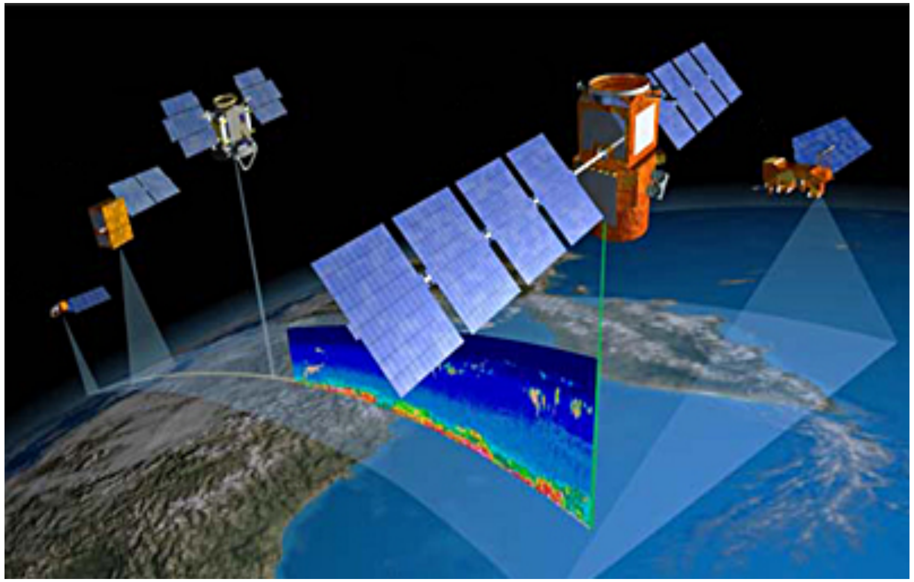
The 'too few, too bright' tropical low-level cloud problem in CMIP5 models.



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Structure

Overview of models, satellites, data sets and simulators used.

Comparison of observations and CMIP5 model output:

- cloud radiative effect
- cloud optical properties
- vertical distribution of low-level clouds.

Conclusions

Identify systematic and compensating errors amongst the vertical representations of clouds and their optical properties using satellite retrievals.

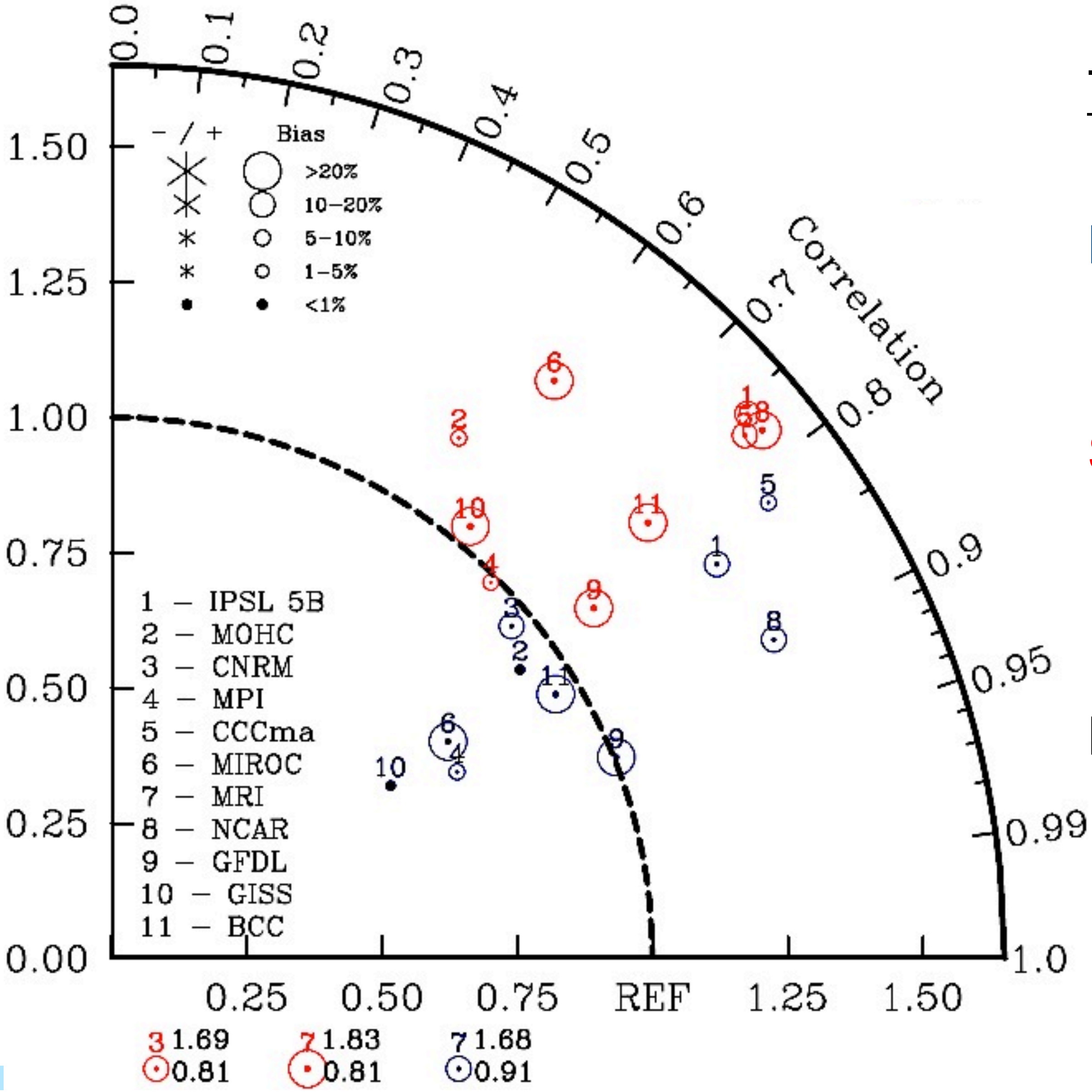
CMIP5 Models & Observations

- CMIP5: AMIP experiments from 06/2006 – 12/2008.
  - IPSL: IPSL-CM5B-LR
  - CNRM: CNRM-CM5
  - MPI-M: MPI-ESM-LR
  - MOHC: HadGEM2-A
  - CCCma: CanAM4
  - MIROC: MIROC5
  - MRI: MRI-CGCM3
  - NCAR: CCSM4

  } With COSP CALIPSO and Parasol satellite simulators.

- Observations: Combine active and passive satellite instruments to understand the vertical structure of multi-layered clouds.
  - CALIPSO (GOCCP): Total/High/Mid/Low & 3D cloud fraction.
  - Parasol Reflectances
  - CERES (EBAF): Cloud Radiative Effect
  - ERA-Interim Re-analysis: Large scale environmental properties.

Cloud Radiative Effects



Standardized Deviations (Normalized)

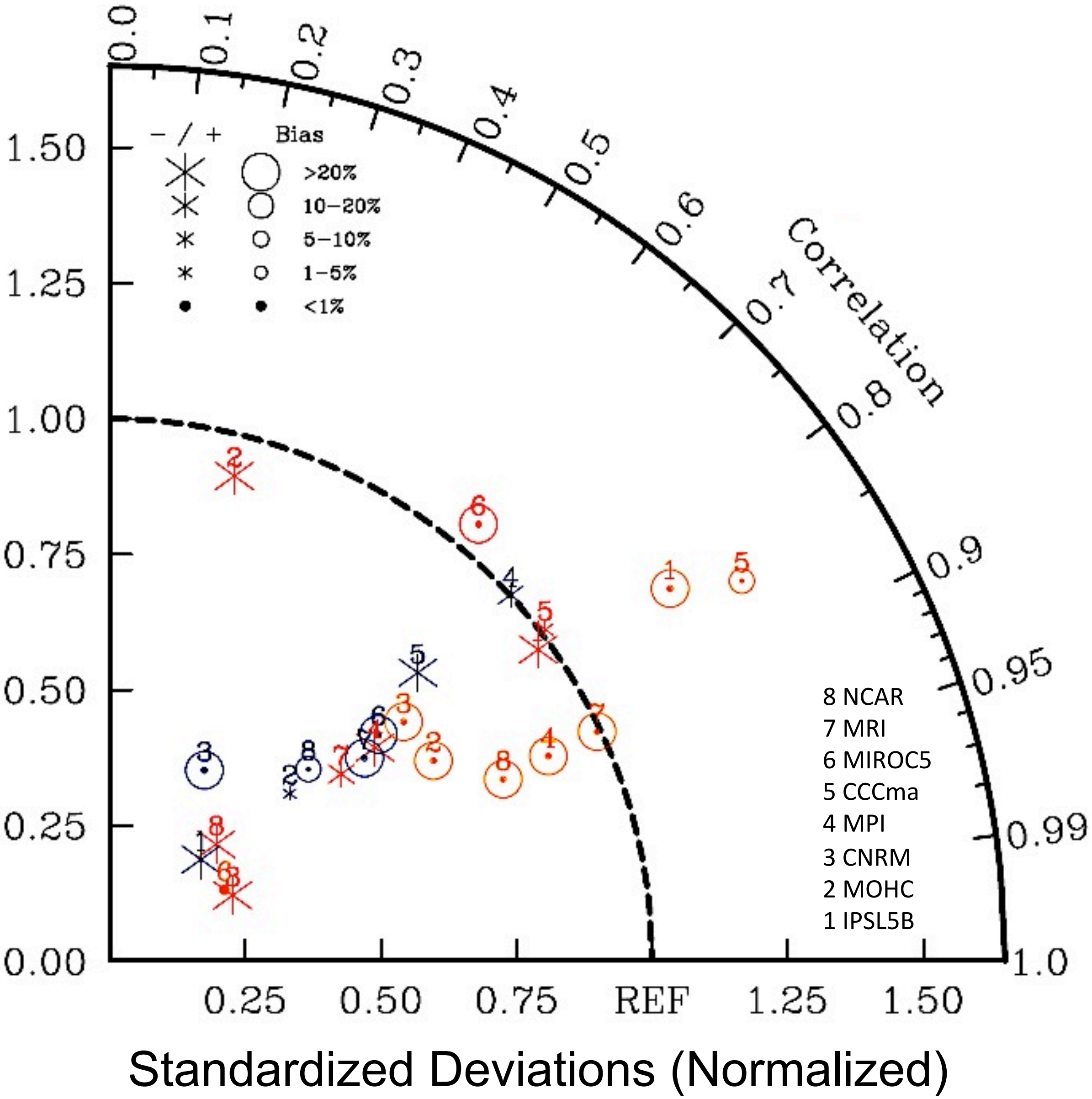
<u>Tropics (30°N to 30°S)</u>:

Longwave CRE: models are positively biased (27Wm^{-2} $_{CERES}$).

Shortwave CRE: models are positively biased (-46 Wm^{-2} $_{CERES}$).

LW CRE shows better spatial variability & correlation with observations than SW CRE.

Cloud Cover



Tropics (30ºN to 30ºS):

Low-level: All but one model is negatively biased ($30\%_{\text{CALIPSO}}$).

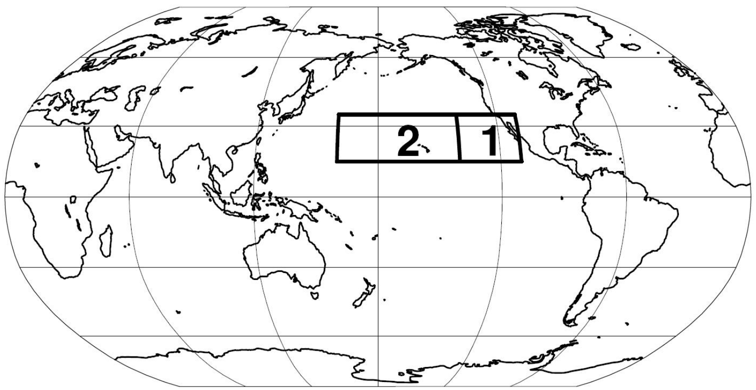
Mid-level: models both positively and negatively biased ($13\%_{\text{CALIPSO}}$).

High-level: models positively biased ($34\%_{\text{CALIPSO}}$).

How is it SW CRE is over-estimated?

Low-level clouds

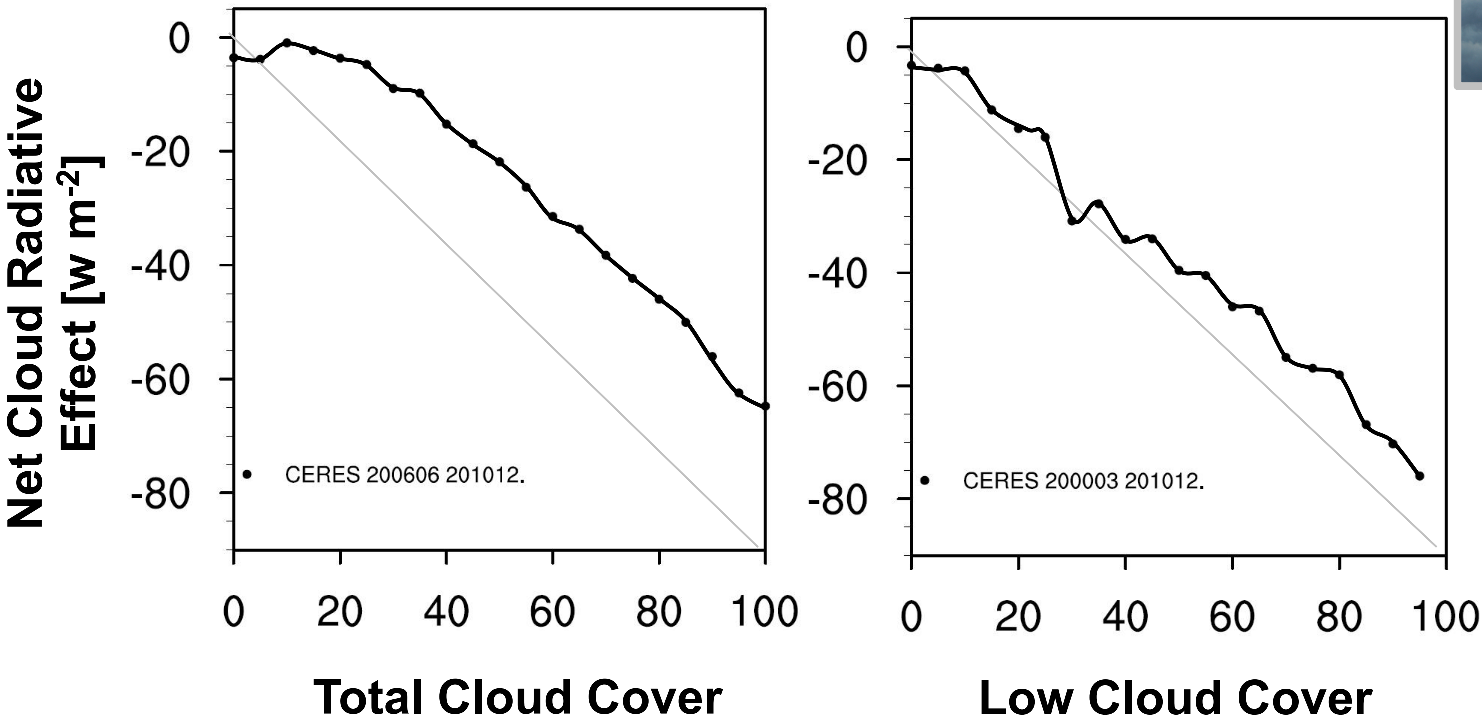
- Cloud Radiative Effect (CRE) above two geographical regions, representing low-level clouds:
  - Californian Stratocumulus
  - Hawaiian Shallow Cumulus.



Tropical, marine boundary layer clouds identified as primary cause for inter-model differences, in particular trade cumulus clouds and stratocumulus-to-cumulus transitions*.

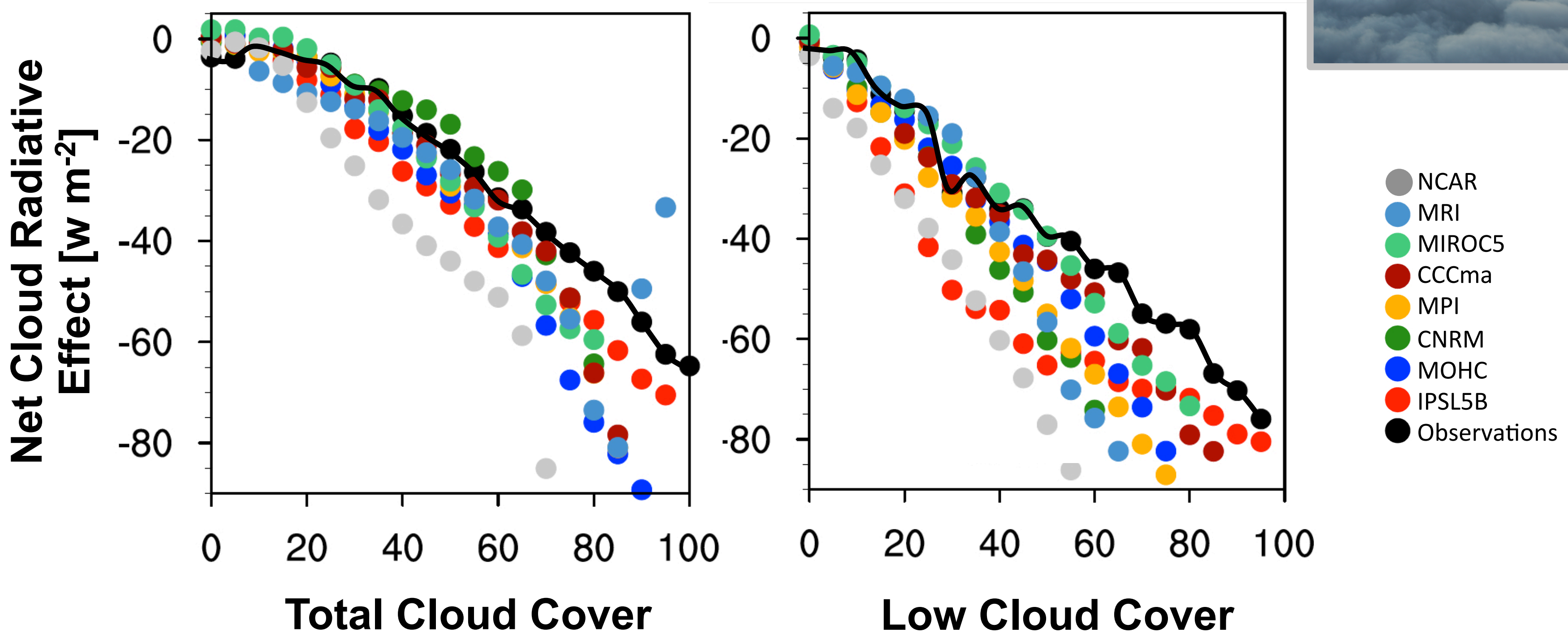
* Bony and Dufresne, 2005

Californian Stratocumulus



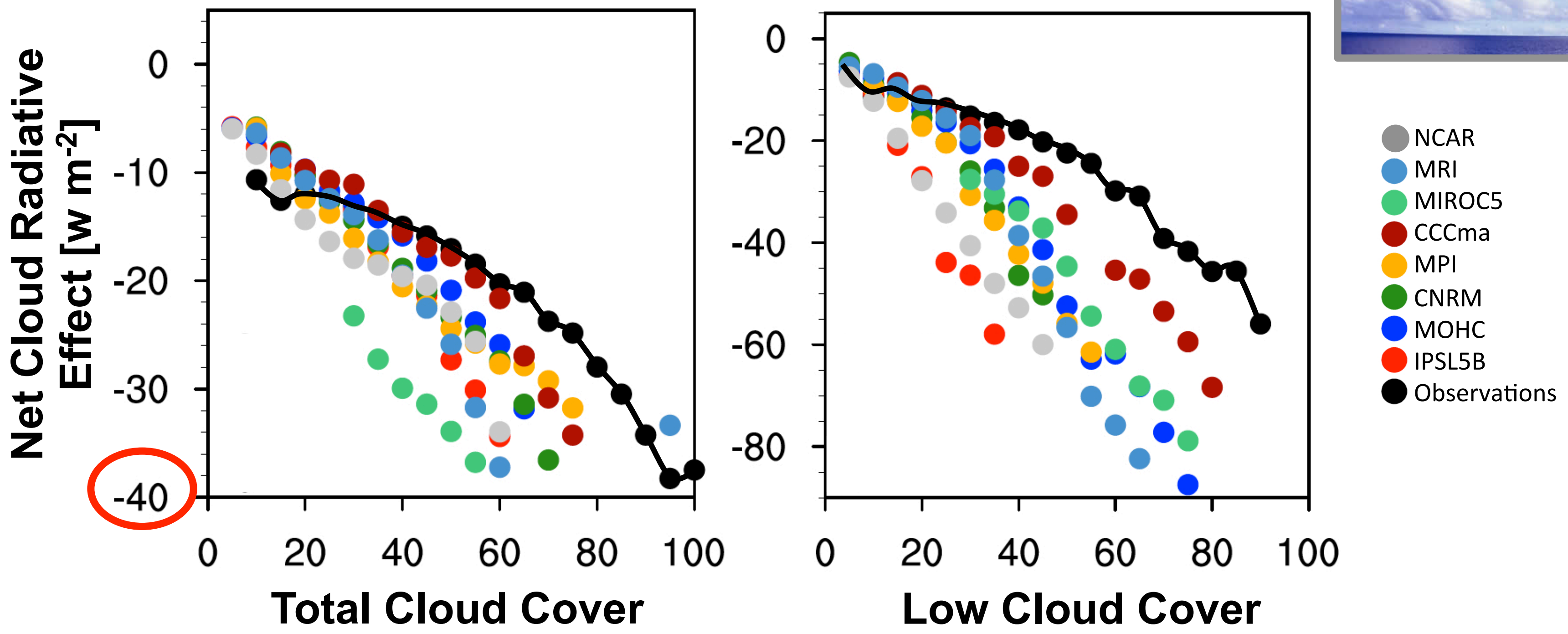
- Non-overlapped low-level cloud conditions occur when high- and mid-level clouds, as defined by CALIPSO, are less than 5%.
- High- and mid-level clouds act to dampening CRE.

Californian Stratocumulus



- CRE of particularly non-overlapped low-clouds are too reflective in models.
- Inter-model spread in CRE is greater under non-overlapped low-level cloud conditions.

Hawaiian Shallow Cumulus

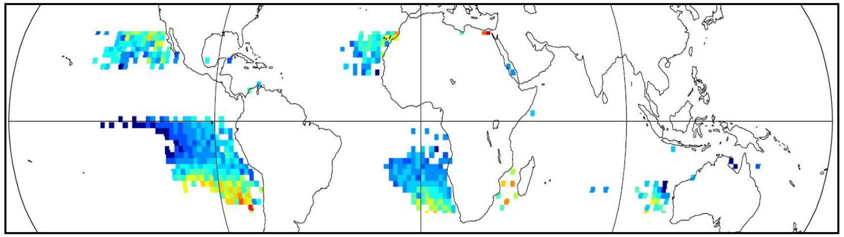


- Spread amongst models and observations, over non-overlapped low-clouds, is greater in Hawaiian region.
- Why is it that models have similar CRE for stratocumulus and shallow cumulus clouds?

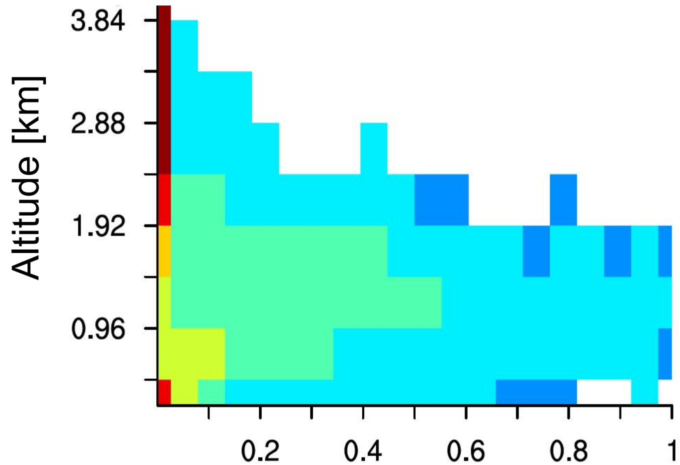
Vertical Distribution

- Expanded study area to 30N/30S.
- Identified non-overlapped low-level clouds (H,M<5%) under large-scale subsidence (w500hPa,w700hPa>10hPa day-1).
- Use LTS determine stratocumulus and shallow cumulus regimes.

Dynamical Stratocumulus



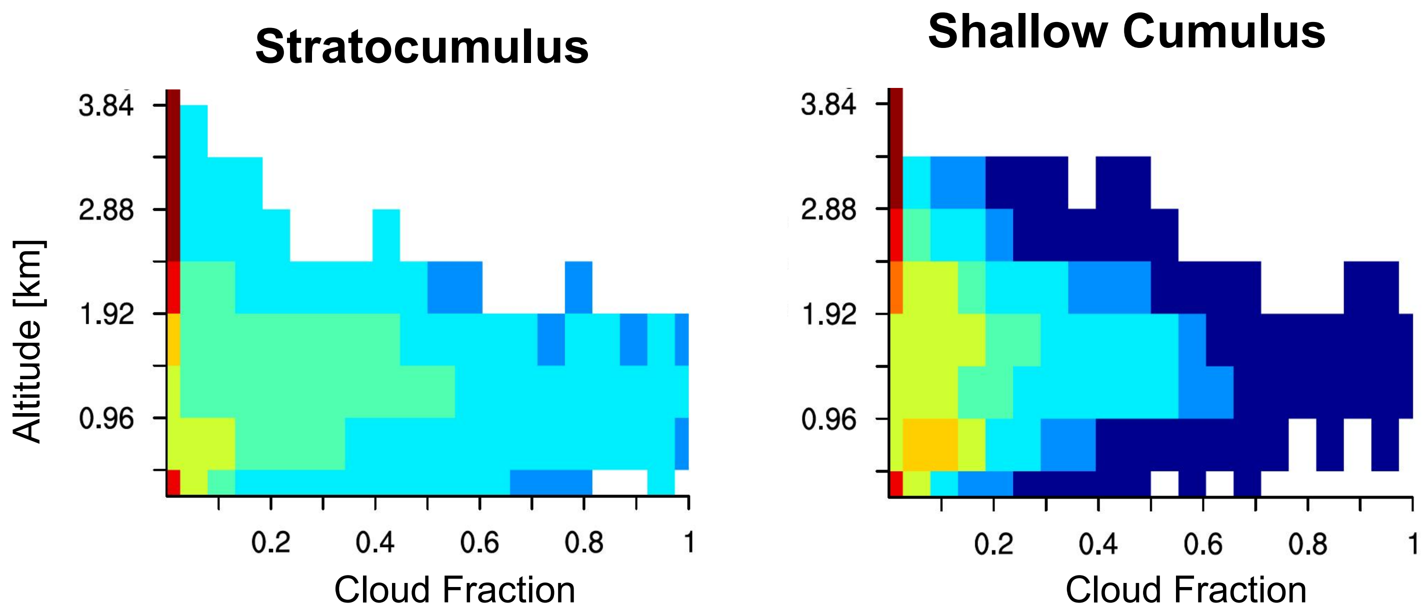
- Determine frequency of clouds of a given fraction at a given altitude in the lowest 4km of atmosphere.



Calipso Cloud Fraction

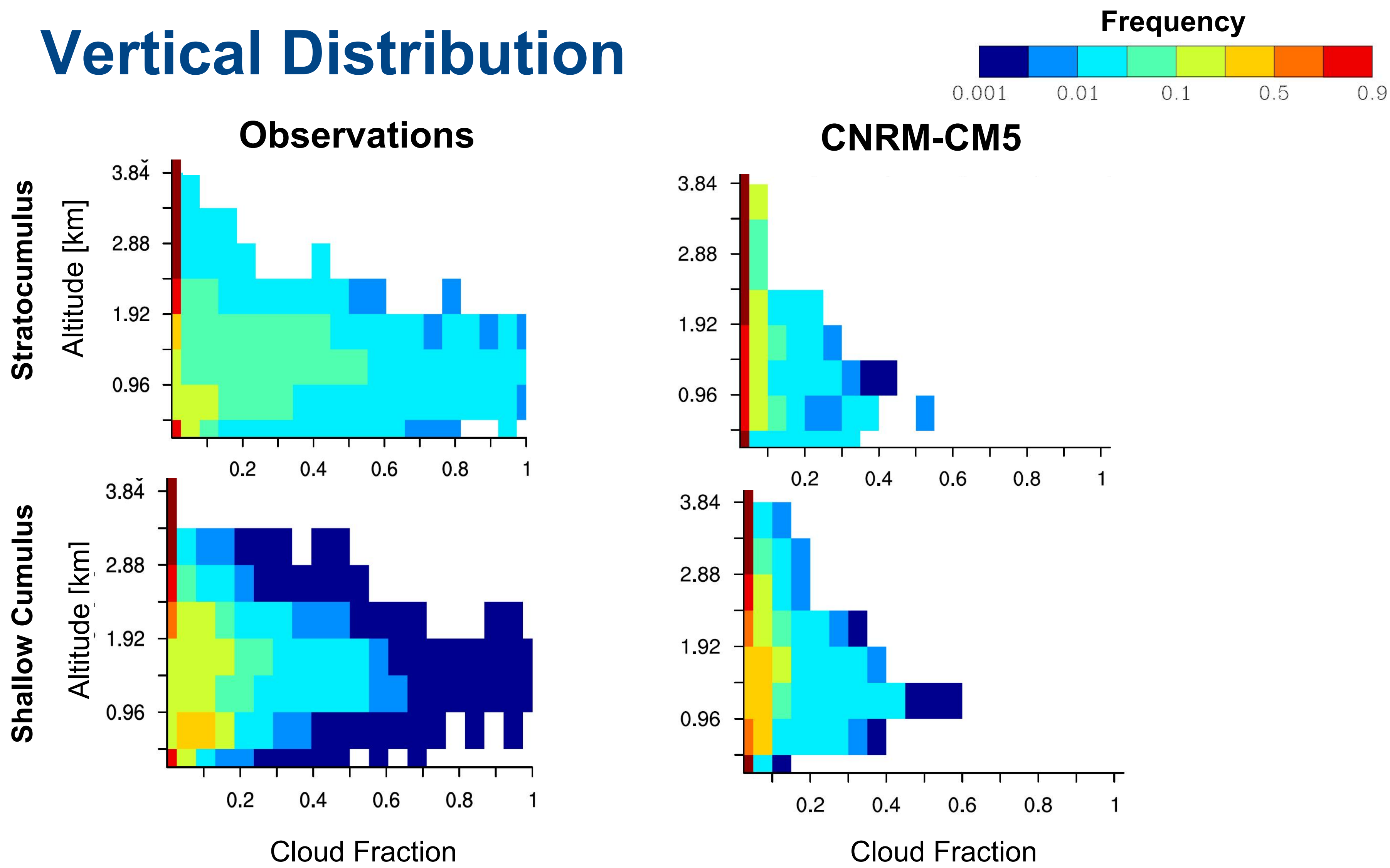
Vertical Distribution

Calipso Observations



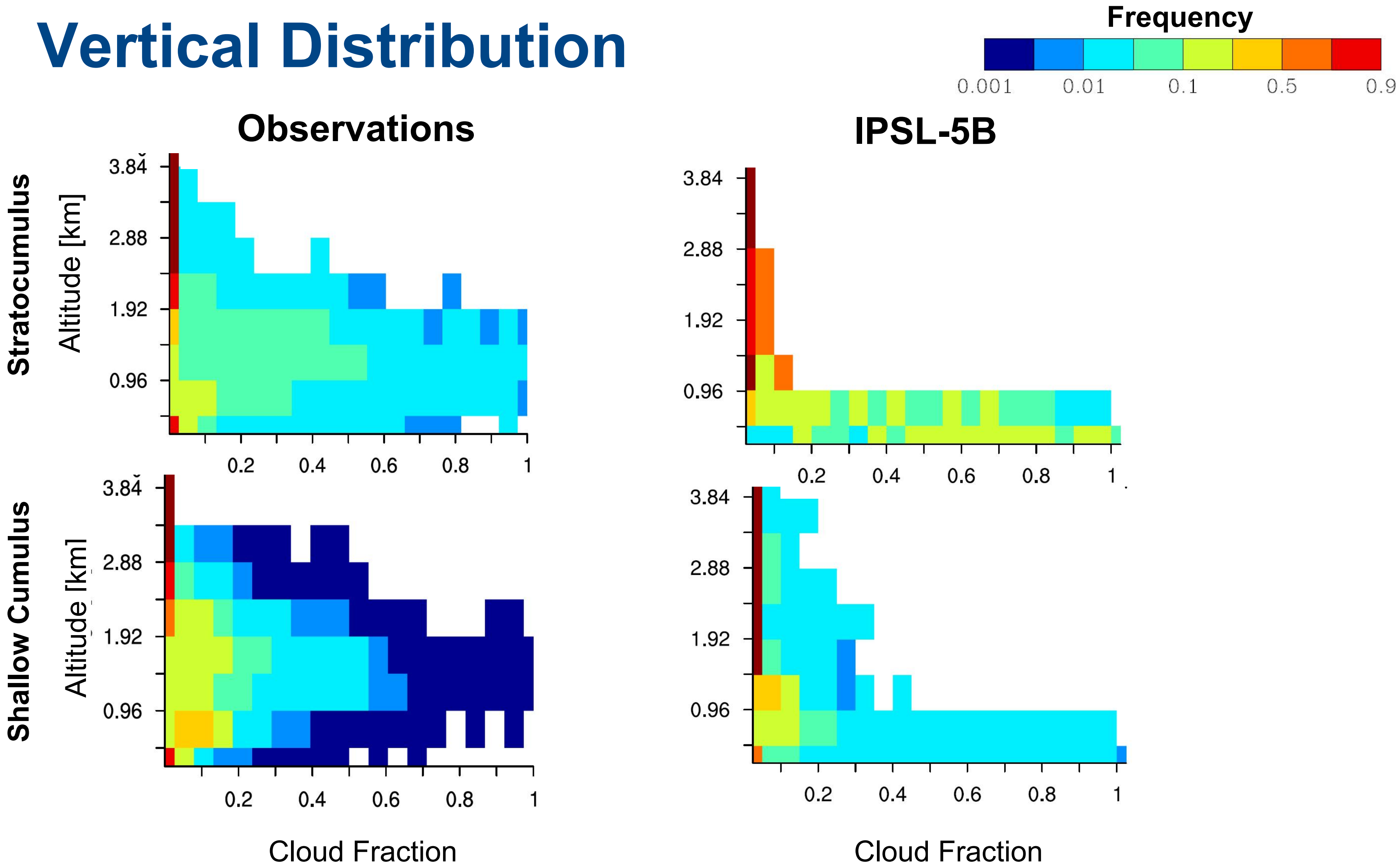
- Stratocumulus regime has a greater frequency of clouds with large fractions lower in the atmosphere than shallow cumulus regime.

Vertical Distribution



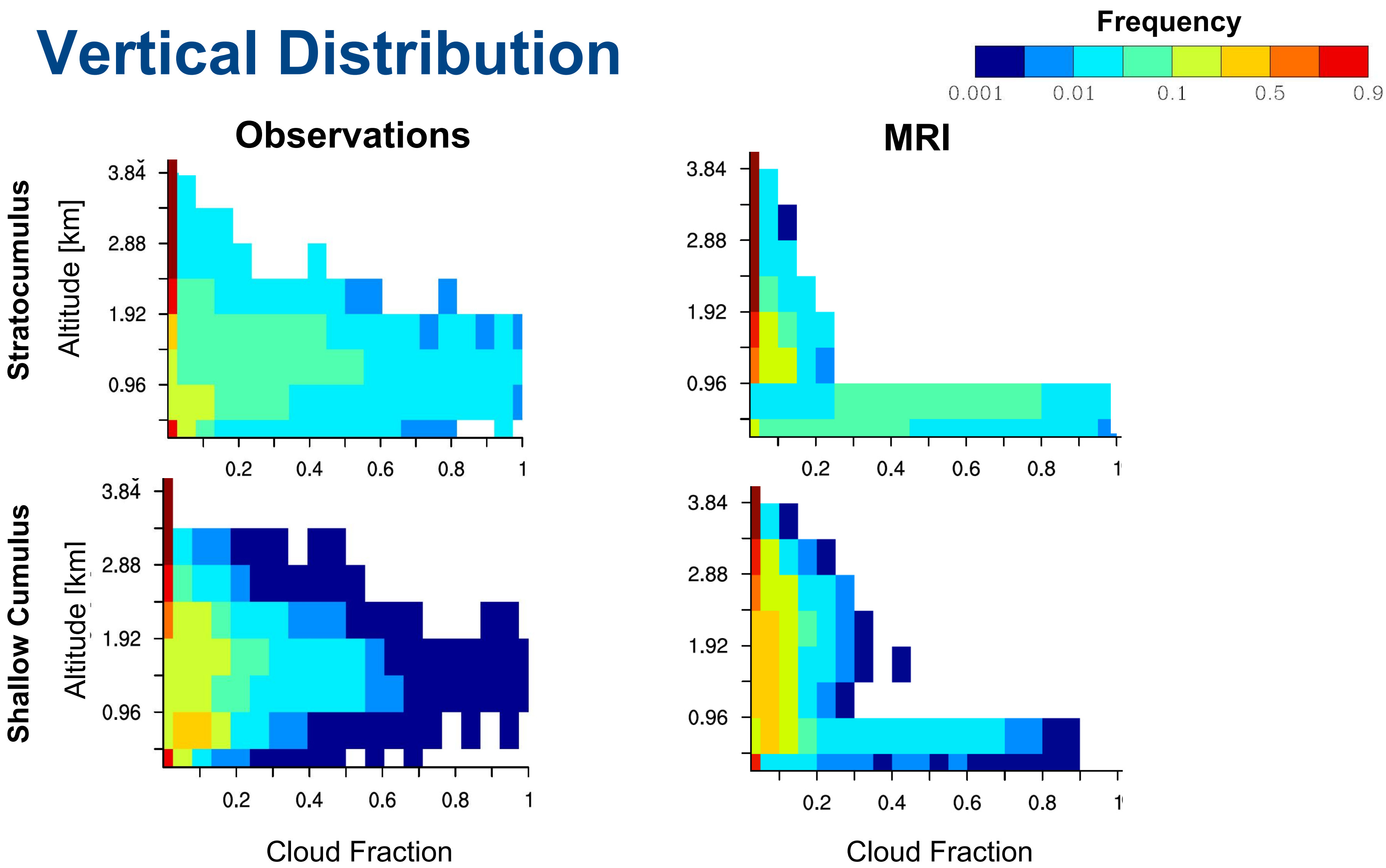
- Clouds distributed vertically, yet lacks presence of clouds with large fractions.

Vertical Distribution



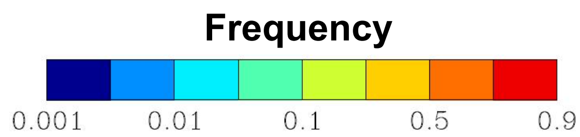
- Greater frequency of clouds below 1 km than observed.

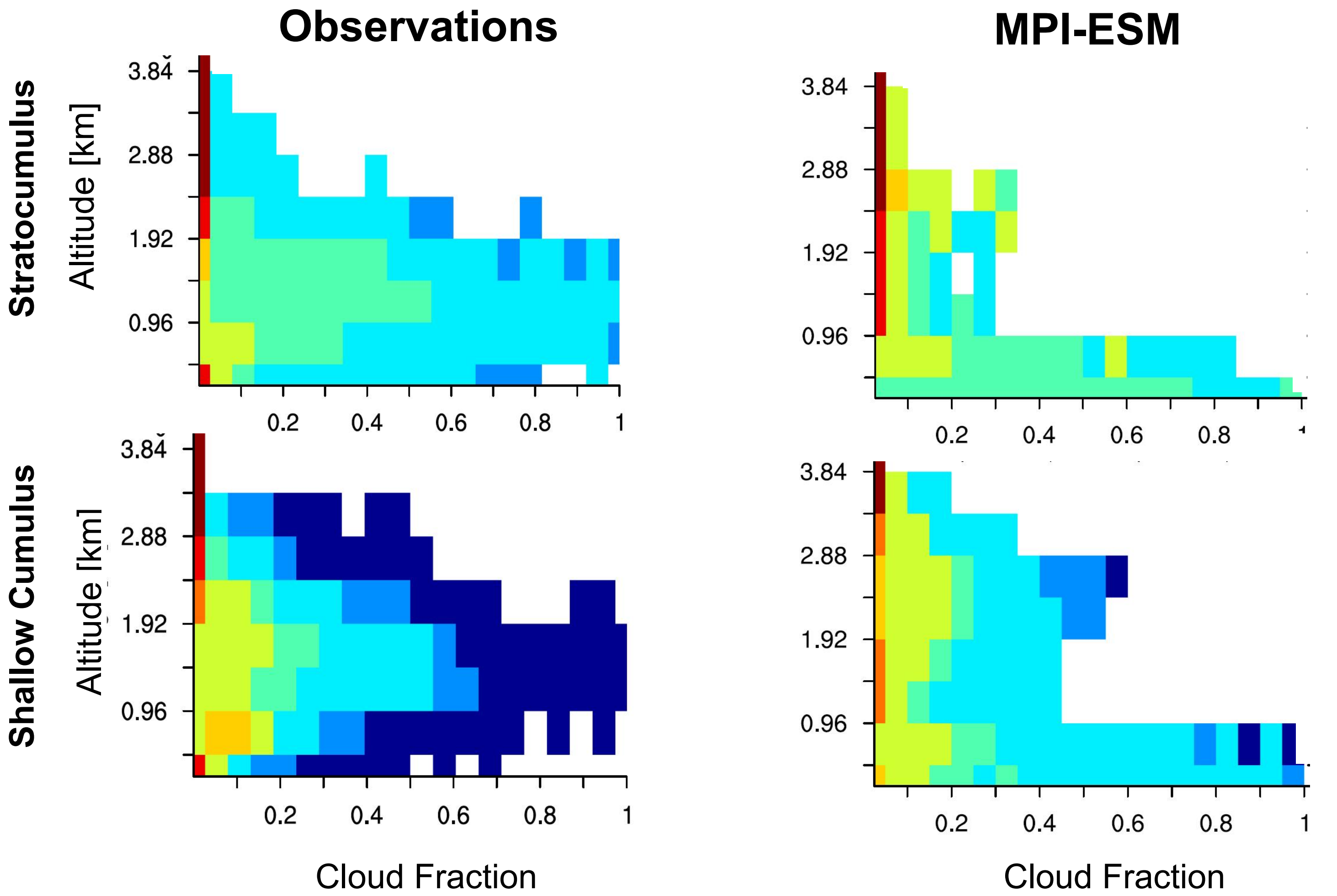
Vertical Distribution



- Greater frequency of clouds above 1 km than previous models.
- Clouds below 1 km occur frequently.

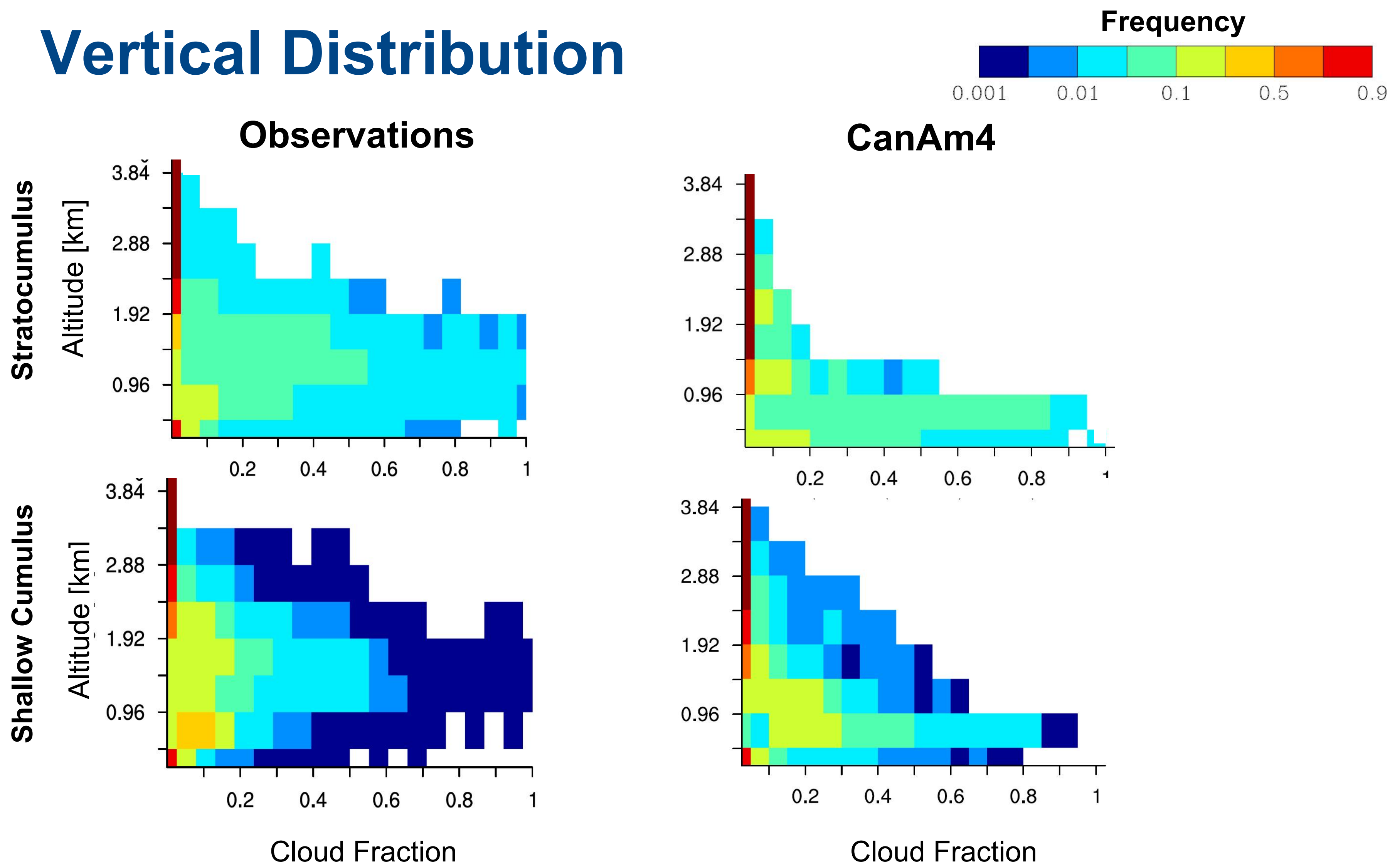
Vertical Distribution





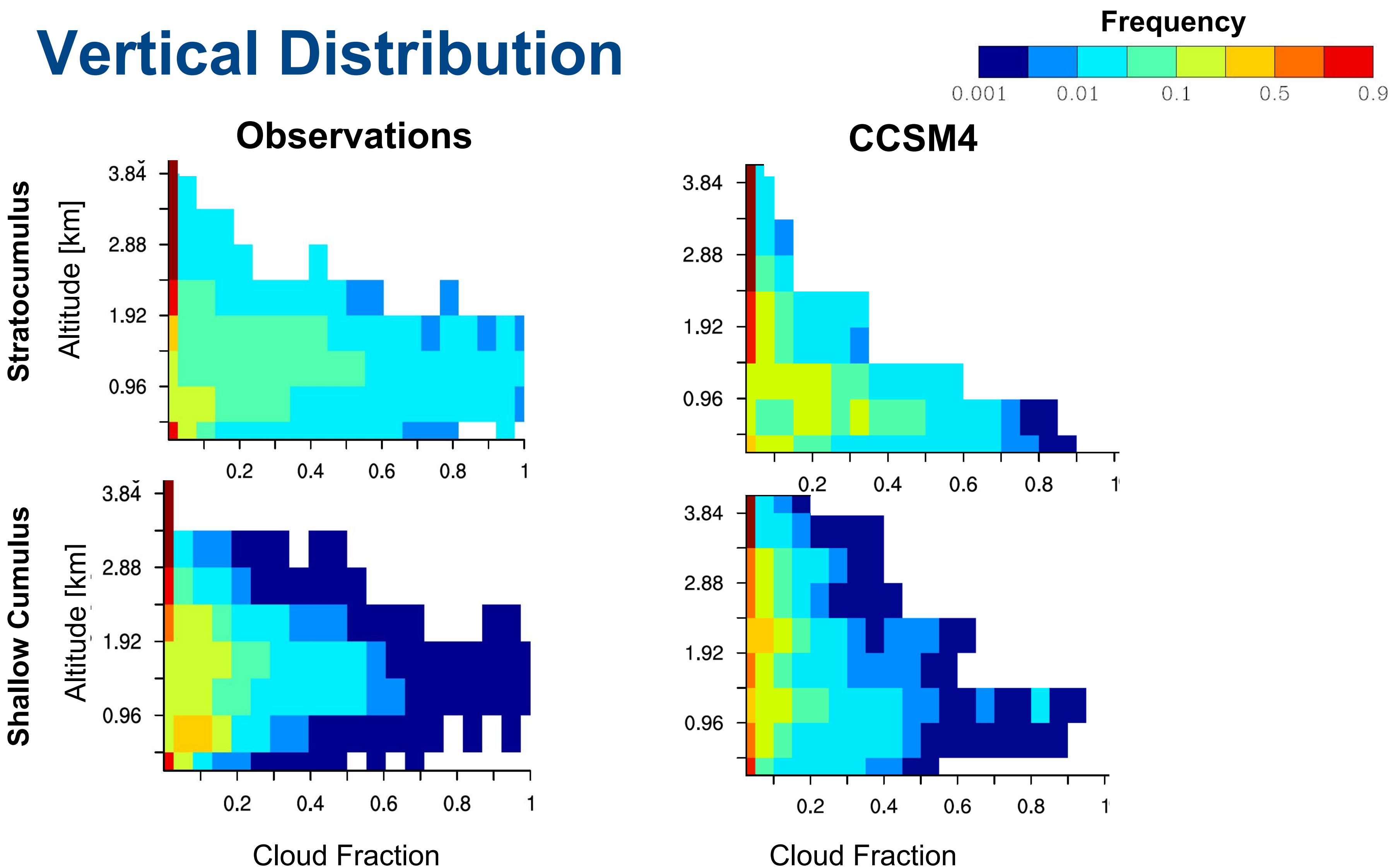
- Produces a greater frequency of clouds higher in the atmosphere.
- Greater frequency of clouds below 1 km than observed.

Vertical Distribution



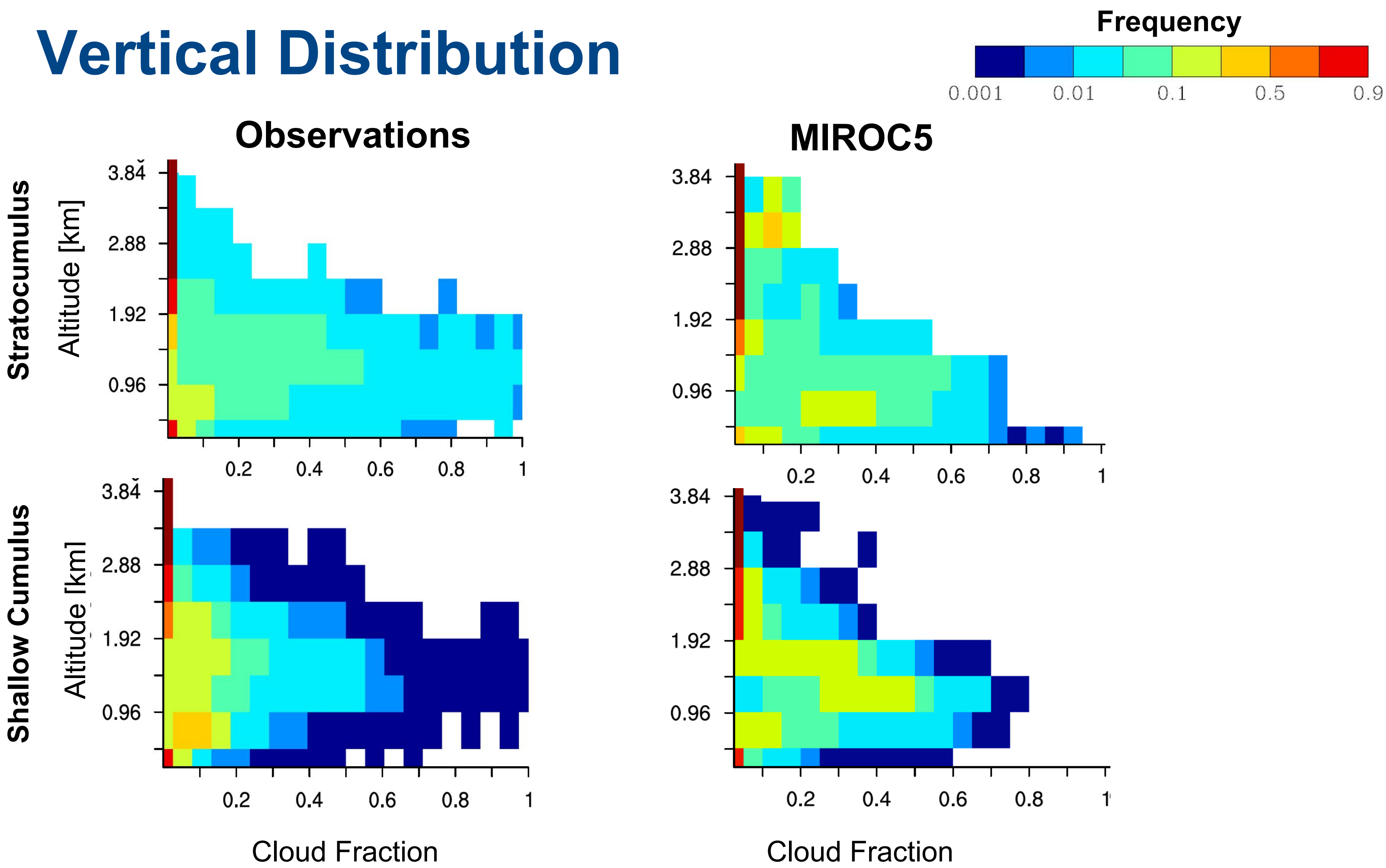
- Vertical distribution for both stratocumulus and shallow cumulus captured well. Greater frequency of clouds below 1 km.

Vertical Distribution



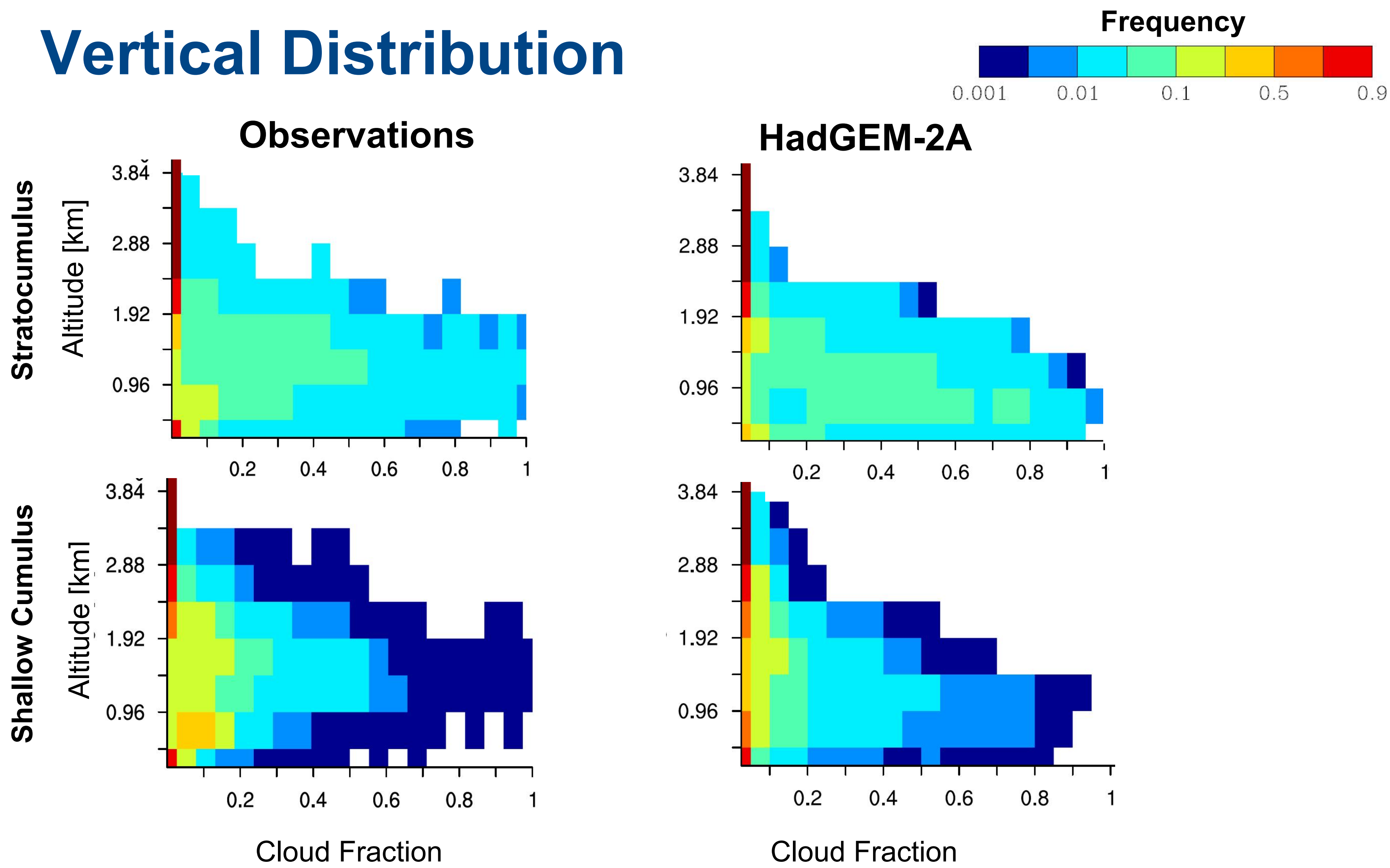
- Lacks clouds with fractions >0.6 above 1km.
- Captures vertical distribution of shallow cumulus clouds well.

Vertical Distribution



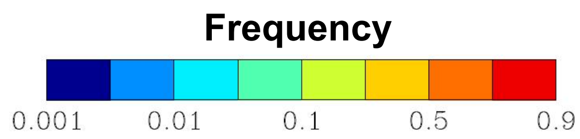
- MIROC5 captures the vertical distribution of clouds in both regimes.
- Overestimates clouds with fractions >0.4 in lower layers.

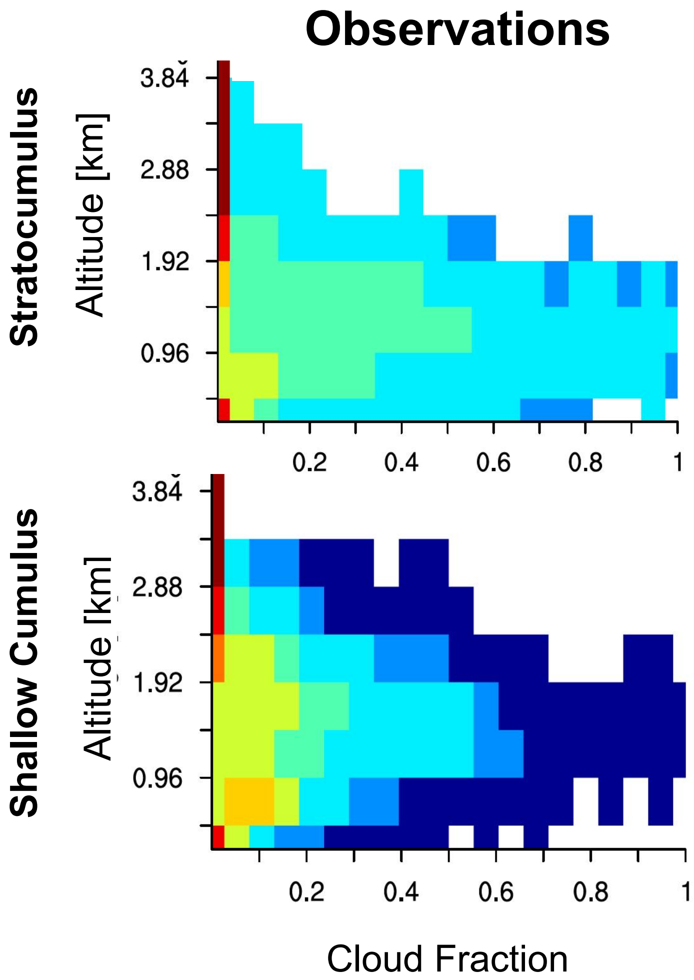
Vertical Distribution



- HadGEM2-A best captures the vertical distribution of clouds.
- Greater frequency of clouds with fractions >0.6 than observed.

Vertical Distribution

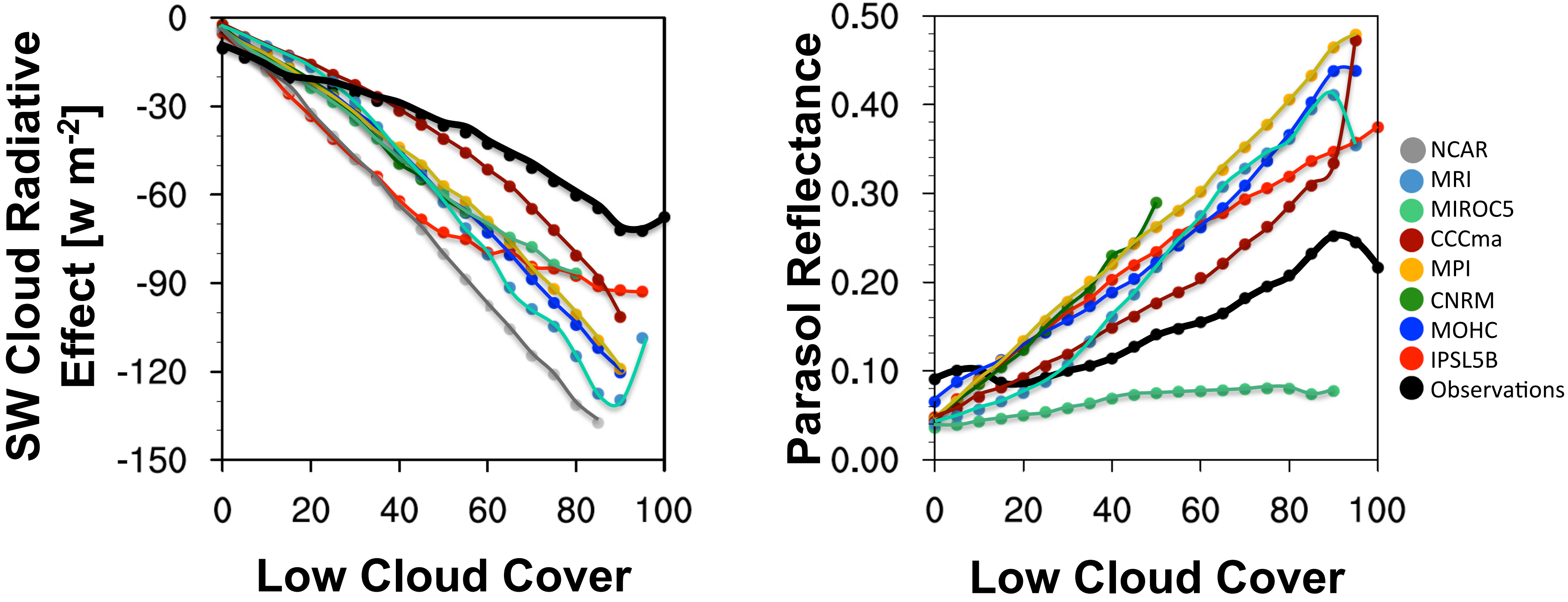




- Models experience difficulties in reproducing observed vertical structure.
- Stratocumulus clouds modeled when shallow cumulus ought occur.
- Reveals shortcomings in coupling of large-scale environment and parameterizations of boundary layer processes.

Cloud Optical Properties

Tropics (30°N to 30°S)



- Models generally have much stronger CRE, for a given cloud cover, than found in CERES observations.
- Parasol reflectances for a given cloud fraction is much greater than observed.

Discussion

What are the consequences of over-estimated low-clouds radiative effects on models' climate sensitivity?

- Strength of CRE in current climate may affect strength of low-cloud feedbacks in climate change.
  - Positive feedback between cloud-radiative effects, boundary layer relative humidity and low-cloud cover.
- Over-estimate of low-cloud radiative effects is likely to strengthen low-cloud feedback of climate models, independent of sign.
- Amplify spread of cloud feedbacks amongst climate models.

– *Brient & Bony, GRL 2012*

"How may low-cloud radiative properties simulated in the current climate influence low-cloud feedbacks under global warming?"

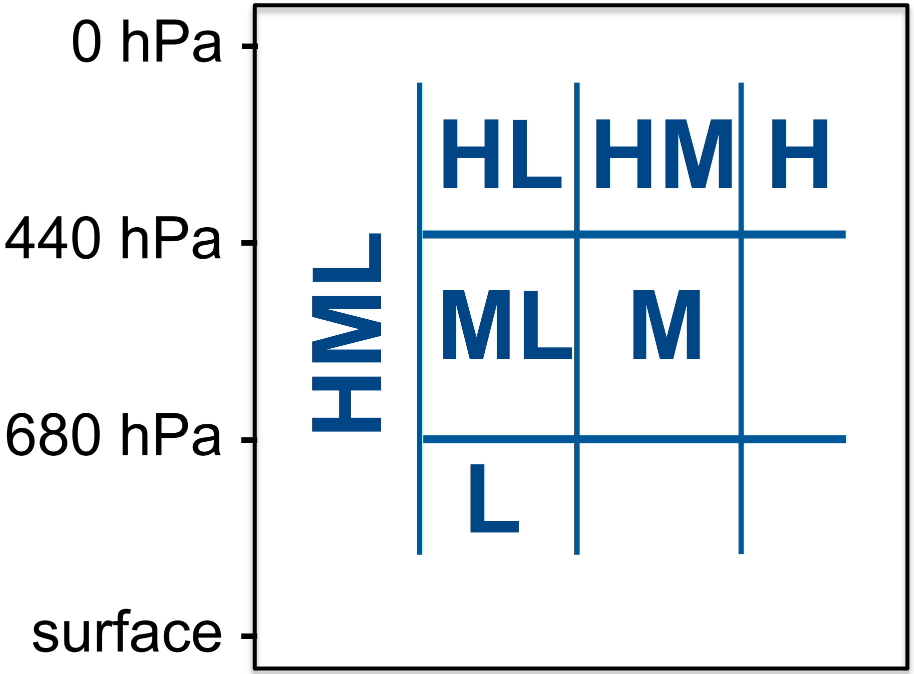
Conclusions

Where do CMIP5 models show systematic and compensating errors in the vertical distribution of clouds and their optical properties?

- Underestimate of Tropical low-level clouds.
- Over-estimate optical thickness of low-level clouds, particularly in shallow cumulus regimes.
- Poor representation of low-cloud vertical structure on large-scale environmental properties.
- Stratocumulus-type clouds predicted in regimes where shallow cumulus clouds should prevail.

Backup Slides

Cloud Combinations



Cloud cover distribution relative frequency of occurrence:

H – high-level clouds

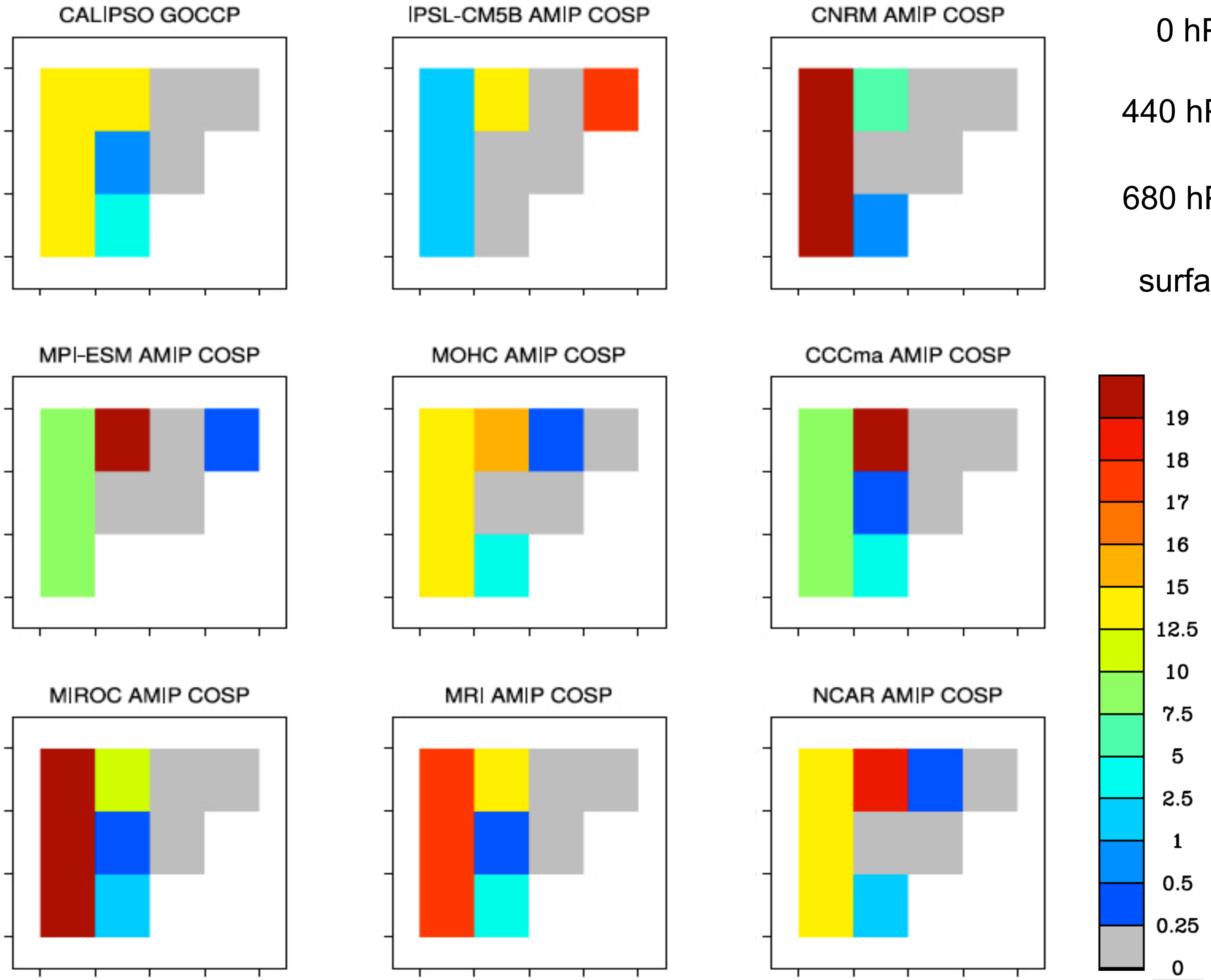
M – mid-level

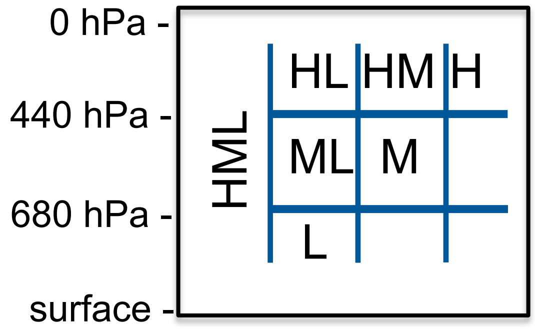
L – low-level

Plot excludes all clear sky (fractions less than 5%)

Cloud Combinations

Hawaiian Shallow cumulus

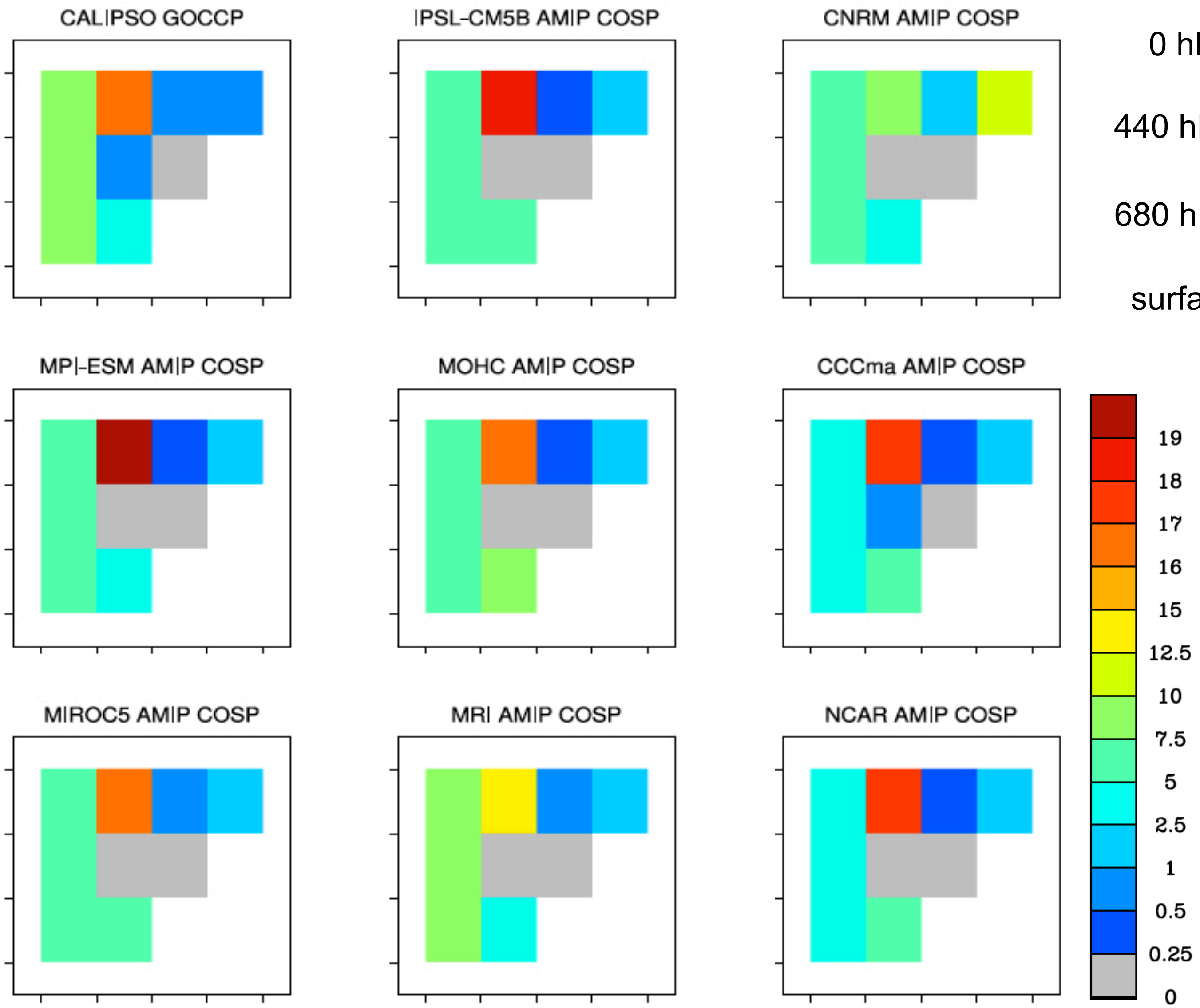


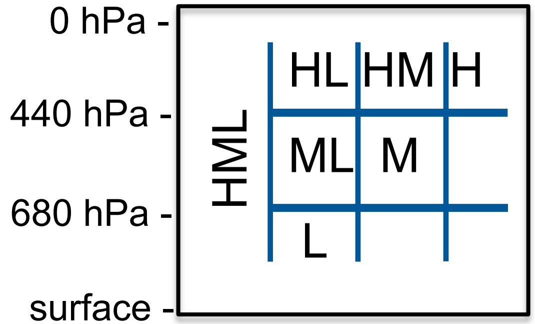


Frequency of 'HL' & 'HML' combination overestimated in several models.

Cloud Combinations

Californian Stratocumulus

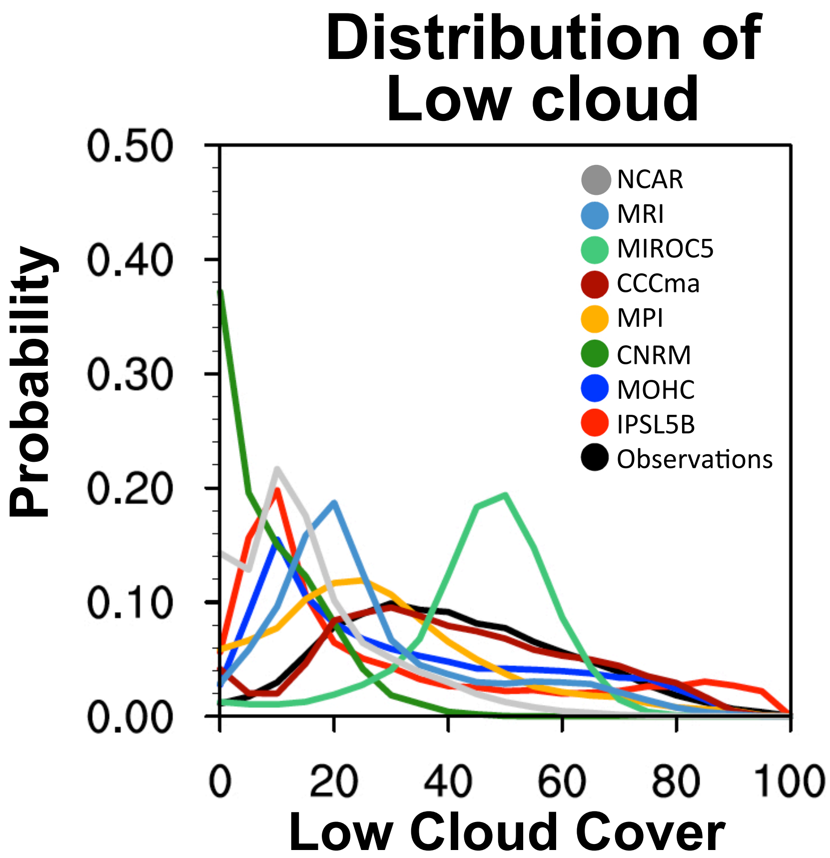


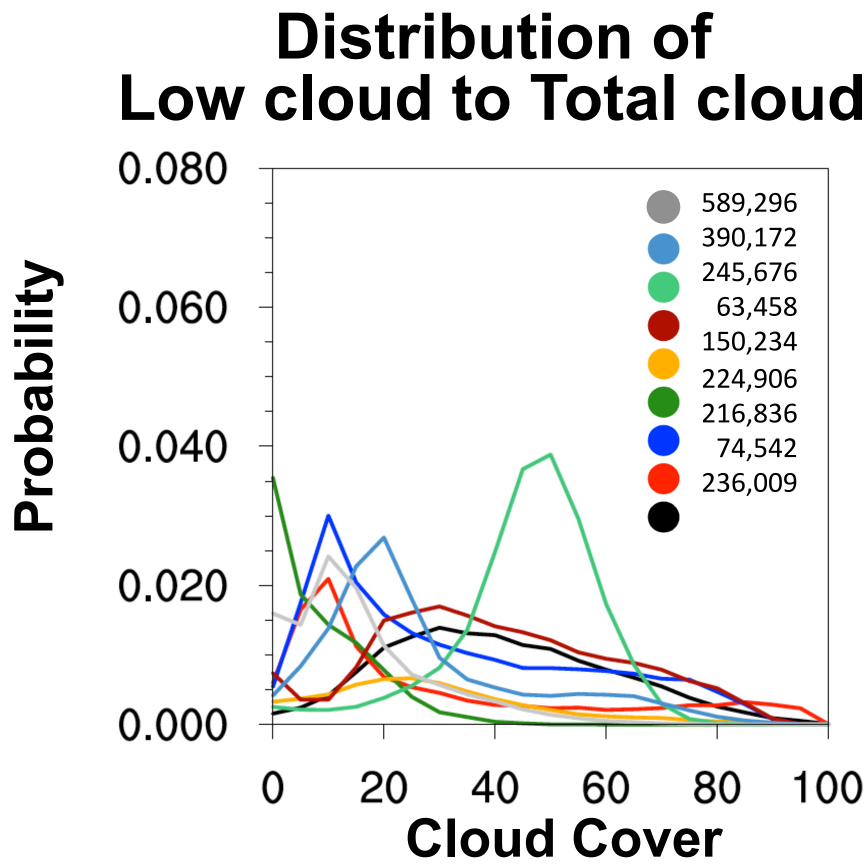


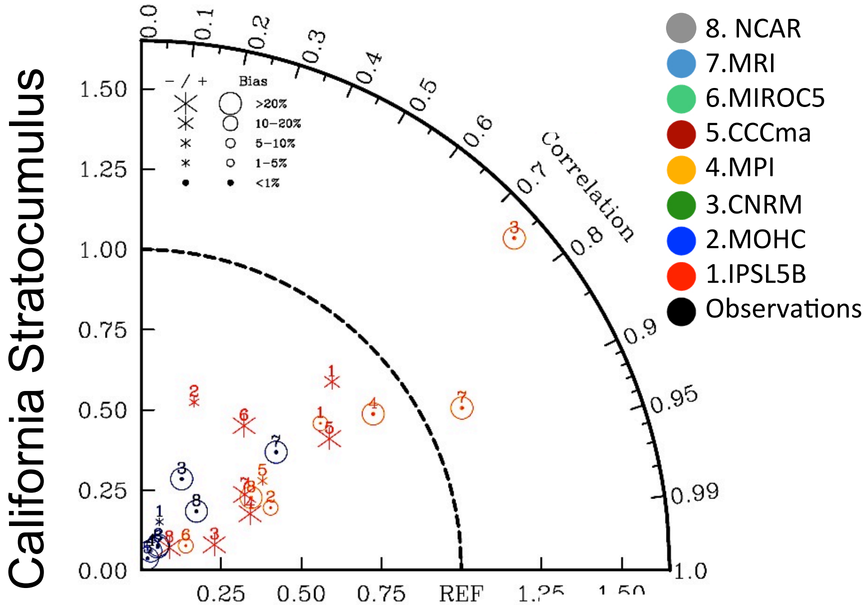
Despite being in a subsidence region, frequency of 'High & Low' combination overestimated in several models.

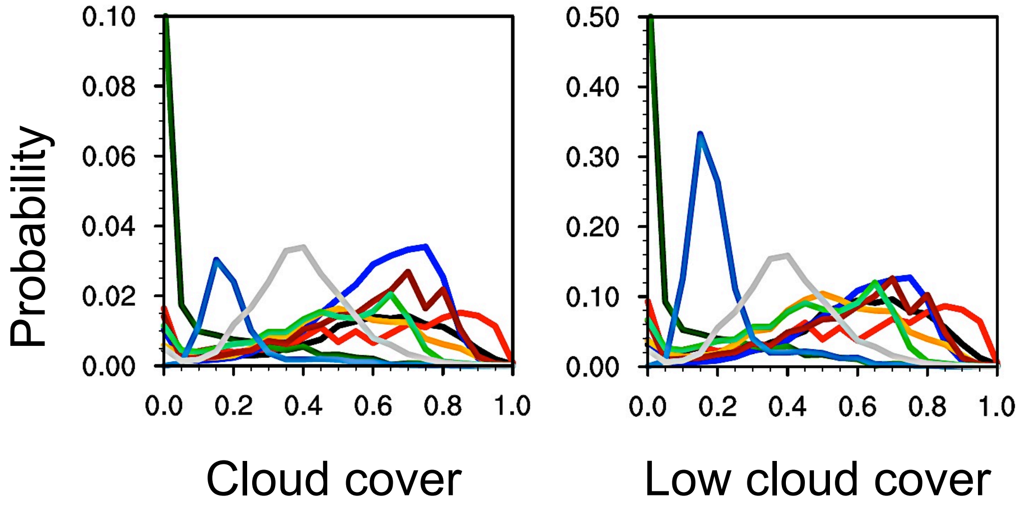
Probability Density Function

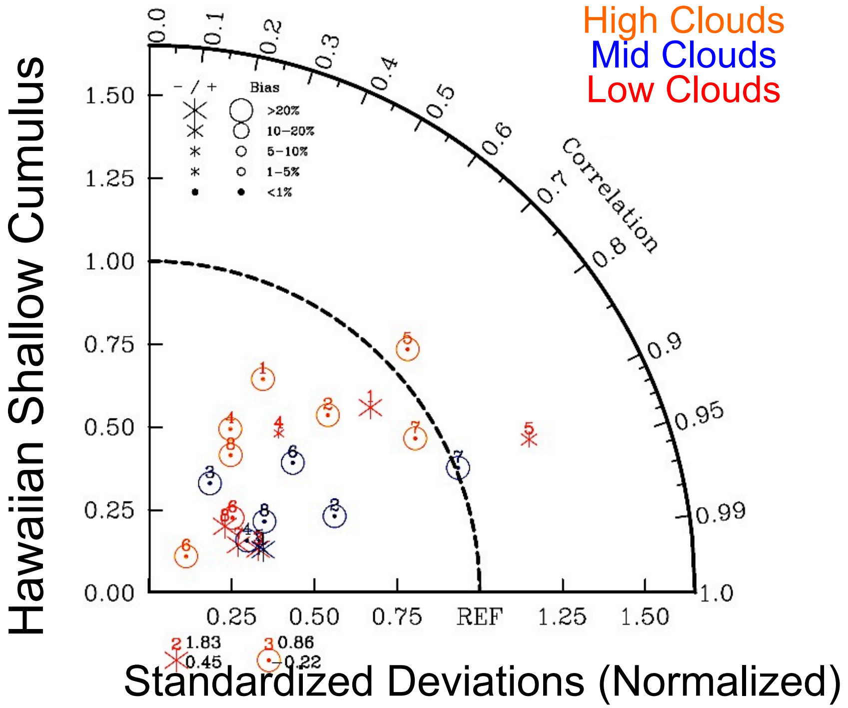
Tropics (30°N to 30°S)

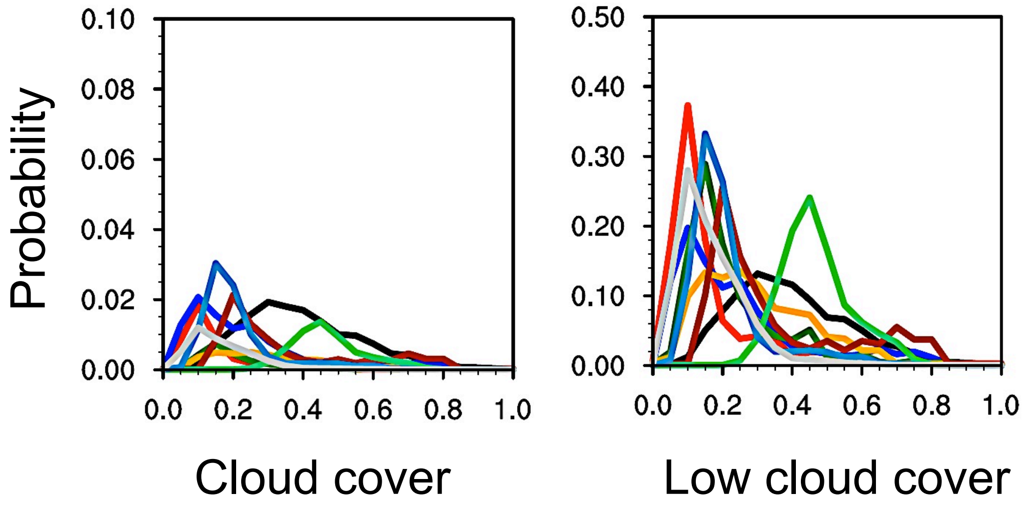





California Stratocumulus
Correlation
Bias
>20%
10–20%
5–10%
1–5%
<1%
REF
8. NCAR
7.MRI
6.MIROC5
5.CCCma
4.MPI
3.CNRM
2.MOHC
1.IPSL5B
Observations

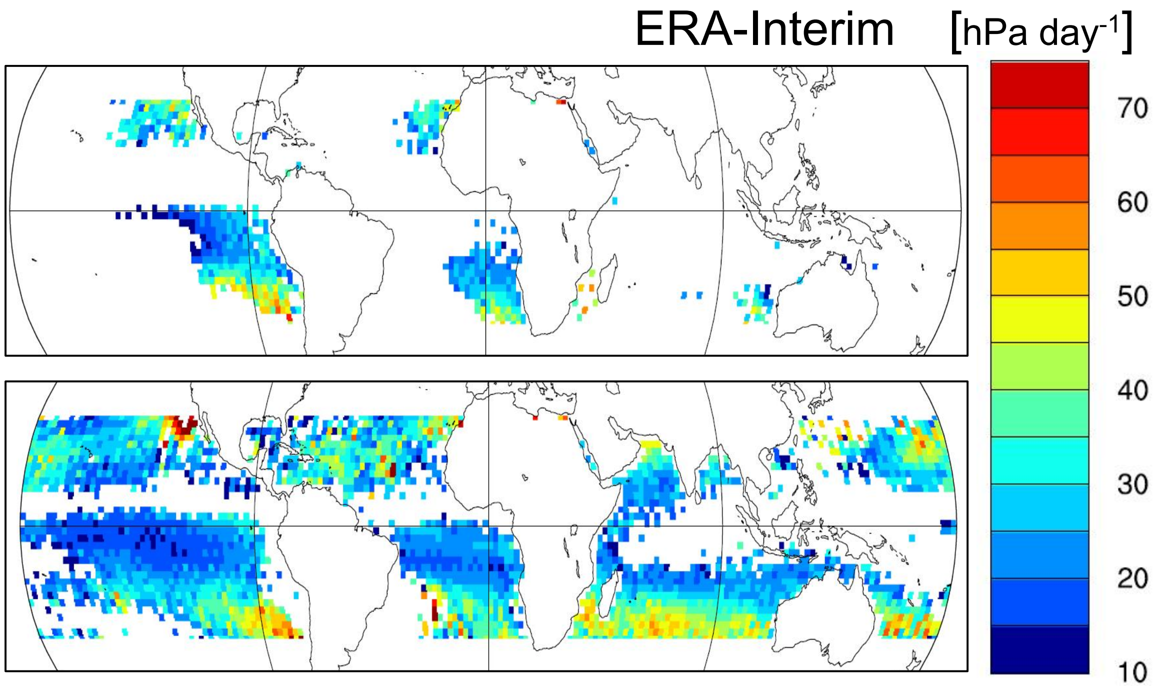

Probability
Cloud cover
Low cloud cover


Hawaiian Shallow Cumulus
Correlation
Bias
>20%
10–20%
5–10%
1–5%
<1%
REF
High Clouds
Mid Clouds
Low Clouds
Standardized Deviations (Normalized)


Probability
Cloud cover
Low cloud cover

Vertical Cloud Distribution

- Study large-scale environmental properties. (Omega)



Omega and Surface Flux

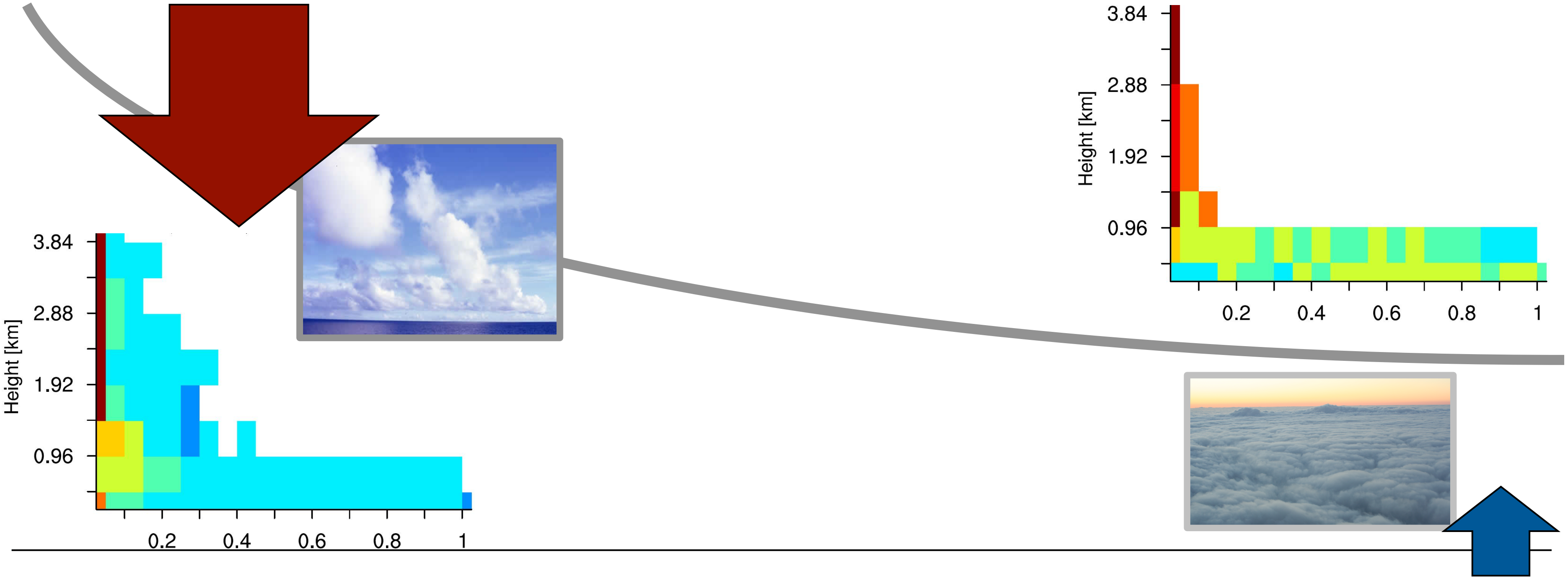
	NCEPCFSR	ERAInt.	IPSL5A	IPSL5B	CNRM	MPI	CanAM4	HadGEM2
Stratocumulus								
Omega500(hPa Day $^{-1}$)	32.78	29.65	29.66	36.99	41.51	34.77	30.18	30.76
Omega850(hPa Day $^{-1}$)	36.82	34.37	25.96	26.92	32.99	27.78	34.32	30.26
Surface Flux(W m $^{-2}$)	109.62	120.77	102.44	97.60	101.14	96.77	106.74	120.32
Shallow Cumulus								
Omega500(hPa Day $^{-1}$)	31.19	28.45	30.63	35.99	43.61	38.61	31.28	34.54
Omega850(hPa Day $^{-1}$)	30.26	26.60	24.00	26.38	33.51	28.76	29.47	31.27
Surface Flux(W m $^{-2}$)	149.18	159.38	153.16	166.12	156.36	158.85	164.24	163.48

Compared to ERA-Int:

- Stratocumulus: Underestimate strength of surface flux.
- Shallow Cumulus: Overestimate strength of Omega500.

Woods Hole: 103.59 (strat)
143.30 (shcu)

Omega and Surface Flux



- Underestimate of surface heat flux implies PBL does not warm or moisten sufficiently. The PBL will be shallower due to less positively buoyant parcels.
- Overestimate of subsidence strength suppresses transport of moisture and energy. (By strengthening inversion?)
- If transport of moisture b/w levels too weak -> greater frequency of clds -> artificially 'jucier' clds (weaker turbulence) -> optically thicker clds + combined with overlap -> yielding too reflective clds(?)

Definitions

- **Cloud Radiative Effect (CRE)**: The difference between net irradiances measured for average atmospheric conditions and those measured in the absence of clouds for the same region and time period.

- **Cloud-climate feedbacks (CCF)**: cooling and warming effects of clouds depend on the height, location, amount, and the microphysical and radiative properties of clouds, as well as their appearance of time with respect to the seasonal and diurnal cycles of the incoming solar radiation.

- **Boussinesq approximation** states density differences are sufficiently small to be neglected, except where they appear in terms multiplied by the acceleration due to gravity (g). Thus, process of neglecting density variation in inertia term but retaining it in the buoyancy (gravity term) is call the Boussinesq approximation.

- **dBZ:** The radar system measures a received signals in 'Volts'. This power ranges from 0V to 10000V easily - thus the need for the log scale. A return power of 0.1V to the radar would give -20dBZe, 1V yields 0dBZeand 250V yields 24dBZe. Since the power received by the radar is proportional to the sixth power of the particle's diameter, rain easily dominates the signal.In nutshell, negative dBZe mean a return power between 0 and 1V.
- Nondimensional "unit" of radar reflectivity which represents a logarithmic power ratio in decibels (dB) of reflectivity (Z). Z is 1 mm6 m-3, and related to the number of drops per unit volume and the sixth power of drop diameter.
  - One dBZ-scale of rain:
    - 40 heavy
    - 24-39 moderate
    - 8-23 light
    - 0-8 Barely anything