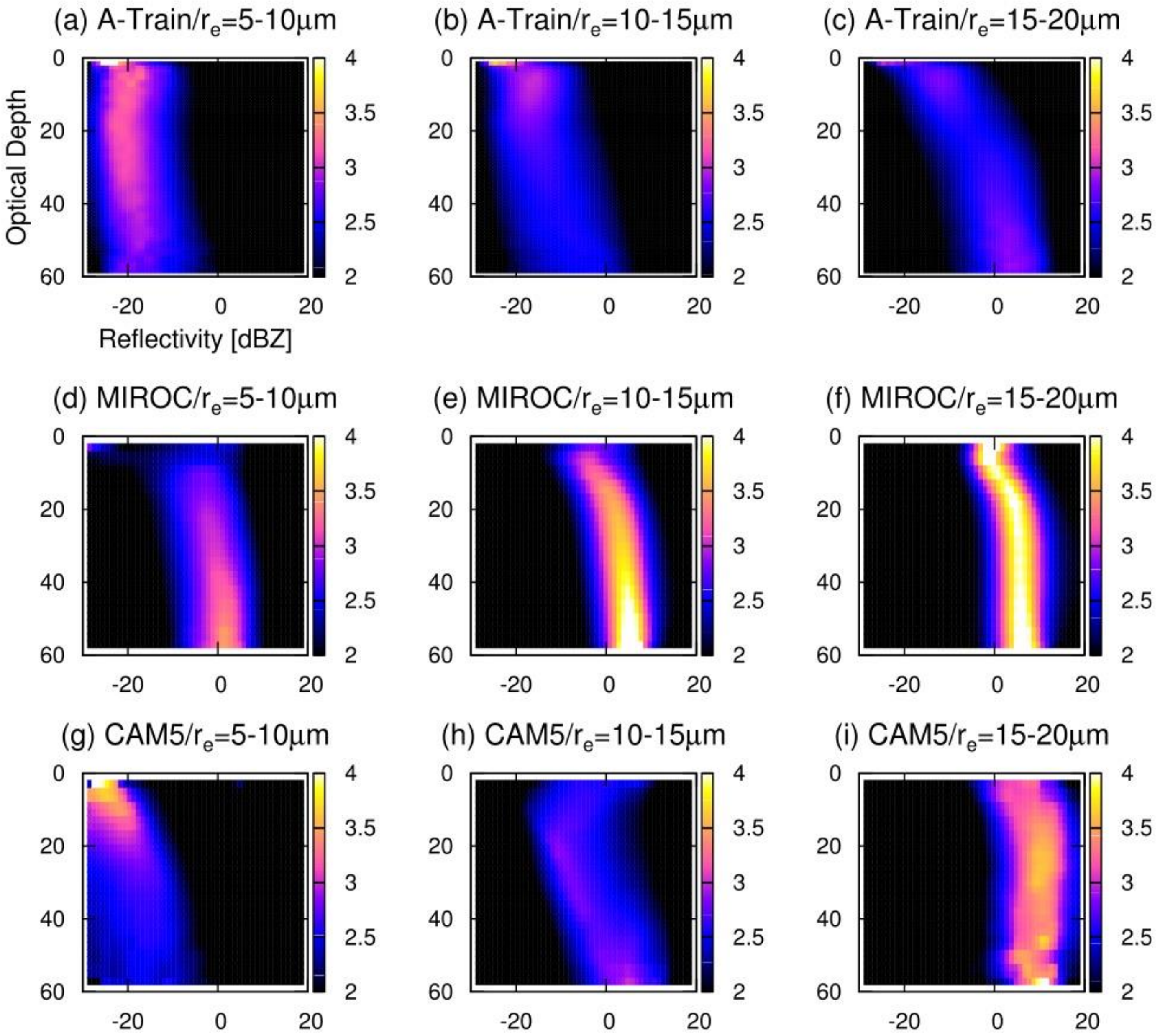
When do Clouds Rain?

PDF of radar reflectivity as a function of optical depth for clouds with different drop sizes

Weak dependence on optical depth (LWP) until large sizes.

Weak Rain (low DBz) until either 15um or thick cloud.

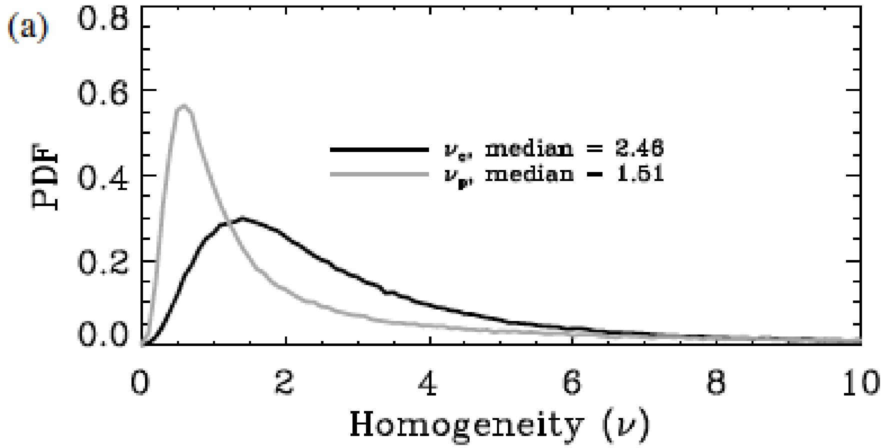
Models (MIROC and CAM) have too much rain with small drops (esp MIROC).

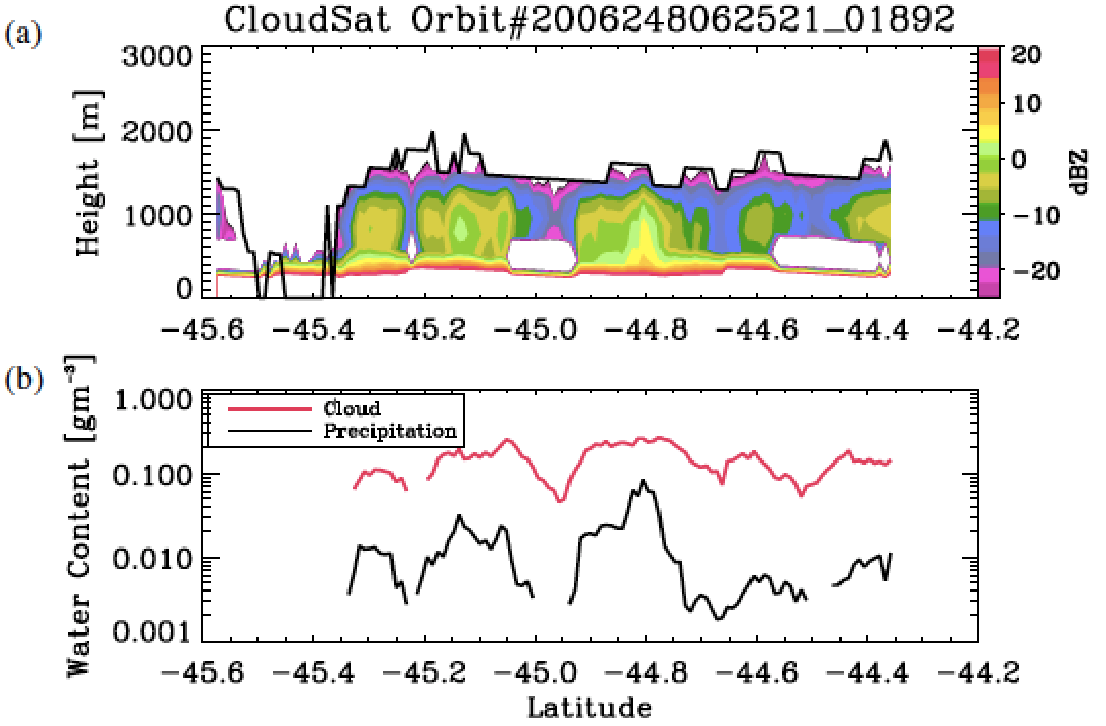


Suzuki et al 2015, JAS

Observing co-variance of cloud and rain

- Co-variance of cloud & rain affects rain formation (accretion & autoconversion)
- Observe cloud/rain from satellites (CloudSat)
- Calculate variance, mean and normalized variance (υ) or homogenaiety
- Yields observational estimate of Ac & Au enhancement factors used in microphysics





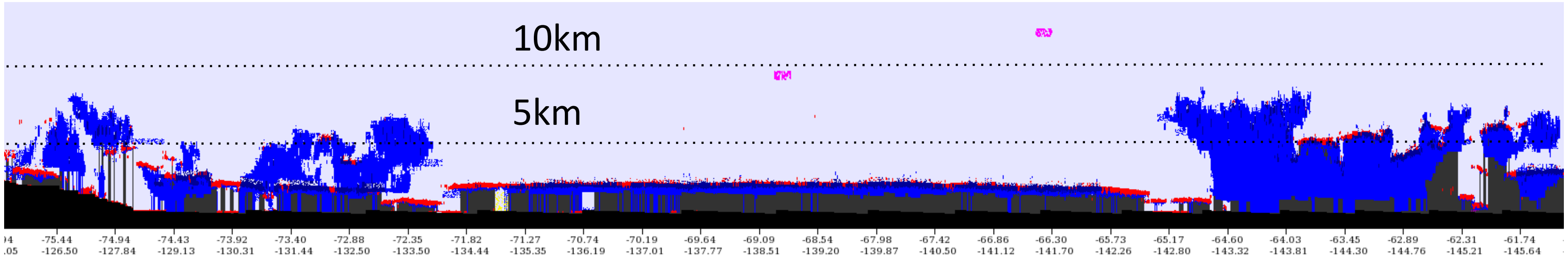
Lebsock et al 2013

What Phase is a Cloud?

Satellite Super-cooled Liquid Water

Radar & Lidar (CloudSat + Calipso) product

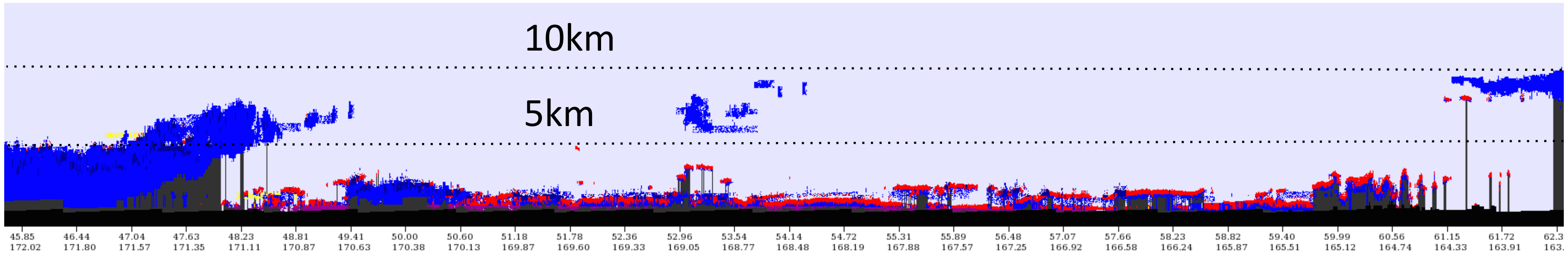
2013-01-01 S. Ocean (S. Of Pacific)



70S 61S

Liquid Ice Supercooled

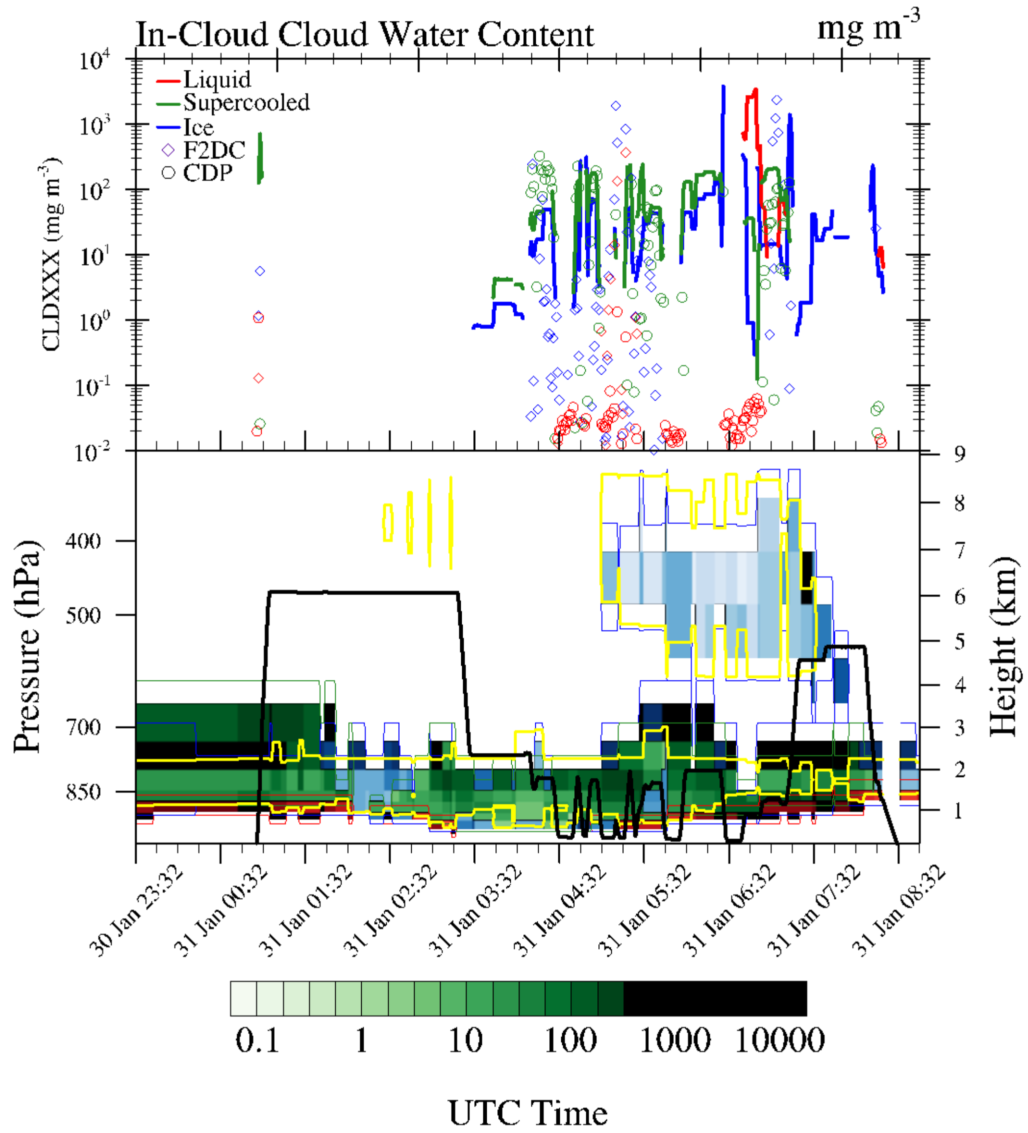
2014-02-07 N. Pacific



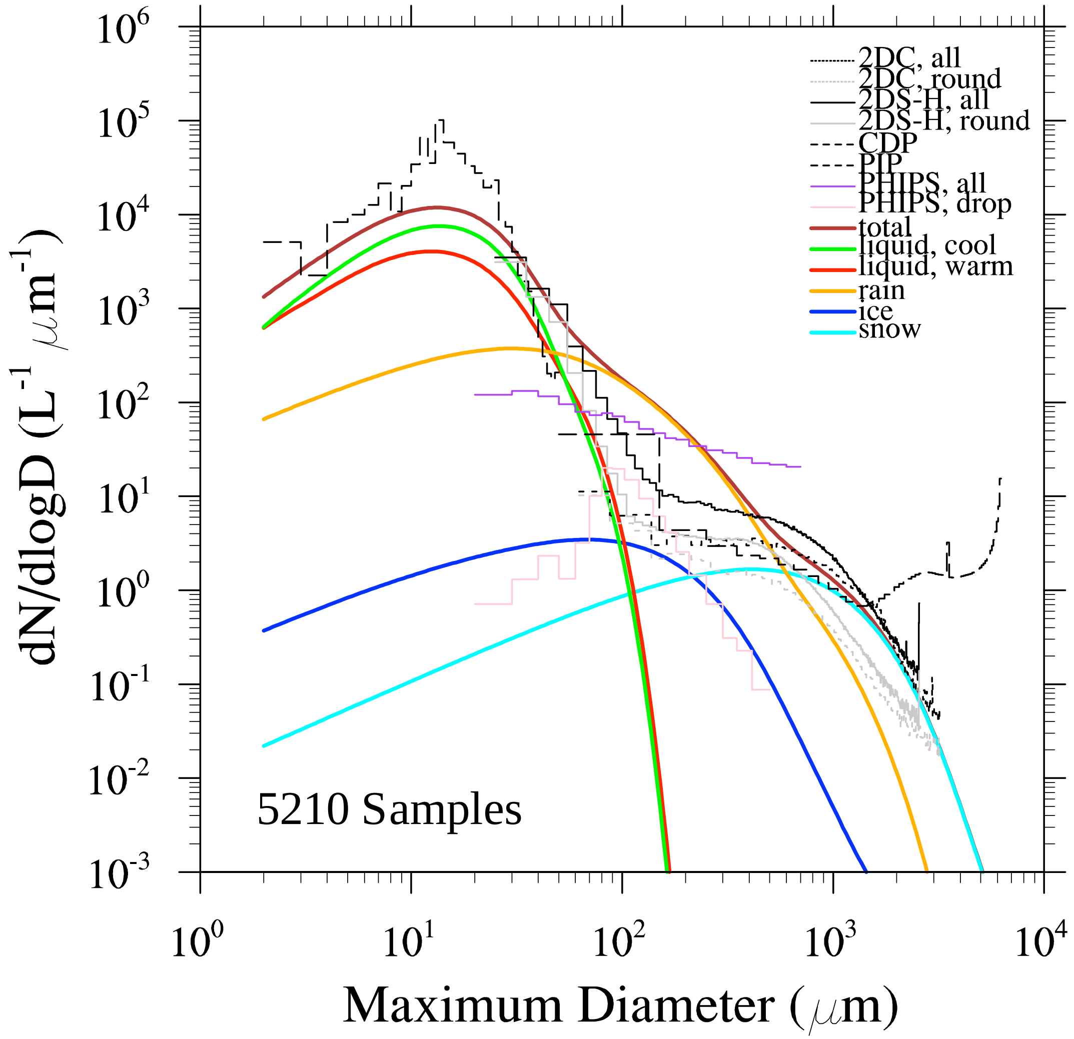
45N 60N

Beyond Satellites: Global models v. In-Situ Aircraft

SOCRATES, RF07



Campaign Average



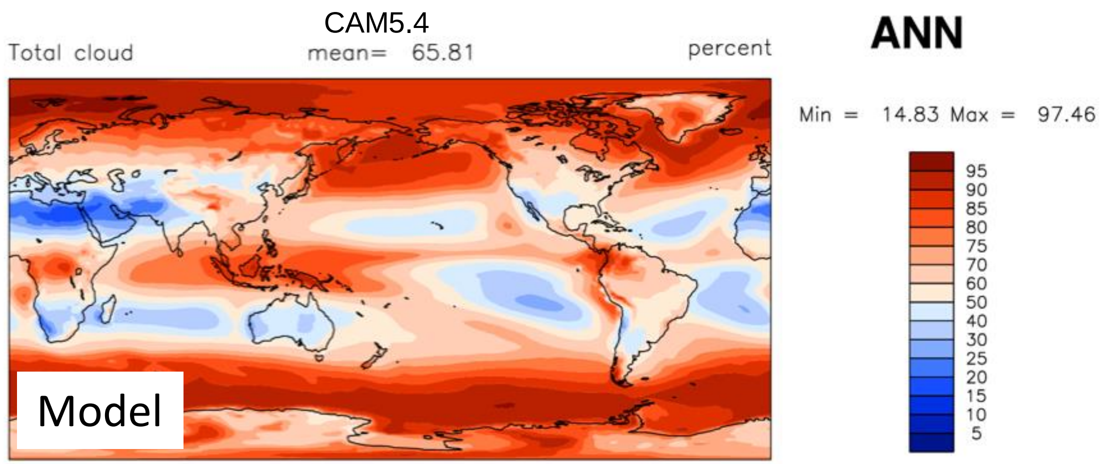
Present Satellite Sensors of Interest (US Bias)

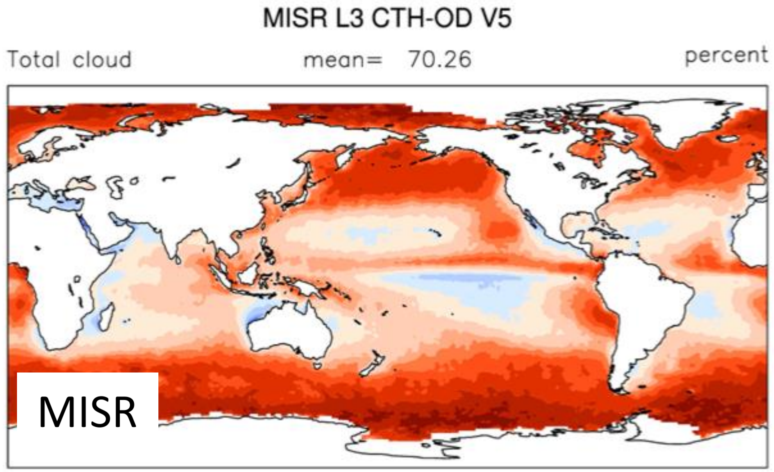
- Radiation (Radiative Fluxes, T & Q Profiles)
  - Broadband (LEO, CERES)
  - Narrowband (LEO, IR-AIRS)
- Imaging/Cloud Top: Passive (Hydrometeor Size, LWP)
  - VIS/IR: LEO: MODIS/VIIRS GEO: Himawari, SEVERI
  - Microwave (Numerous, AMSR)
- Active (Phase, Aerosols, Vertical Structure, Precipitation)
  - Radar: TRMM, CloudSat, GPM, EarthCare
  - Lidar: CALIPSO

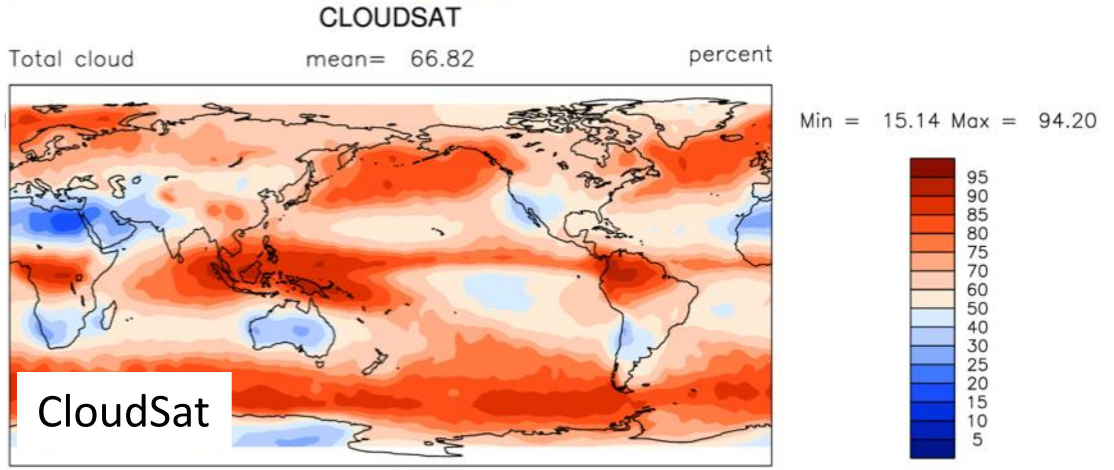
Climate Model Evaluation

Example: Cloud fraction…

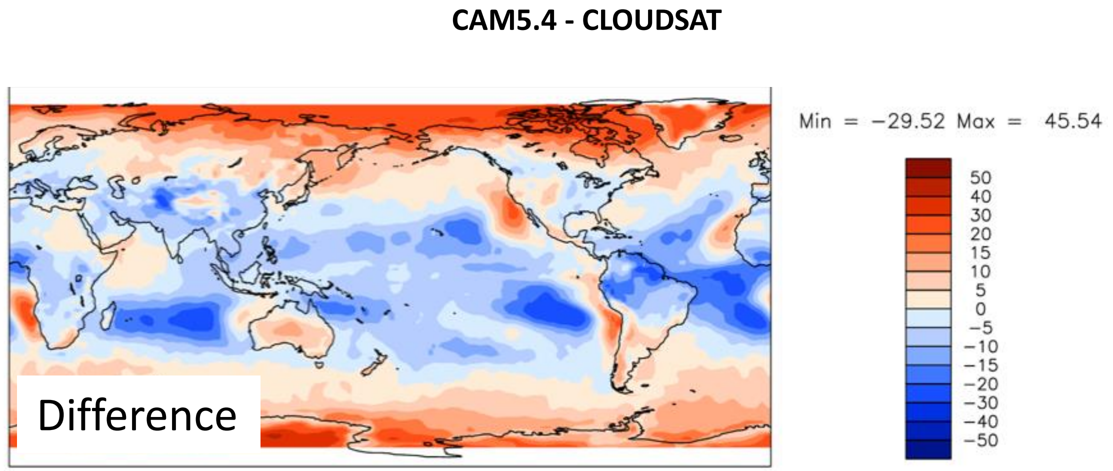
Traditional View: Model – CloudSat (Radar+ Lidar)







Biases change with data set.
May even change sign!



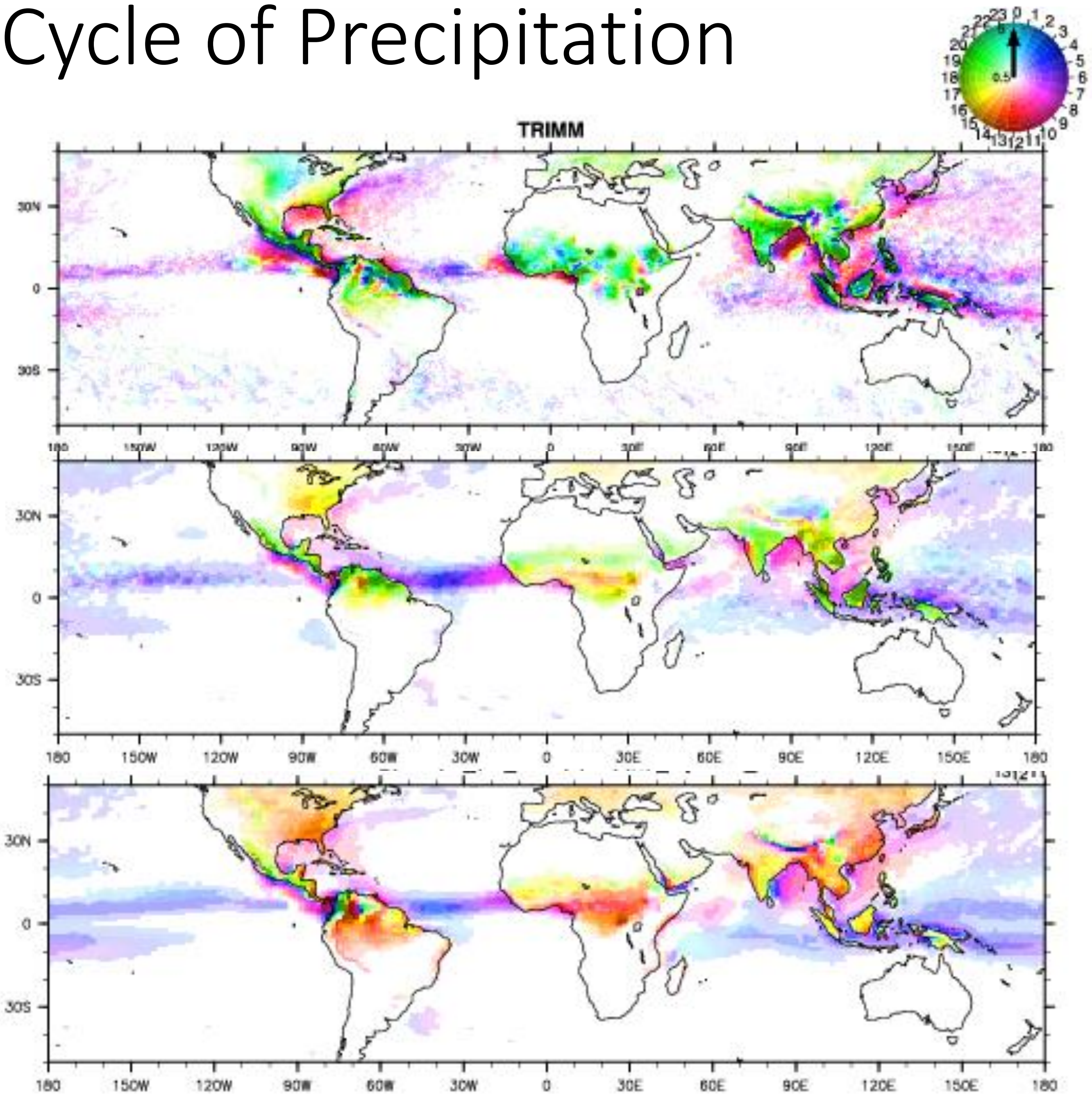
Variability: Diurnal Cycle of Precipitation

JJA Precipitation Rate

TRMM: OBS

CAM5.5 (new)

CAM5.3 (Old)

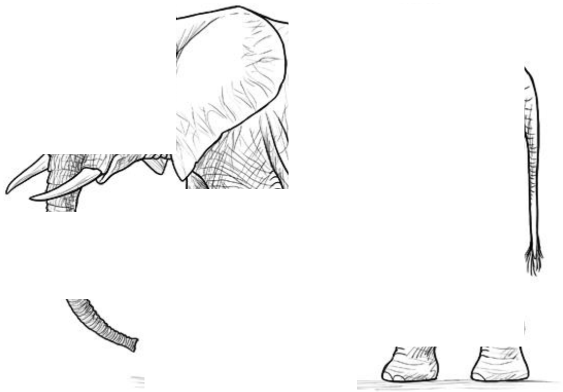


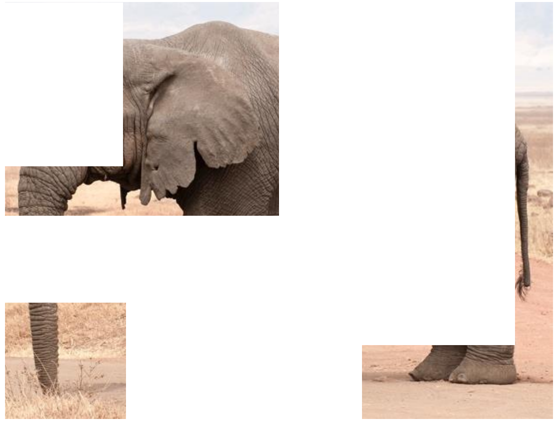
Thanks to R. Neale, C-C. Chen

Instrument Simulators

- Why? Better comparisons between models and observations
- Designed to “simulate” retrievals of a variety of satellites: includes MODIS, MISR, CloudSat, CALIPSO, ISCCP
  - Similar to assimilation methods: bring models and observations together
  - Sample models using sampling and retrieval algorithm assumptions
- Mostly cloud fraction, but also cloud microphysics from MODIS
- CFMIP Observation Simulator Package (COSP)
  - CFMIP = Cloud Feedback Model Intercomparison Project

Model



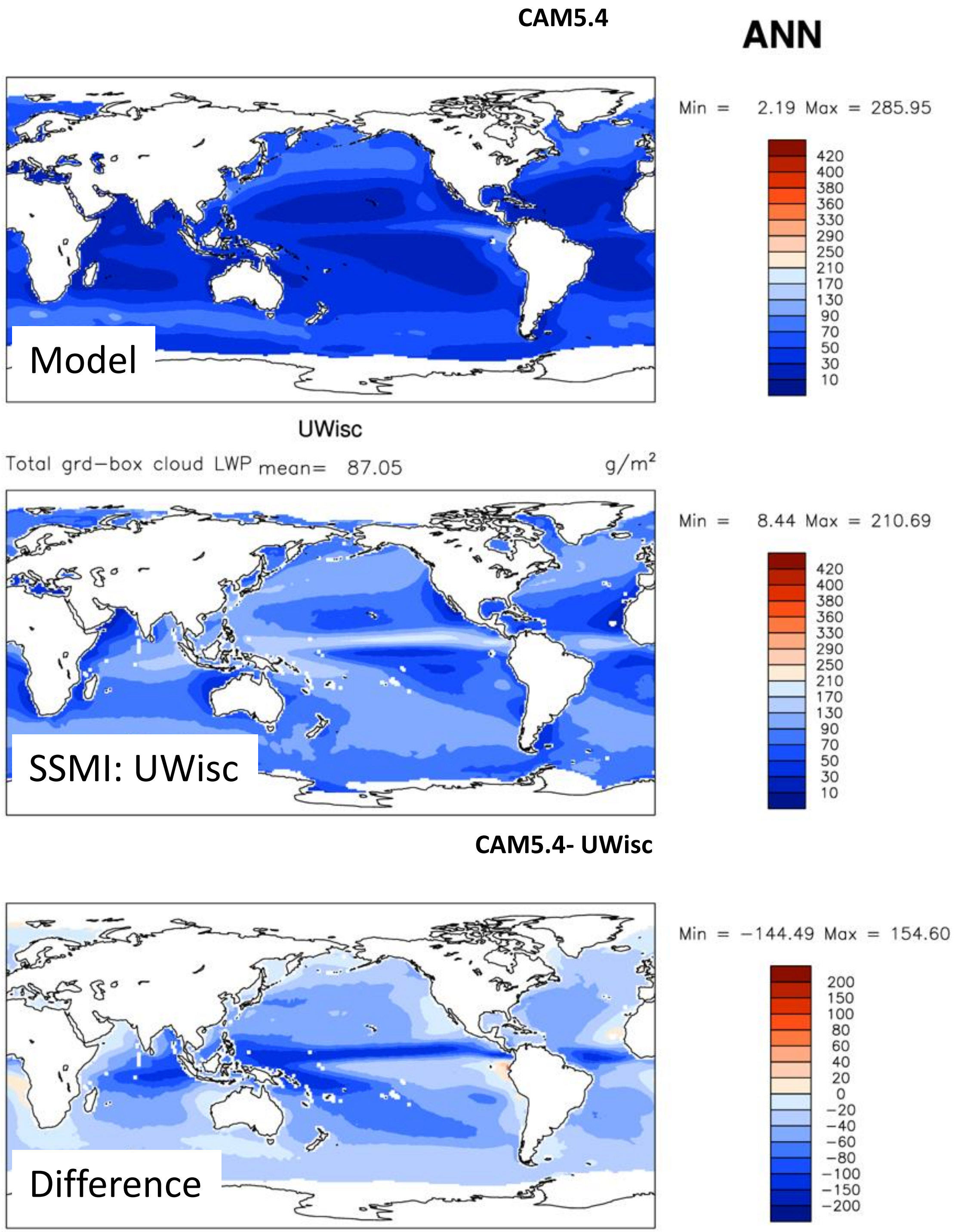


Observations

Traditional LWP
Wrong Message

Traditional comparison of Model LWP field against Microwave Satellite Observations of LWP. Model is low. But cloud forcing looks okay, and the cloud fraction looks okay. What is going on?

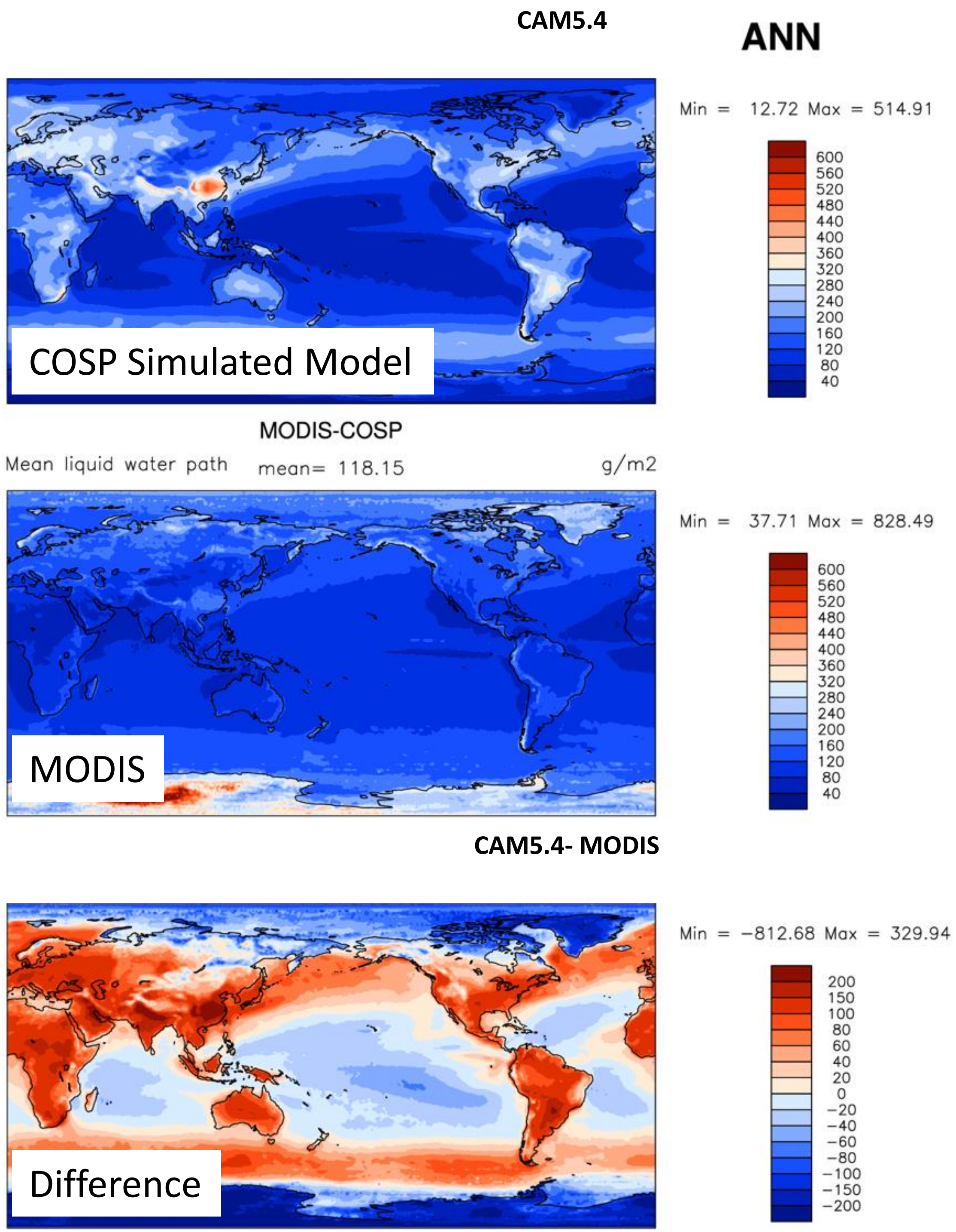
Same problem with comparison with MODIS LWP retrievals…



LWP: Correct Message

Use of the MODIS simulator for LWP: implies an Adiabatic assumption for low clouds. The model is not Adiabatic, but assuming it is Adiabatic increases LWP, especially over land and storm tracks

Now the model is slightly HIGHER than observations (+20%) rather than -50% LOW.



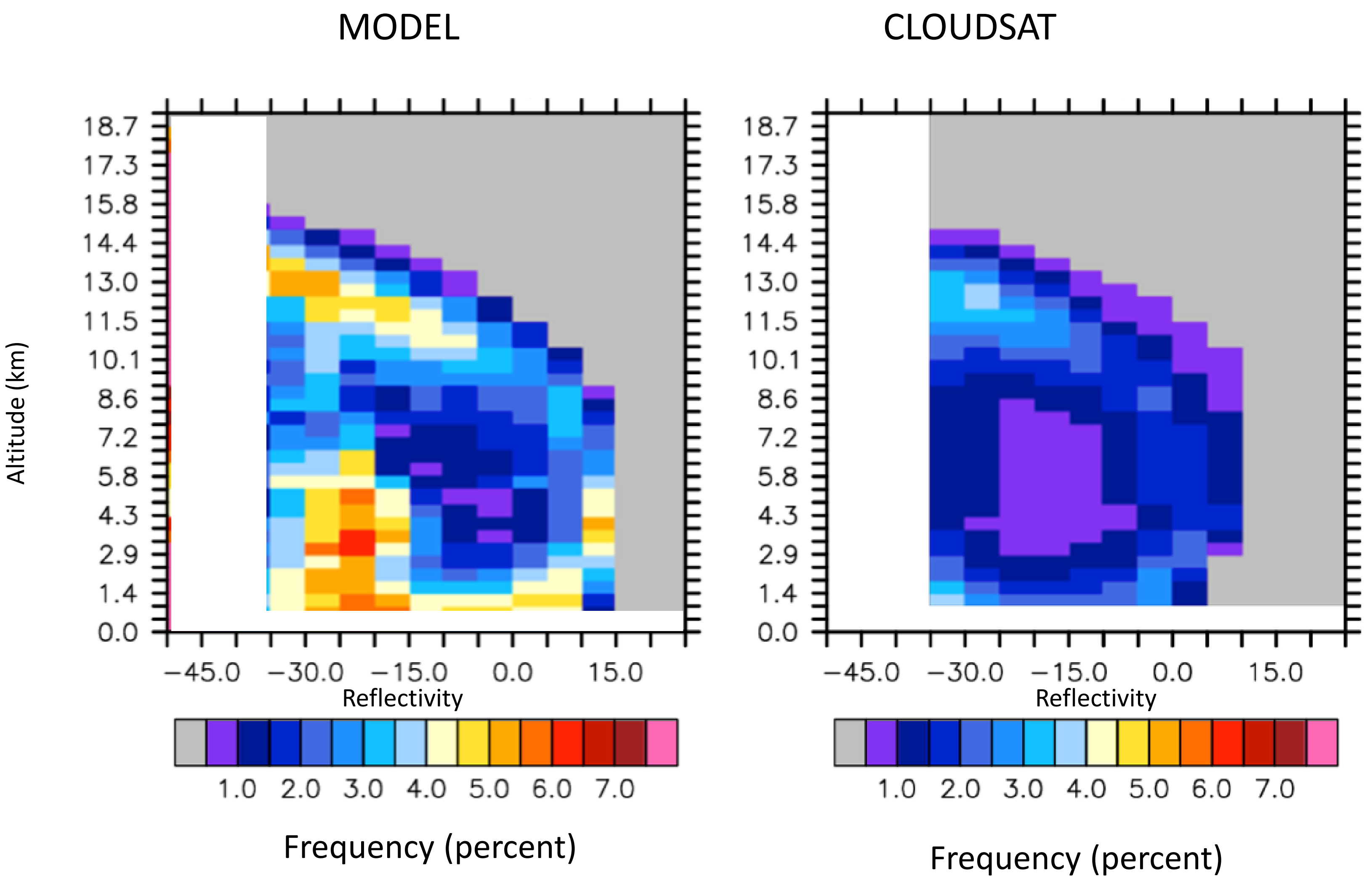
Simulate Reflectivity

Simulate observed quantities: in this case, Reflectivity ($Z \propto D^{-6}$)

Cumulative Frequency by Altitude Diagram (CFAD)

CFADs reveal modes of variability and regimes in models and observations

Here: low thin clouds too extensive, too much moderate drizzle



‘Next Generation’

- Research → Operations → Research
  - Many ‘A-Train’ (2000s-today) research sensors now ‘operational’
    - VIS/IR: AIRS/MODIS → CrIS, IASI-NG, VIIRS
  - Improved GEO capability (getting to cloud top size)
    - SEVIRI, Himawari-8
    - MTG-IR is ‘interesting’ (AIRS/CrIS/IASI in GEO)
- Next Gen Research Satellites
  - EarthCare (Doppler Radar)
  - Big goals for NASA (ACCP, 2029, Next generation):
    - HSRL Lidar (aerosol size/speciation, phase)
    - Doppler Radar: Cloud and Precipitation
    - Cloud Scale vertical velocities. Vertical motion all the way to severe storms
    - Platforms still being discussed: LEO & GEO or constellation considered

Summary/Opportunities

- Models are now getting more detailed microphysics
  - Sub-grid distributions of microphysics
  - Mass, number of drops, crystals
  - Riming and Phase
  - Shape of ice crystals
  - Precipitation and Cloud distributions
- Lots of interesting uses of observations for evaluation
  - Active sensors are quite interesting: rain formation processes
  - Even passive sensors have value for mass (MW) and size (IR)
- Simulators provide a way forward
  - Shown how we can work with forward operators to compare fields
  - Assimilation (increments) can do similar things
- Scale separation is not a problem for large scale models and satellite observations of microphysics
  - Enough scale separation to (10^{-6}m → 10^{3}m) to treat statistically
- Will standardization of assimilation workflows facilitate climate research?
  - OOPS, JEDI
- Excited to hear more details and experiment!

Extra

Auto-conversion (Ac) & Accretion (Kc)

Khairoutdinov & Kogan 2000: regressions from LES experiments with explicit bin model

Ac = $$\left(\frac{\partial q_r}{\partial t}\right)_{\mathrm{auto}} = 1350 q_c^{2.47} N_c^{-1.79}, \qquad (29)$$

Kc= $$\left(\frac{\partial q_r}{\partial t}\right)_{\mathrm{accr}} = 67 (q_c q_r)^{1.15}. \qquad (33)$$

- Auto-conversion an inverse function of drop number
- Accretion is a mass only function

Balance of these processes (sinks) controls mass and size of cloud drops

Autoconversion and Accretion & Sub Grid

- If cloud water has sub-grid variability, then the process rate will not be constant.
- Autoconversion/accretion: depends on co-variance of cloud & rain water
- Assuming a distribution (log-normal) a power law $M=ax^b$ can be integrated over to get a grid box mean M

$$\bar{M} = \int ax^b P(x)dx = E[v_x, b]a\bar{x}^b$$

$$E[v_x, b] = \left(1 + \frac{1}{v_x}\right)^{\frac{b^2-b}{2}}$$

E = Enhancement factor

and v_x is the normalized variance $v_x = x^2/\sigma^2$

E.g.: Morrison and Gettelman 2008, Lebsock et al 2013