Coupling between clouds and their environment: using observations to constrain models

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Photograph: Frederic Batier

Coupling between clouds and their environment

- Clouds can be viewed in many different ways
- Clouds cannot be coupled to their environment with a single physical law

Using observations to constrain models

- Good models have been built with few, imperfect observations
- Observations can be used as input for models, but also to inspire models and validate models in qualitative ways

Outline

1. **Excursion into the past:**
   three examples of successful advances in understanding and modeling the coupling between clouds and the environment through observations

   a. Clouds as radiative entities

   b. Clouds as turbulent multi-phase flows

   c. Clouds as a heat source

   (Clouds as a collection of particles, …)

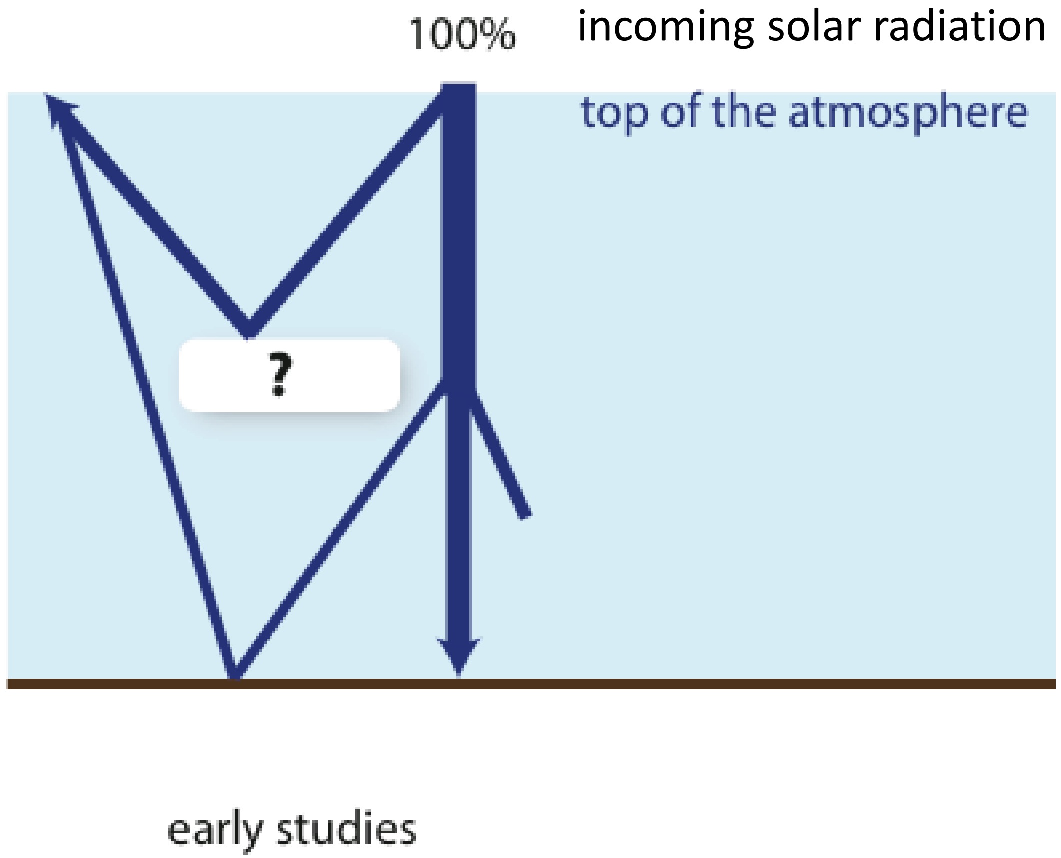
2. **Exploring new pathways:**
   an example of using state-of-the-art remote sensing to find constraints on cloud behavior for models

1. Excursion into the past:

a. Clouds modulate electromagnetic radiation

Modeling Earth's energy budget

The first time clouds were considered in a climate model, they were prescribed as a constant



Cloud albedo = 0.5

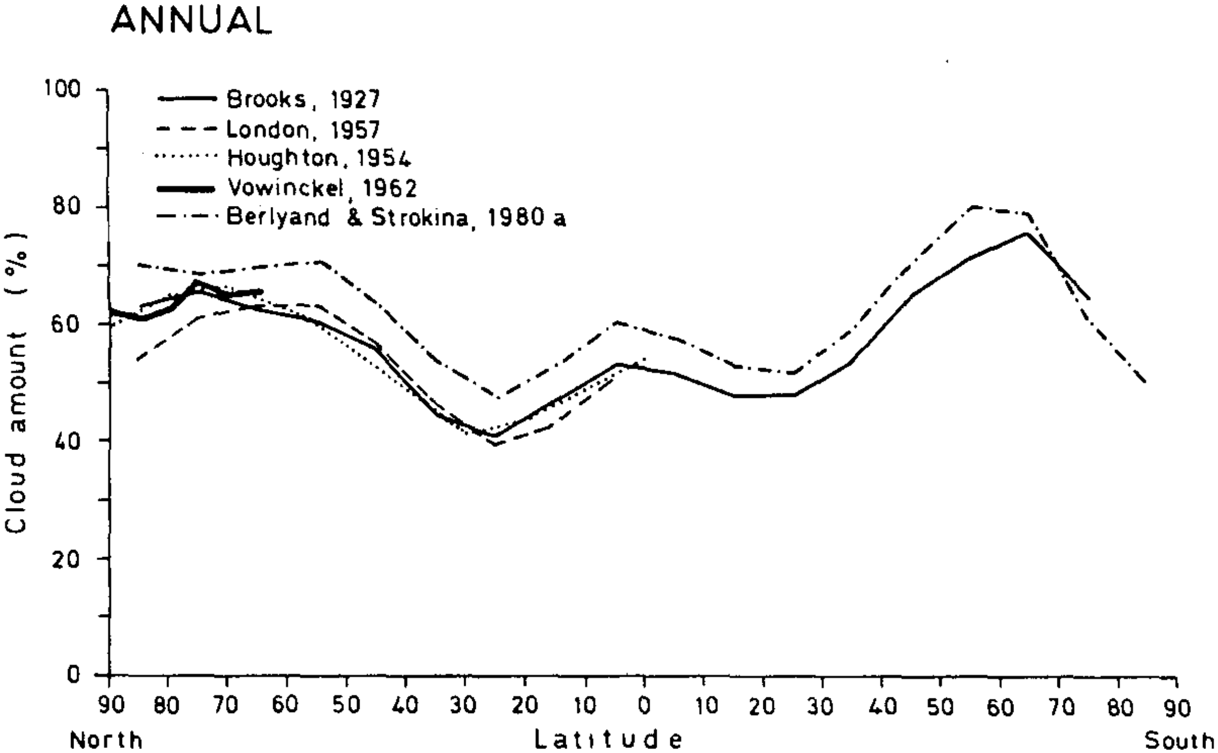
Cloud cover = 52.5%

Arrhenius (1896)

Modeling Earth's energy budget

Cloud albedo = 0.67

Cloud cover = 55%



Abbot and Fowle (1908), Simpson (1928)

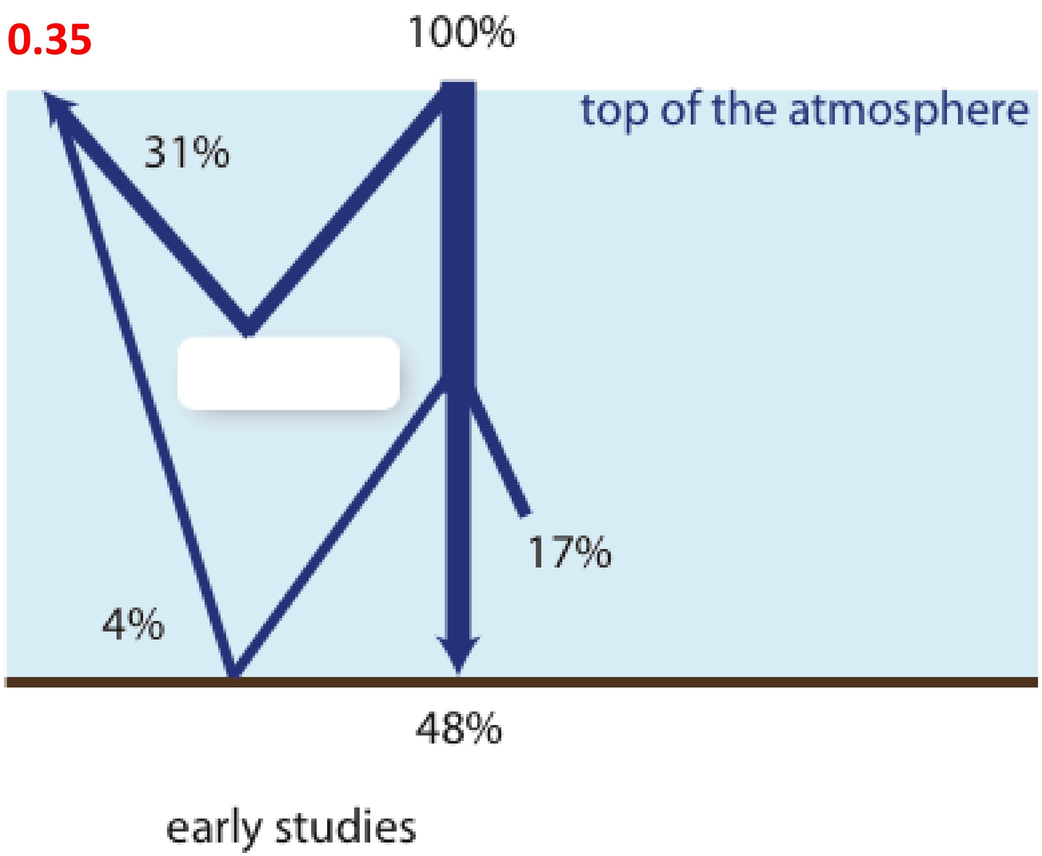
Modeling Earth's energy budget

Planetary albedo of 0.43 higher than the dark side of the moon suggests

Fritz (1949), Houghton (1954), London (1957)

Modeling Earth's energy budget

Planetary albedo of 0.43 higher than the dark side of the moon suggests



Fritz (1949), Houghton (1954), London (1957)

Modeling Earth's energy budget

radiative entities

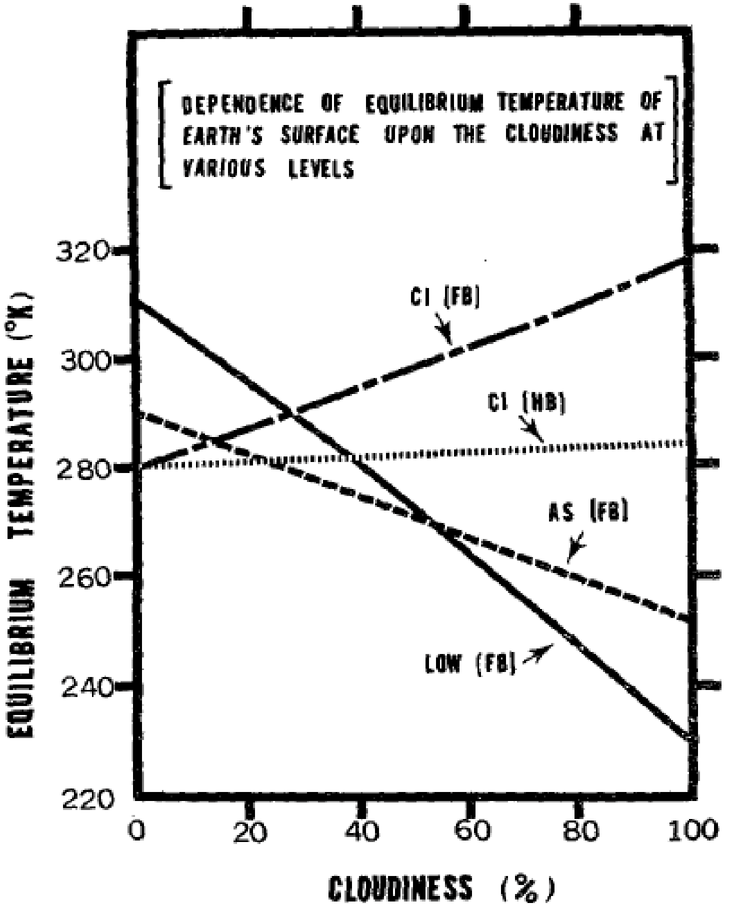


FIG. 20. Radiative convective equilibrium temperature at the earth's surface as a function of cloudiness (cirrus, altostratus, low cloud). FB and HB refer to full black and half black, respectively.

warming with increased high cloud

cooling with increased low cloud

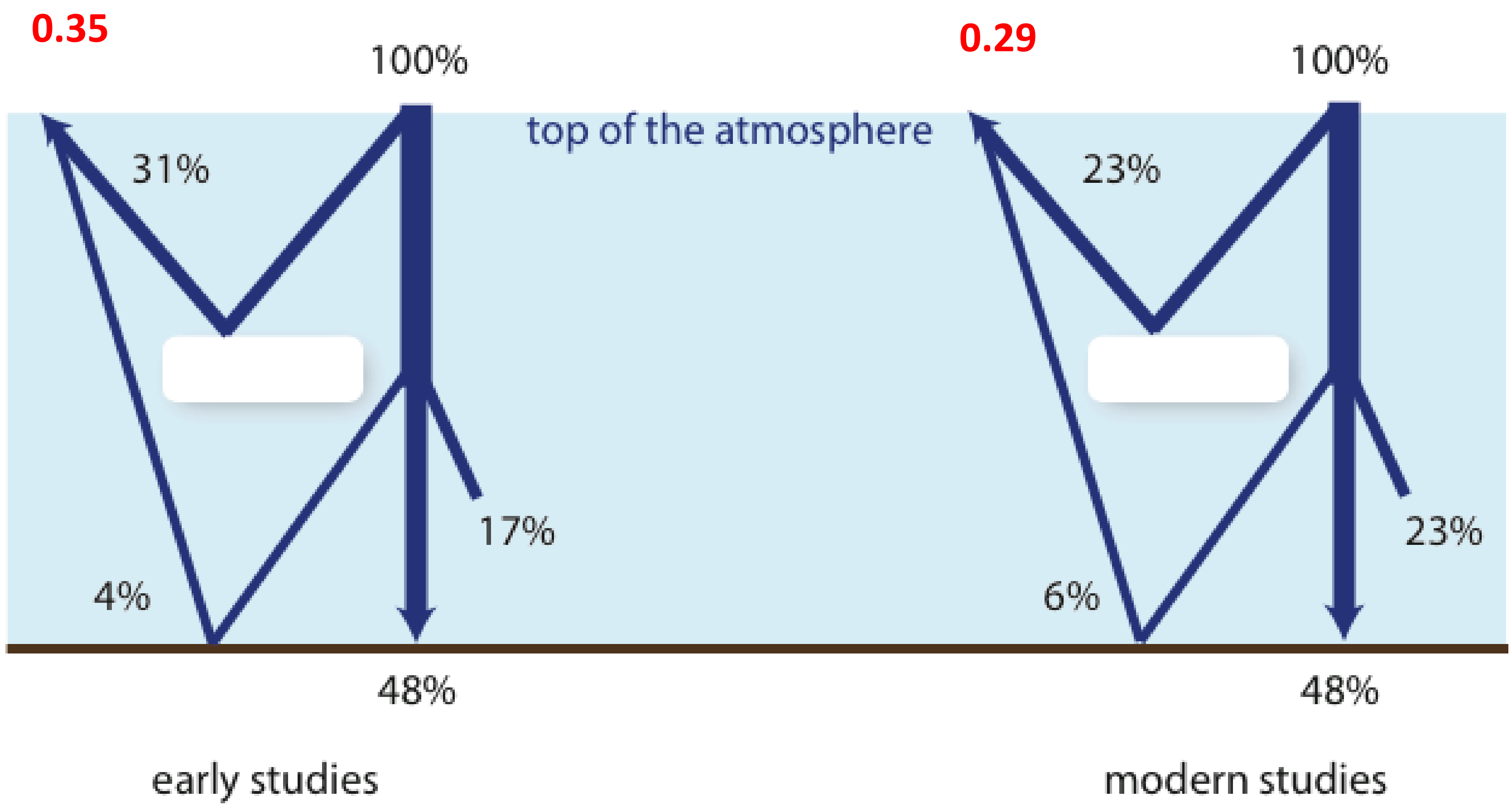
TABLE 1. Cloud characteristics employed in radiative convective equilibrium model.

Cloud	Height (km)	Amount	Albedo
High	10.0	0.228	0.20
Middle	4.1	0.090	0.48
Low			
top	2.7	0.313	0.69
bottom	1.7		

Manabe and Wetherald (1967), Schneider (1972)

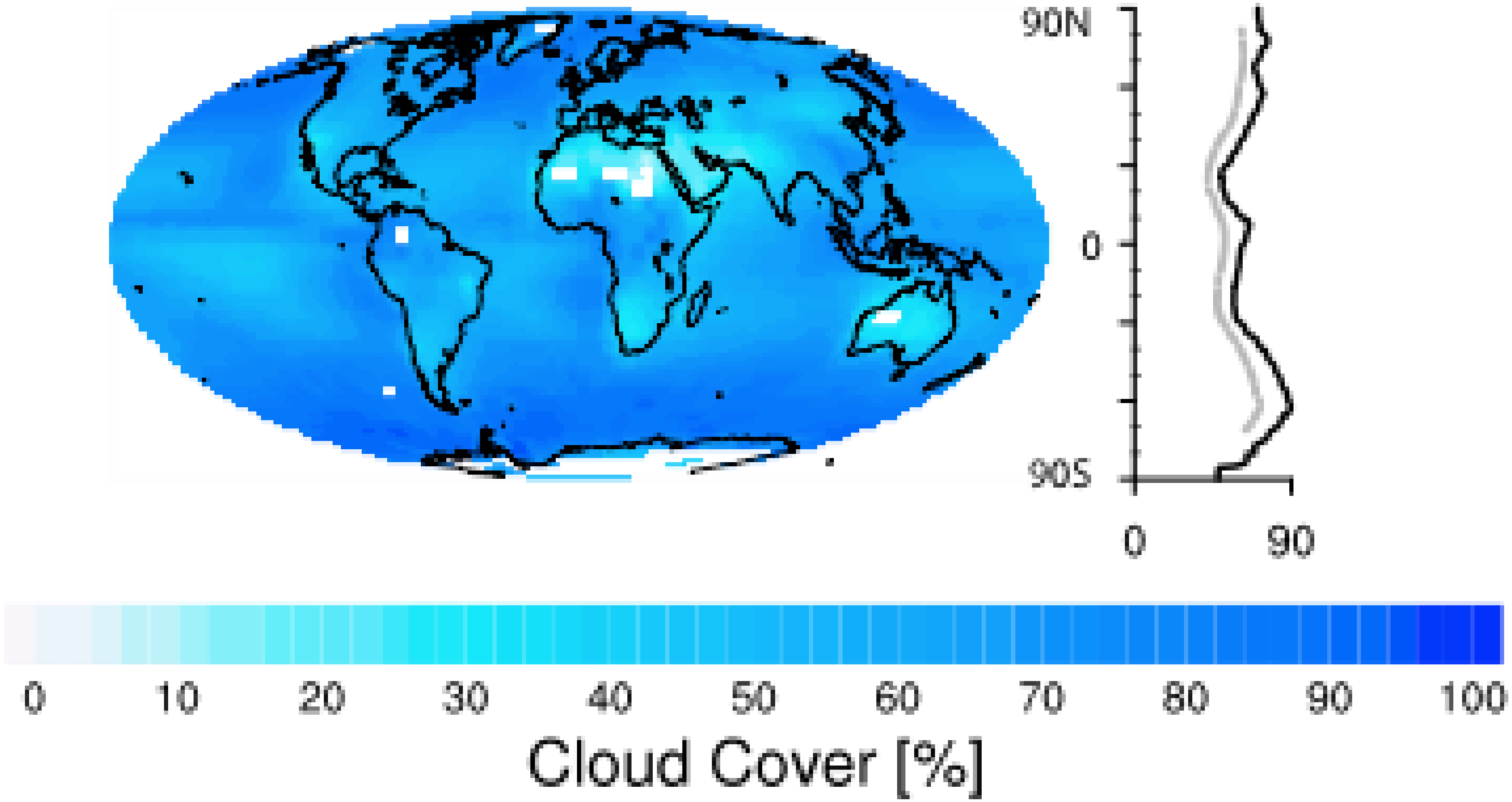
Modeling Earth's energy budget

Studies in the pre-satellite era were quite successful at estimating the planetary albedo.



Trenberth (2009)

Modeling Earth's energy budget



The clouds missed in early observations ended up being optically thinner.
Early observations were remarkably good at estimating the zonal distribution of cloudiness, which tells us that clouds are tied to the large-scale circulation.

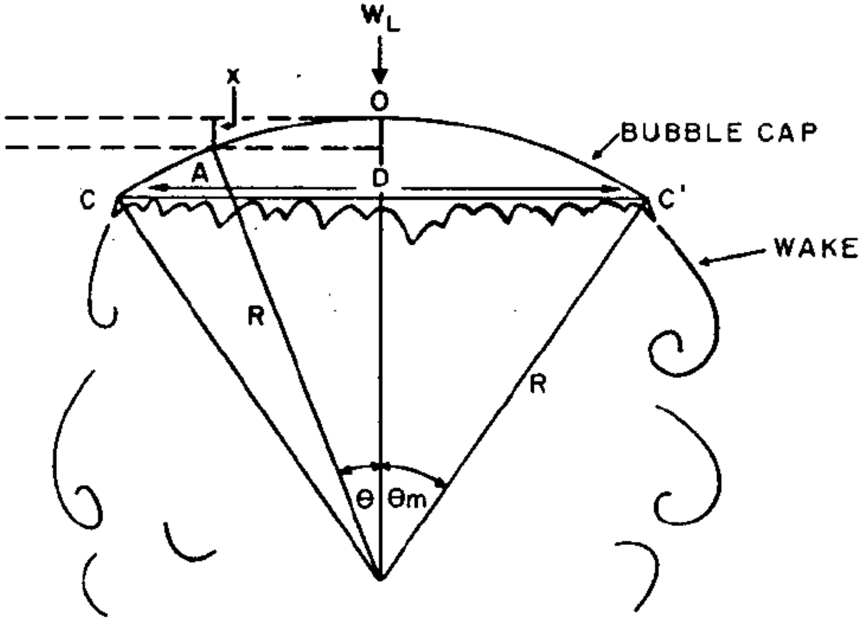
Brooks (1927), Warren and Hahn (1984)

1. Excursion into the past:

b. Clouds are a turbulent dispersion of condensate

The bubble/plume cumulus models

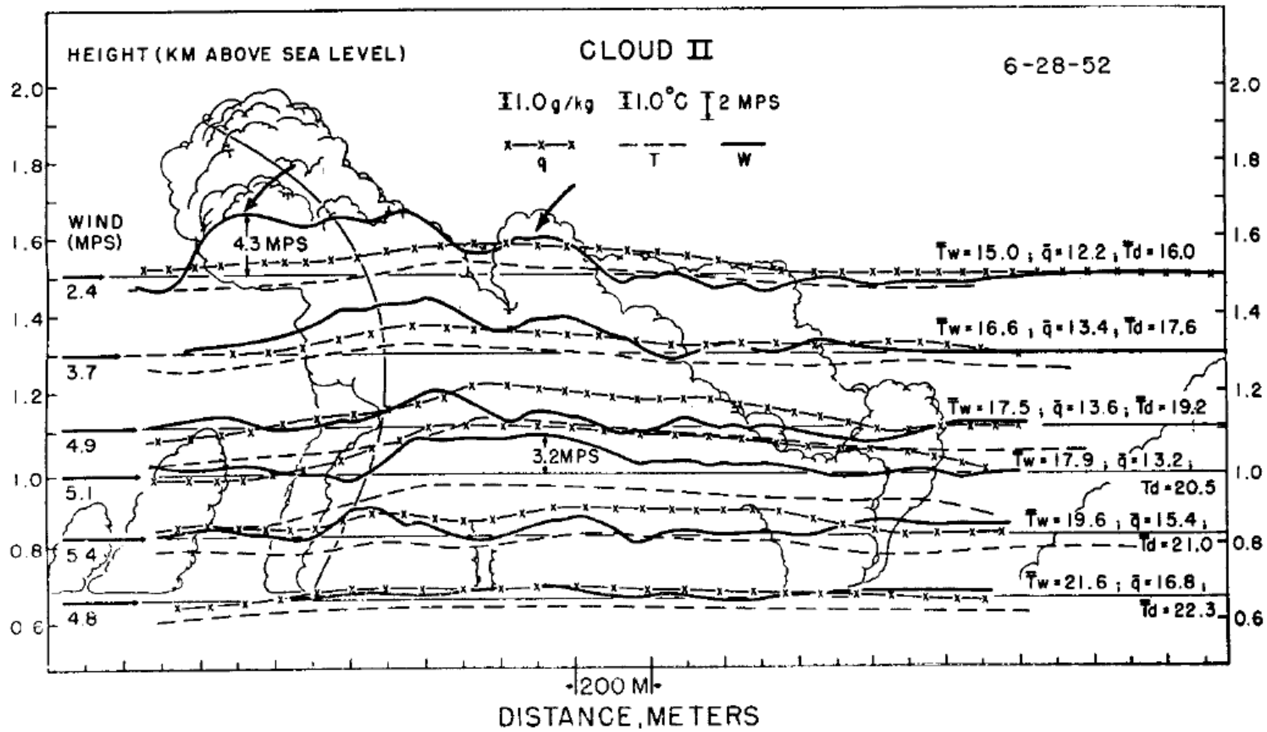
Clouds were the prototype of convection in a fluid, against which theoretical and laboratory studies could be tested



Scorer and Ludlam (1952)

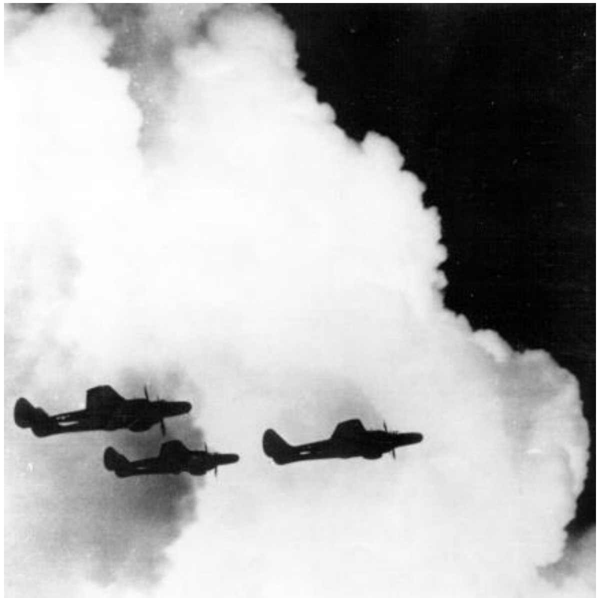
Challenged by the first field study of clouds

The Thunderstorm Project - 1946



Malkus (1953)

Challenged by the first field study of clouds



The Thunderstorm Project - 1946

"Cumulus clouds, like people, go through a life cycle; they are born, grow to maturity, age and die.

Unlike people, however, the the fatter they are the longer they live, and the taller and more successfully they grow."

$$\varepsilon = \frac{1}{M_c}\frac{dM_c}{dz}$$

M_c = *cloud mass*

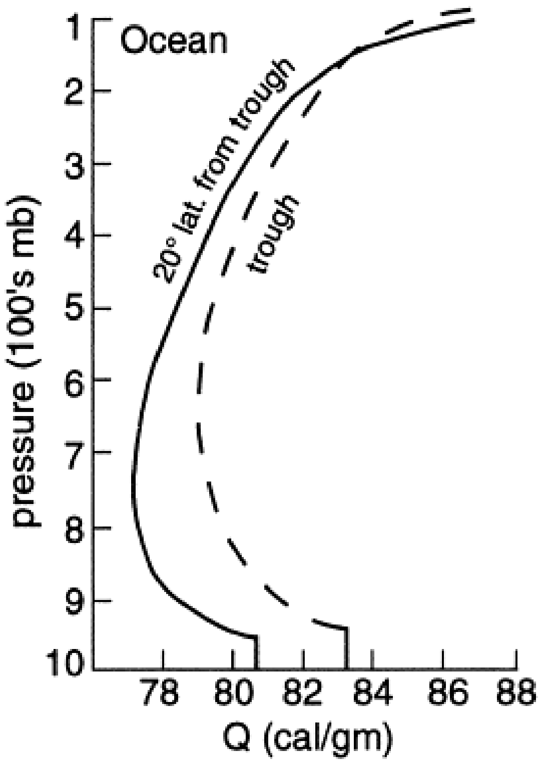
Malkus (1953)

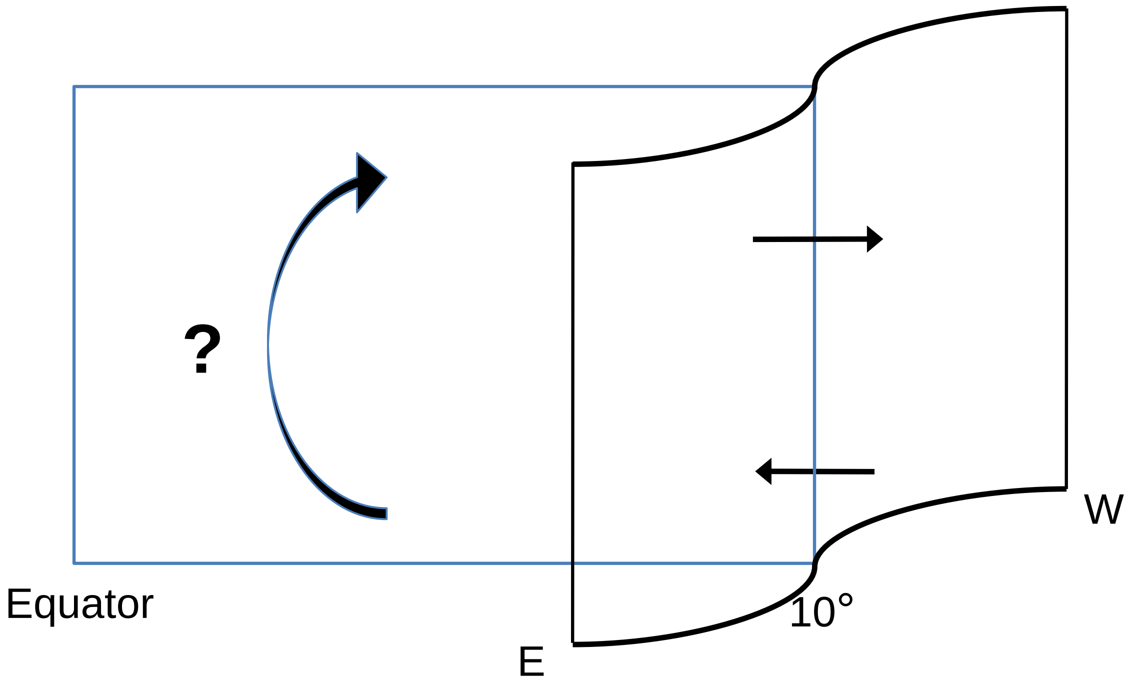
1. Excursion into the past:

c. Clouds as a heat source

The heat balance in the equatorial trough zone

heat source





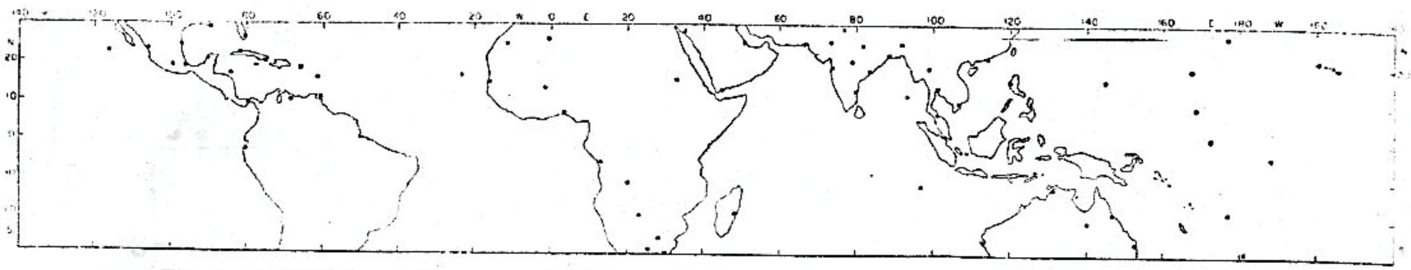
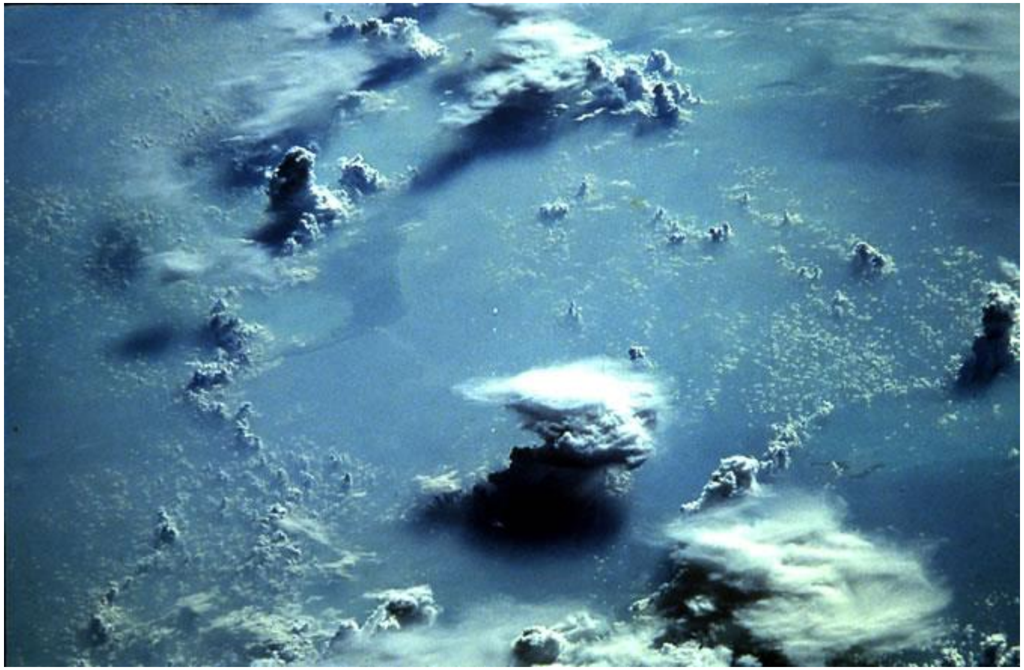


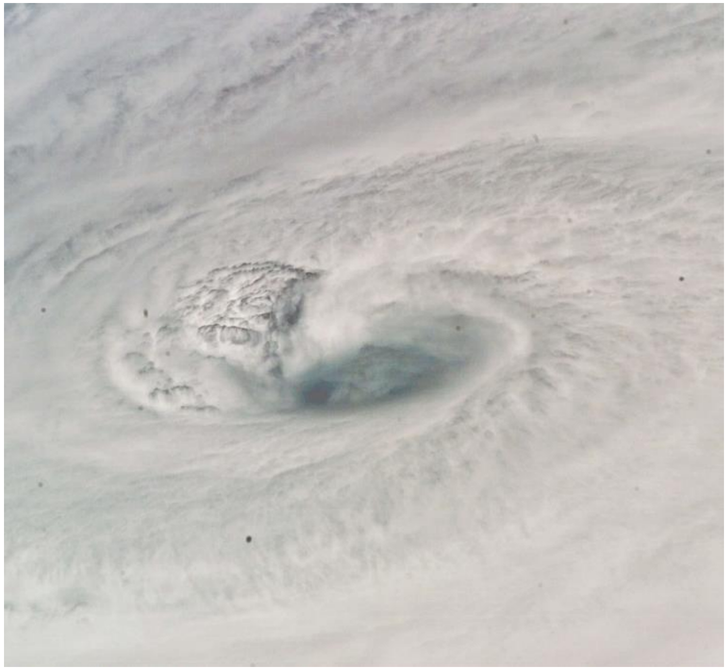
Fig. 4. Radiosonde stations around globe used for computation of equatorial trough structure.

Riehl and Malkus (1958)

The “hot tower” hypothesis

A relatively small sample of about 1500 - 5000 undiluted cloud "towers" (cores) is responsible for upward heat transport

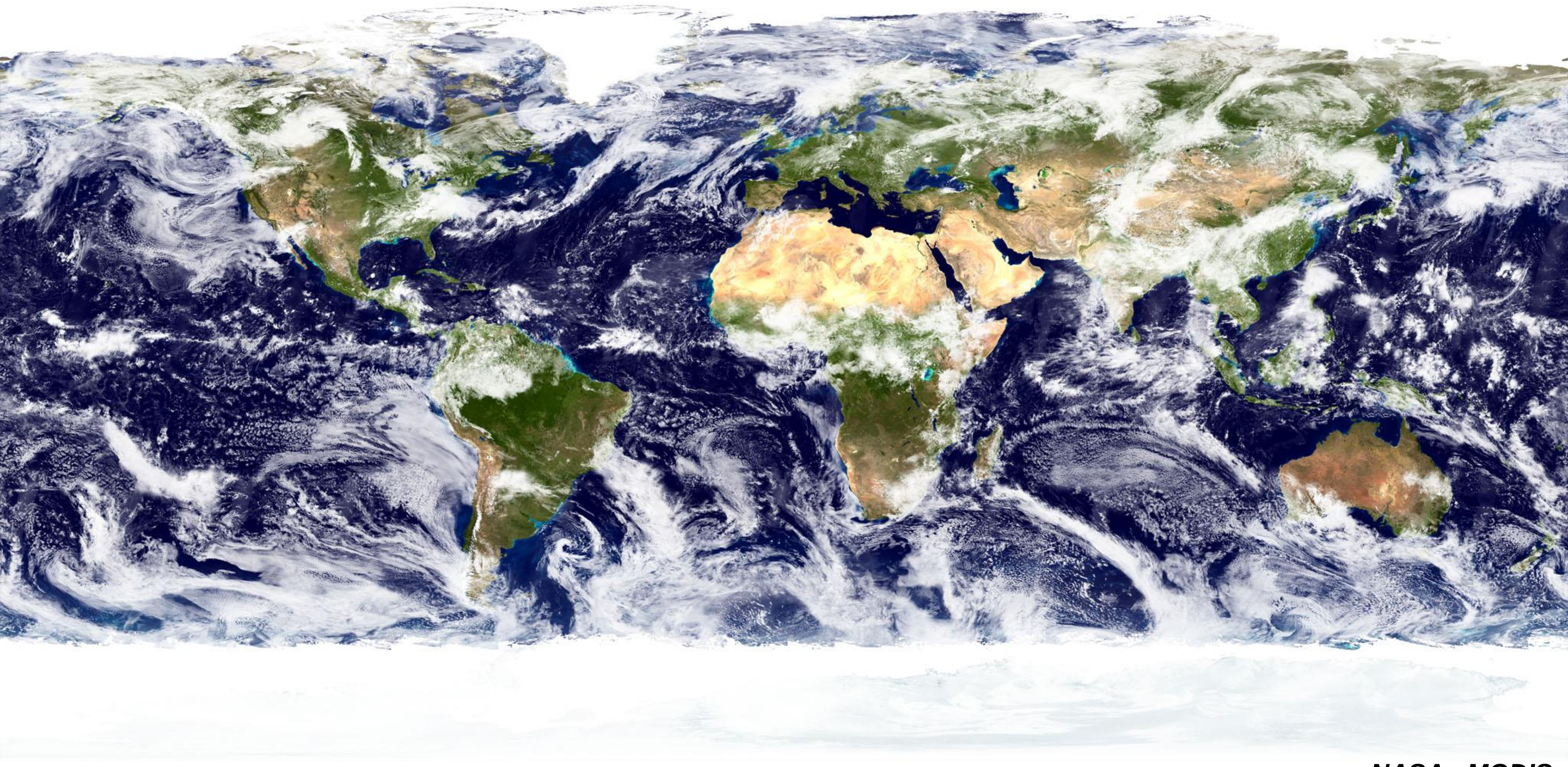




Riehl and Malkus (1958), Malkus (1958)

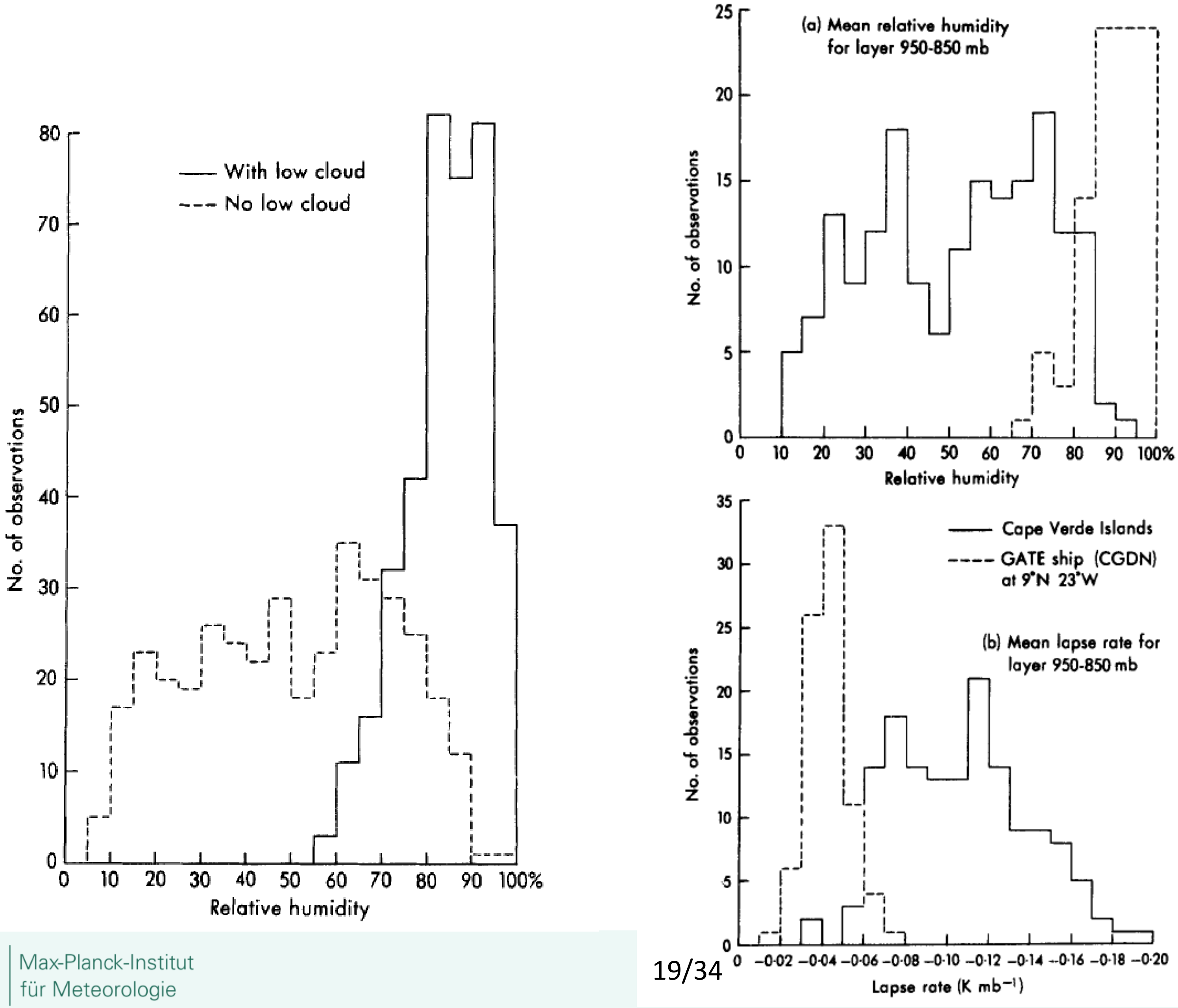
Clouds are coupled to the general circulation of the atmosphere

Clouds couple radiative processes to turbulent and dynamical flow



NASA - MODIS

From fixed distributions of cloud to cloud parameterizations



Slingo (1980)

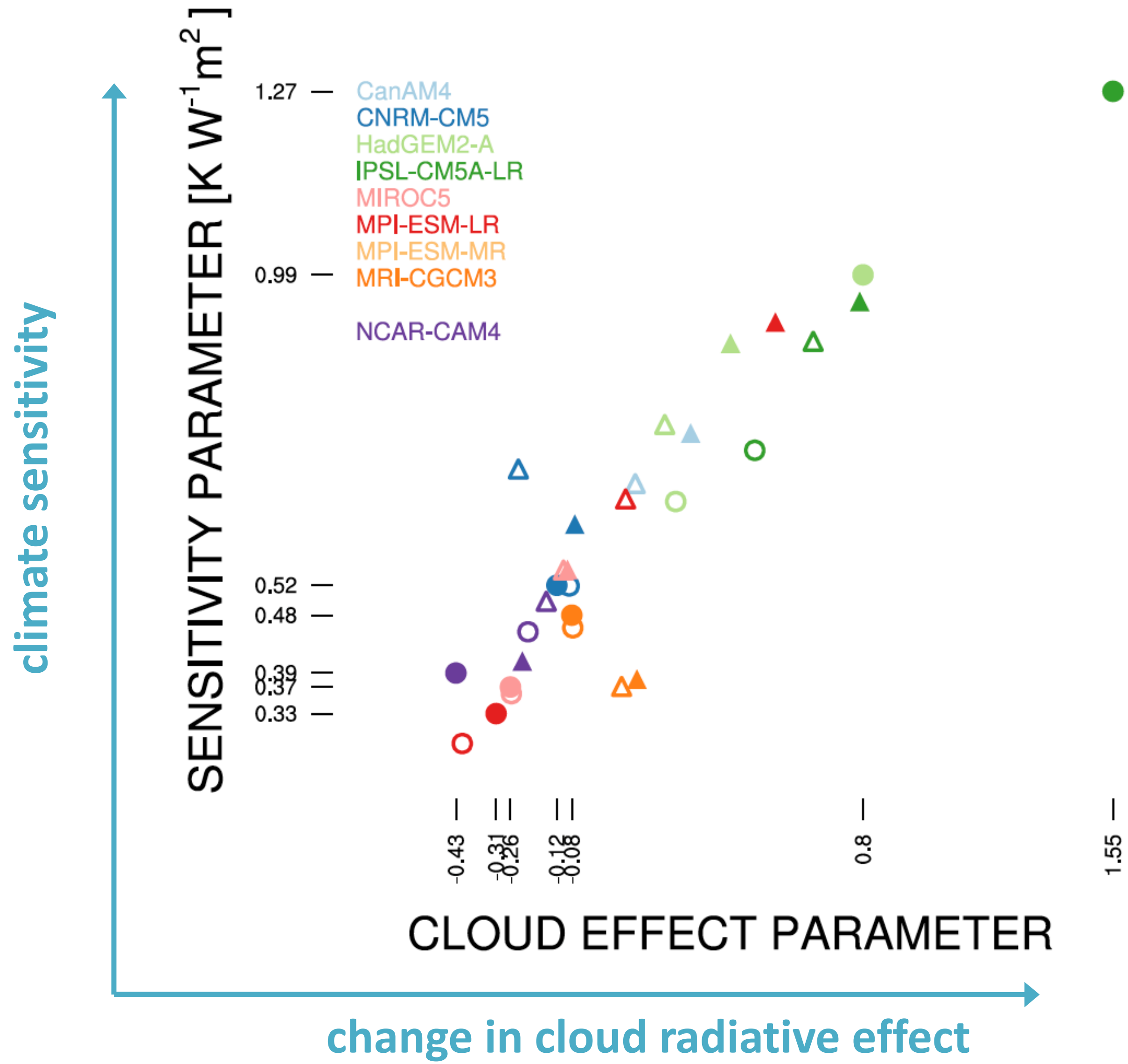
Current generation of global models

- Include all the processes through which clouds couple to their environment
- Many of those processes still occur on scales smaller than the model grid and are parameterized
- These parameterizations have grown increasingly complex – with many parameters or "disposable constants "
- These parameters are often not observable (or used for model tuning)

Do parameterizations collectively exert the right effect?

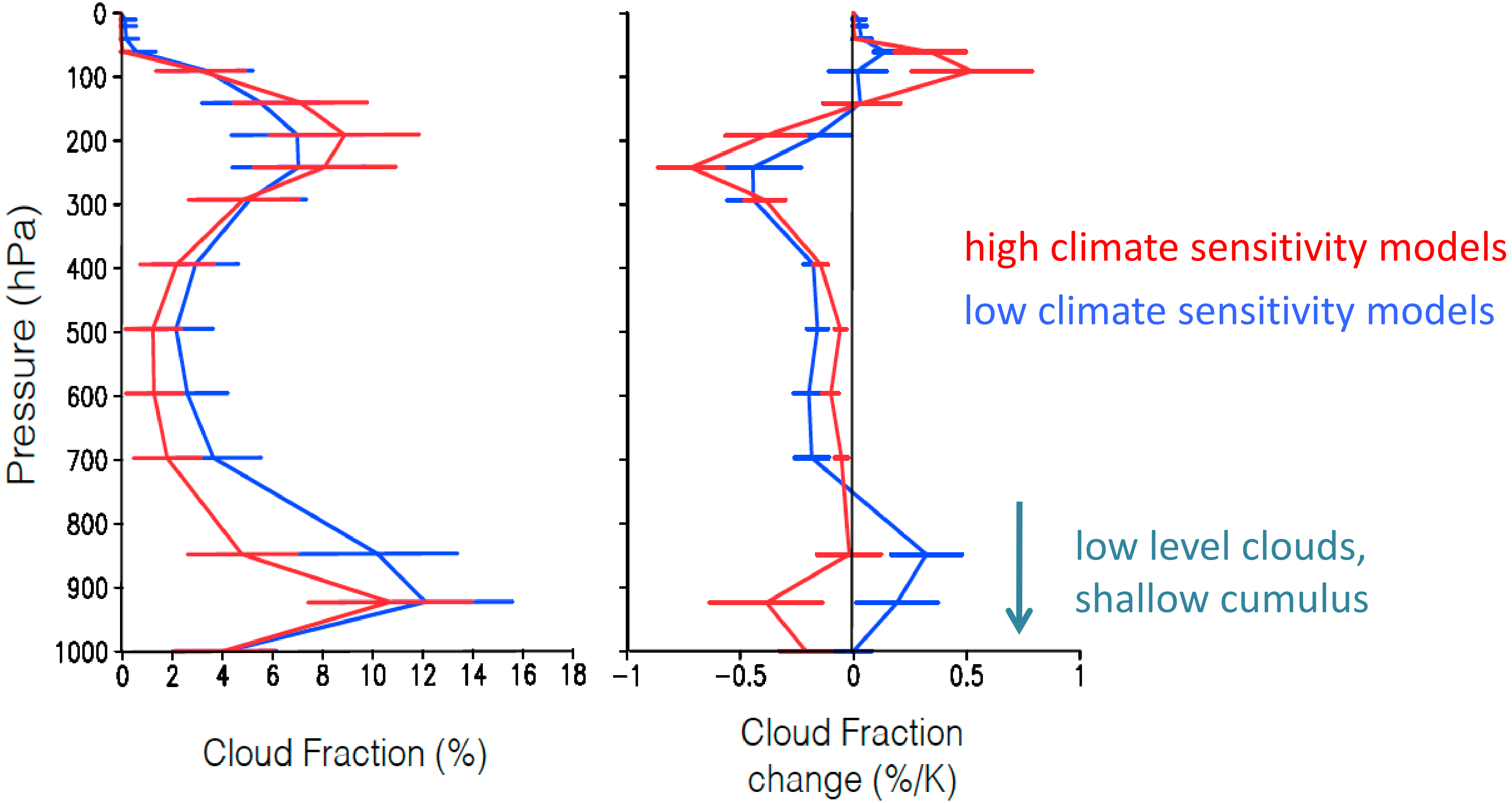
Can we accurately predict how changes in clouds forced by increasing greenhouse gases help mediate global warming?

Uncertainty in climate sensitivity lies in different cloud effects



Cess et al (1989), Medeiros, Stevens & Bony (2013)

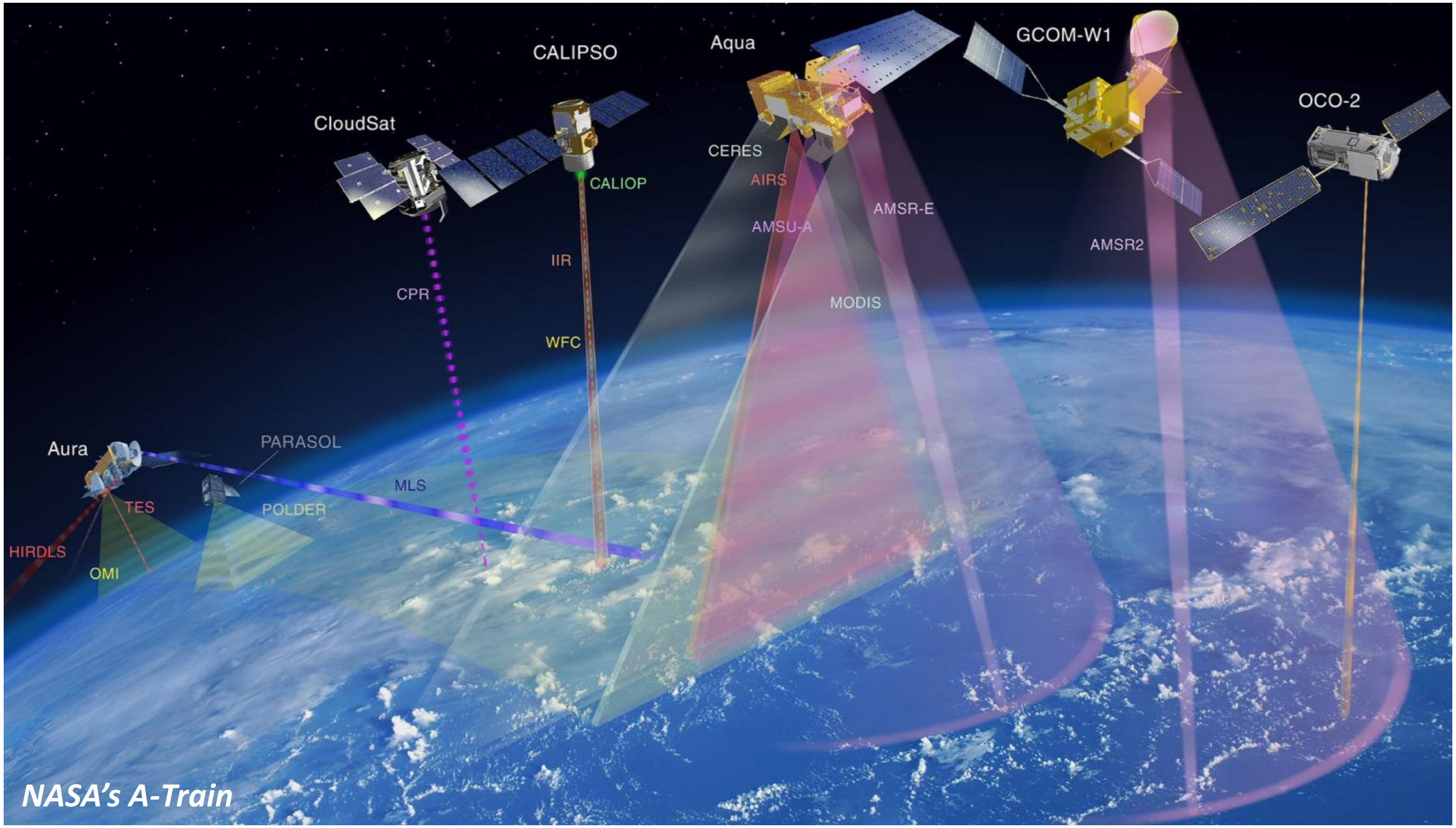
Changes in low-level clouds dominate modeled spread



Brient et al (2015)

2. Exploring new pathways:

Do modeled shallow cumulus – one of climate's uncertain low cloud regimes – respond to changes in their environment in the same way they do in nature, in our present day climate?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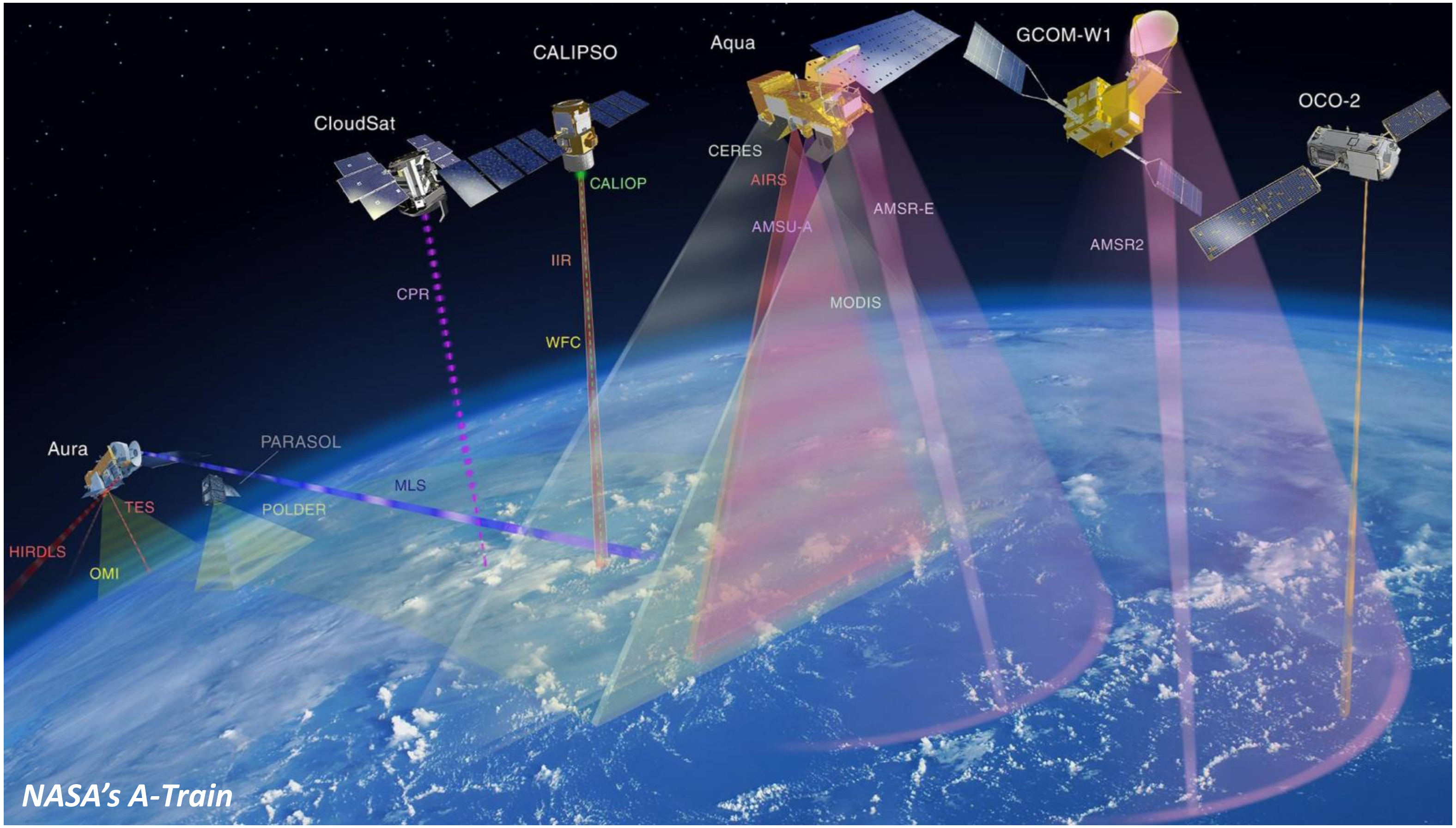
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Strategically located meteorological sites

A single-point comparison at high resolution

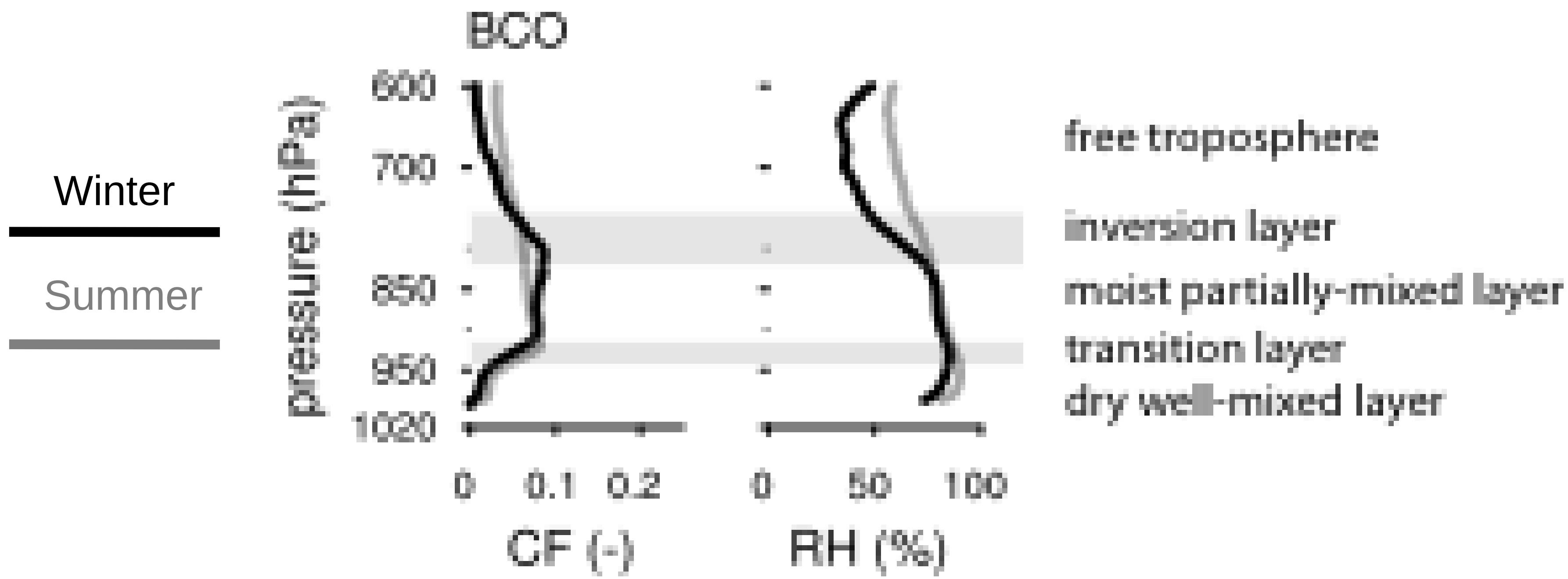
The data:

3 years of cloud, rain, temperature and humidity profiles measured at the **Barbados Cloud Observatory (BCO),** situated in a typical trade-wind region, representative of the open ocean

The model output:

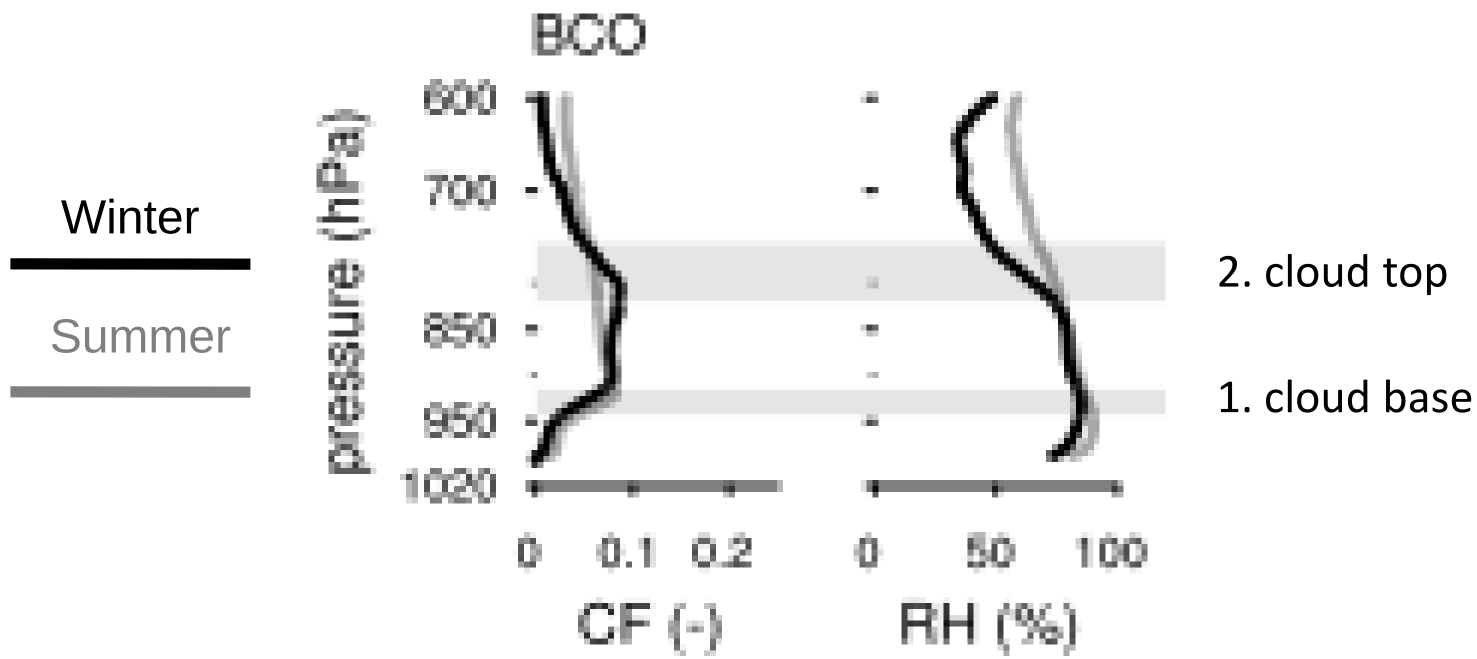
30 years of **single time step output** at one grid point **upstream of Barbados**, from the ECMWF Integrated Forecast System and CMIP5 models

A single-point comparison at high resolution



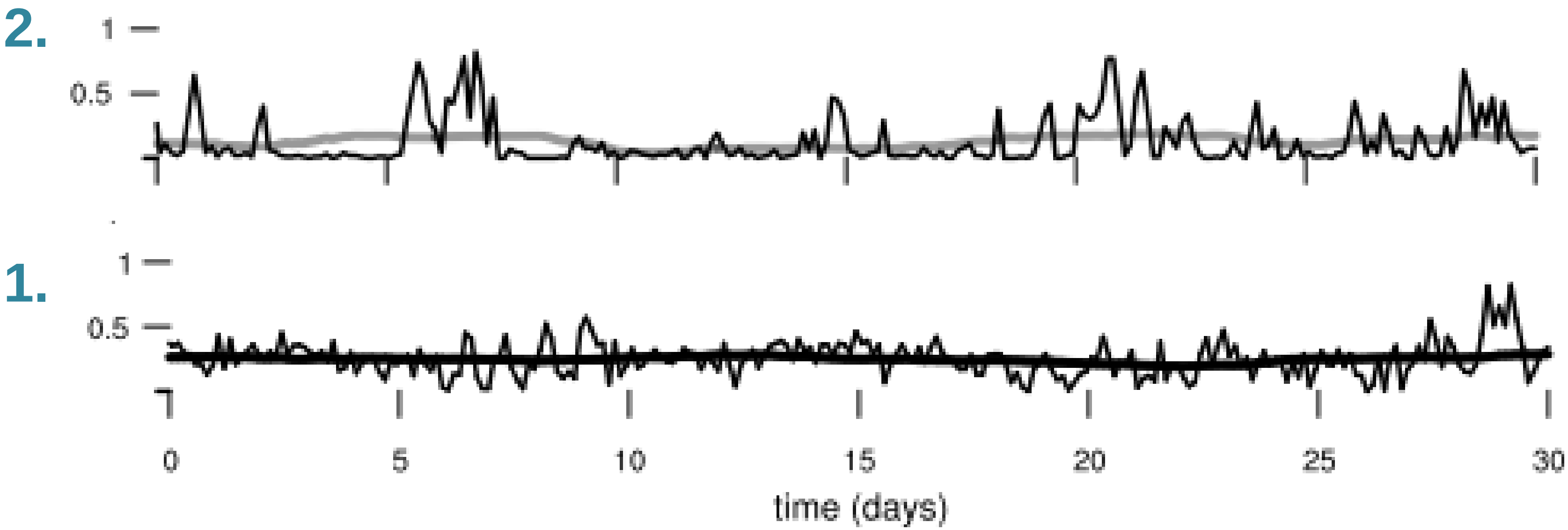
Nuijens et al (2015)

Differences in the low cloud profile between seasons are only modest, but there is less cloud at the inversion in Summer



Nuijens et al (2015)

Cloud near cloud base dominates total cloud cover, whereas cloud near cloud top dominates its variance



Nuijens et al (2015)

Why might cloud base cloudiness vary little in nature?

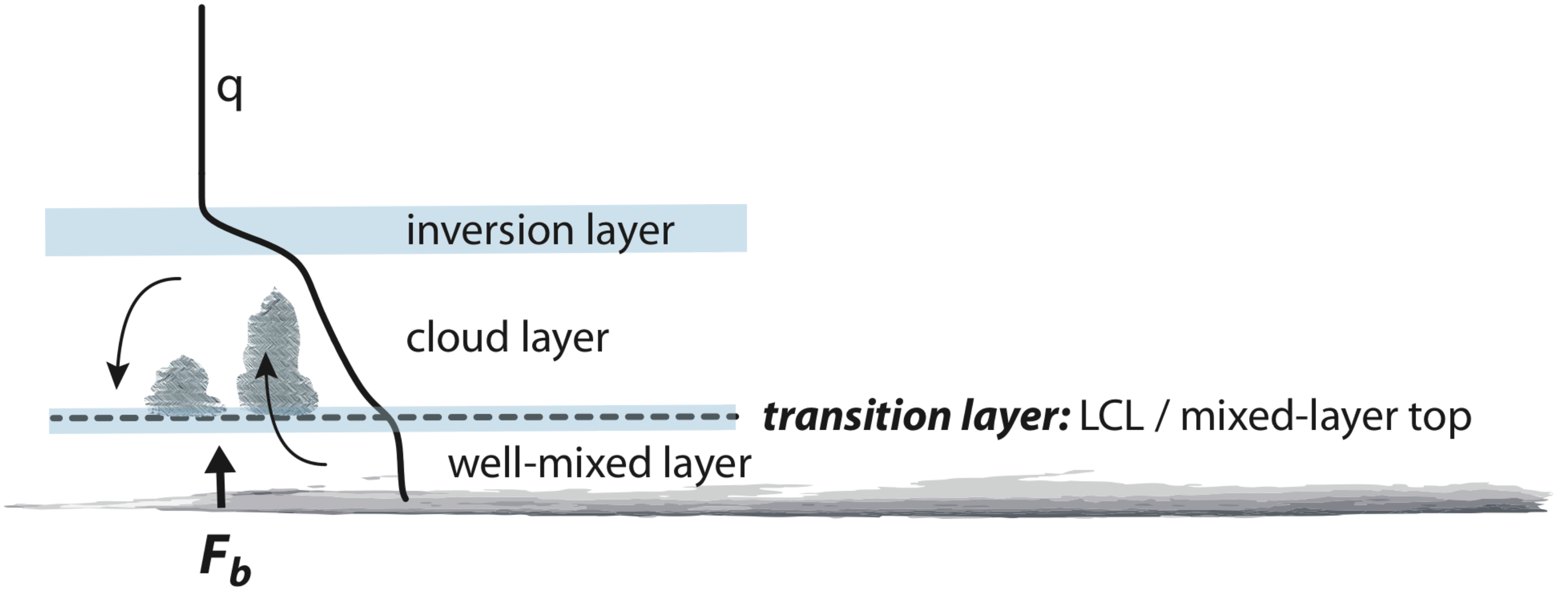


Illustration adapted from Neggers (2006), Nuijens et al (2015)

See also Stevens (2006), Fletscher and Bretherton (2004), Bellon and Stevens (2013)

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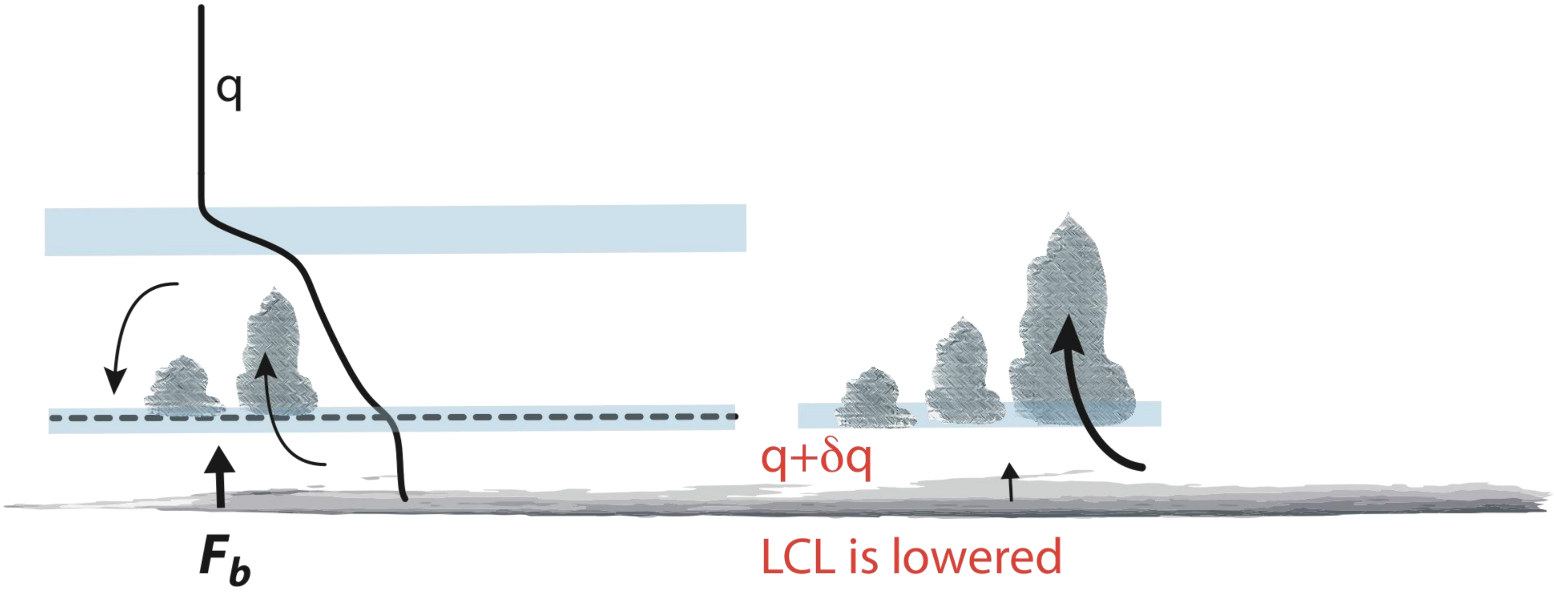

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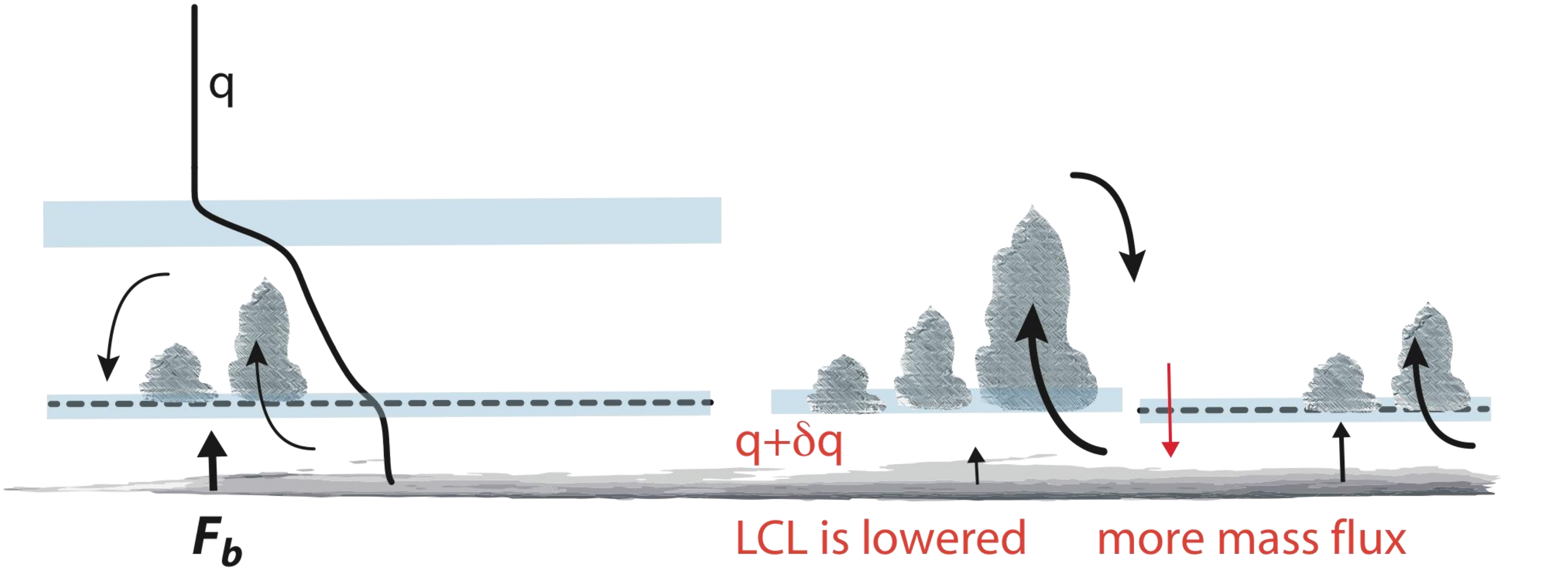

Illustration adapted from Neggers (2006), Nuijens et al (2015)

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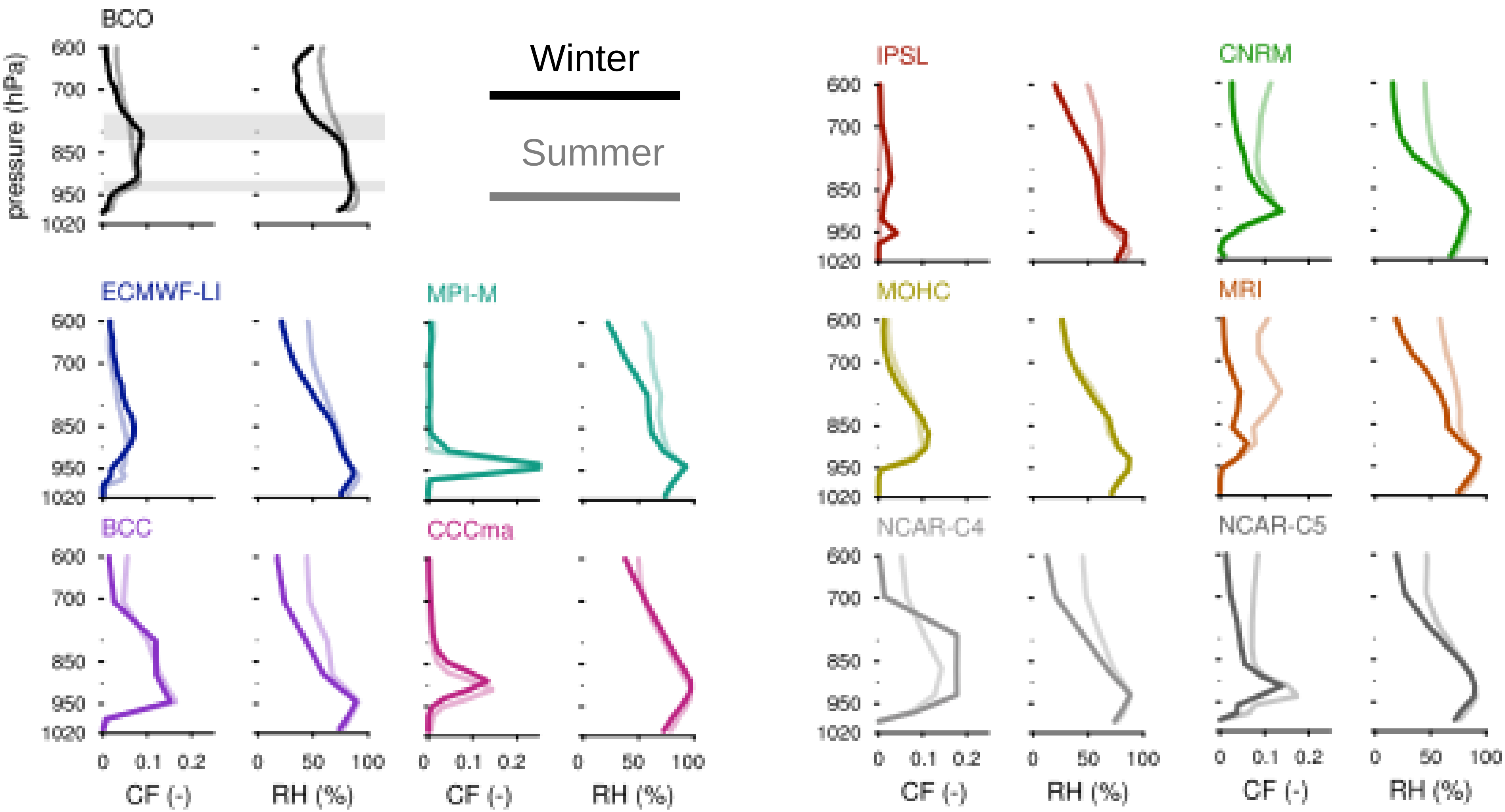
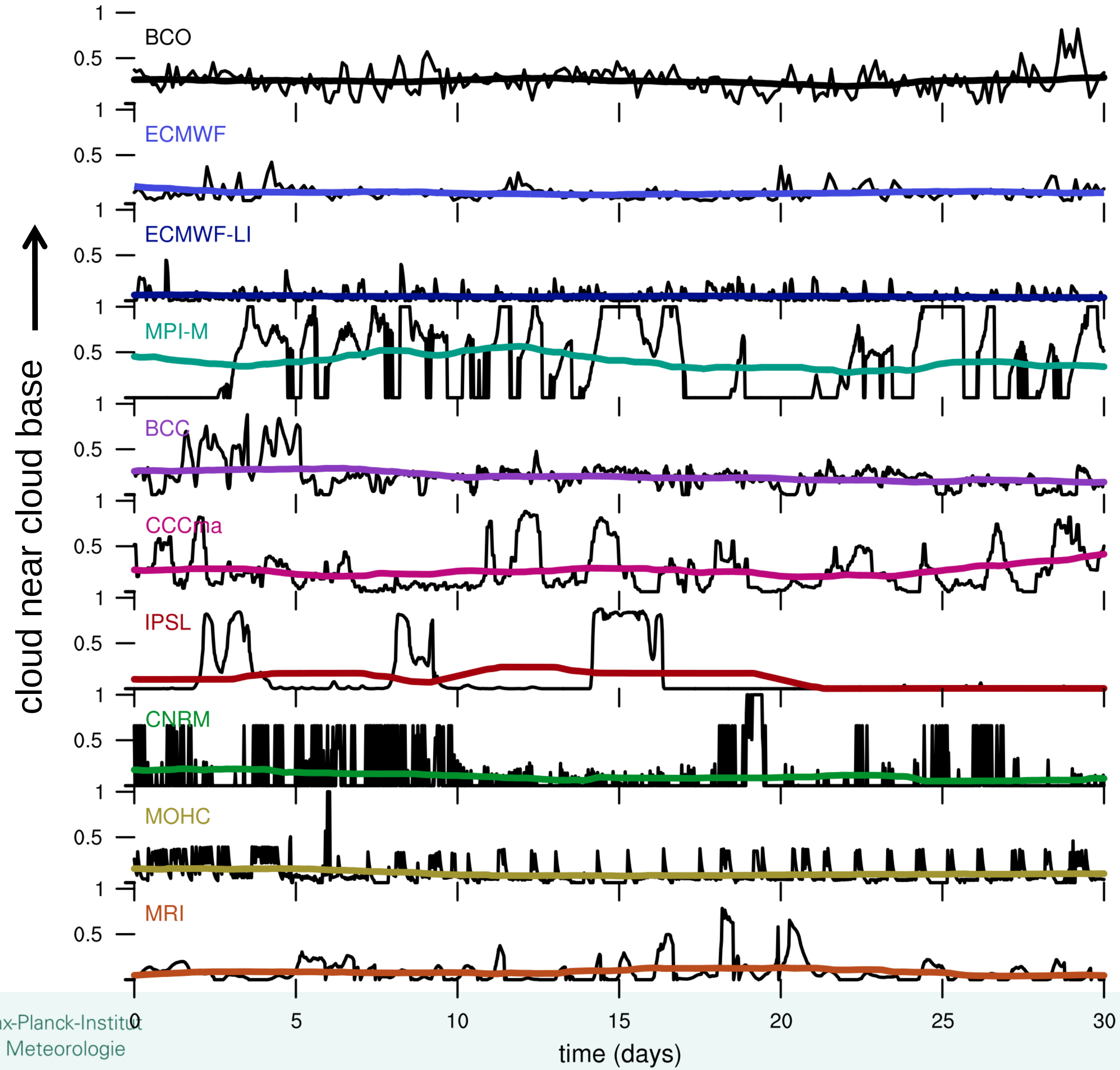
Models reproduce the shallowness of the trade-wind layer and the modest seasonality, but differ in the details





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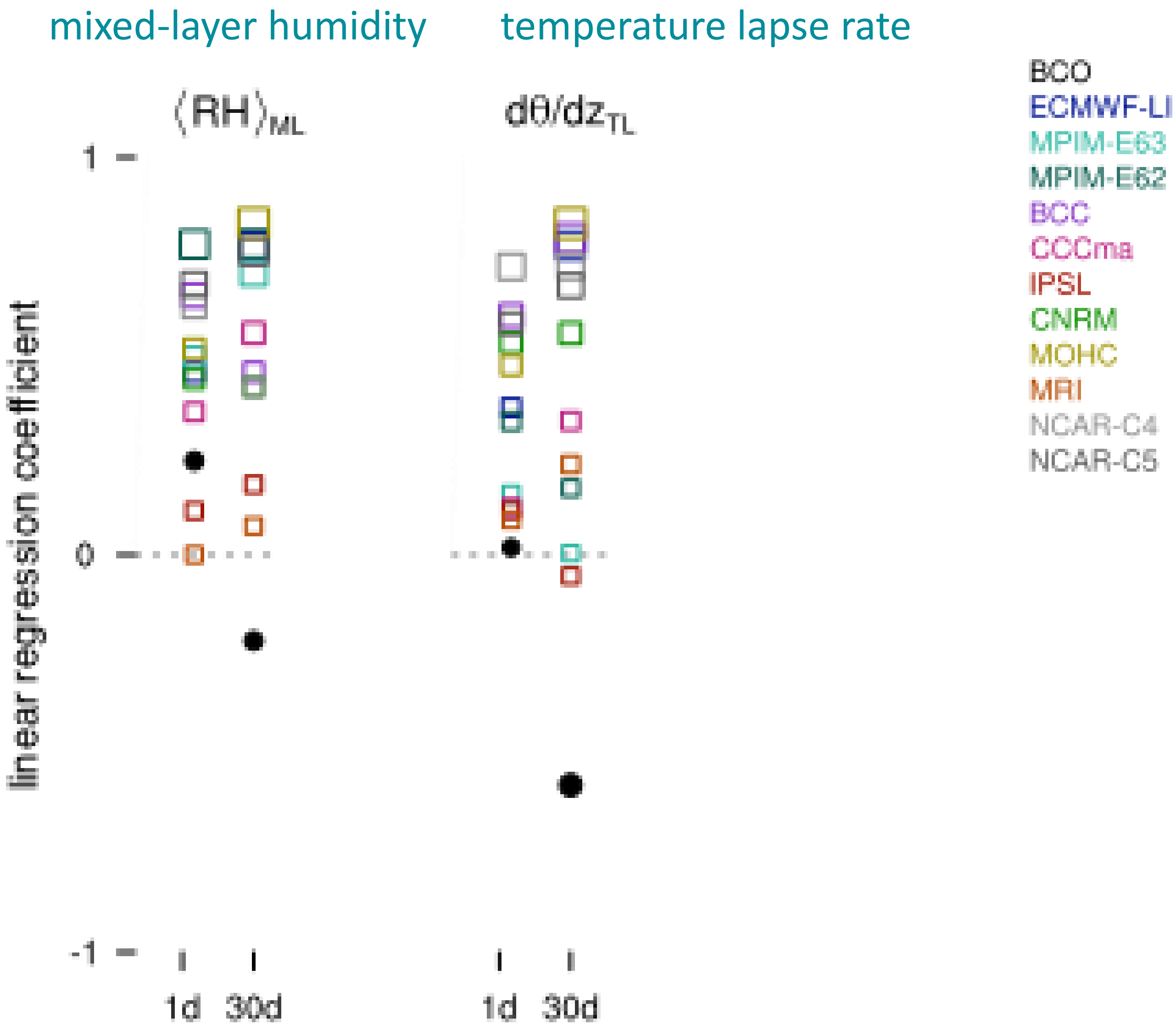
Models have stronger than observed relationships with boundary layer humidity and temperature lapse rates



Nuijens et al (2015)

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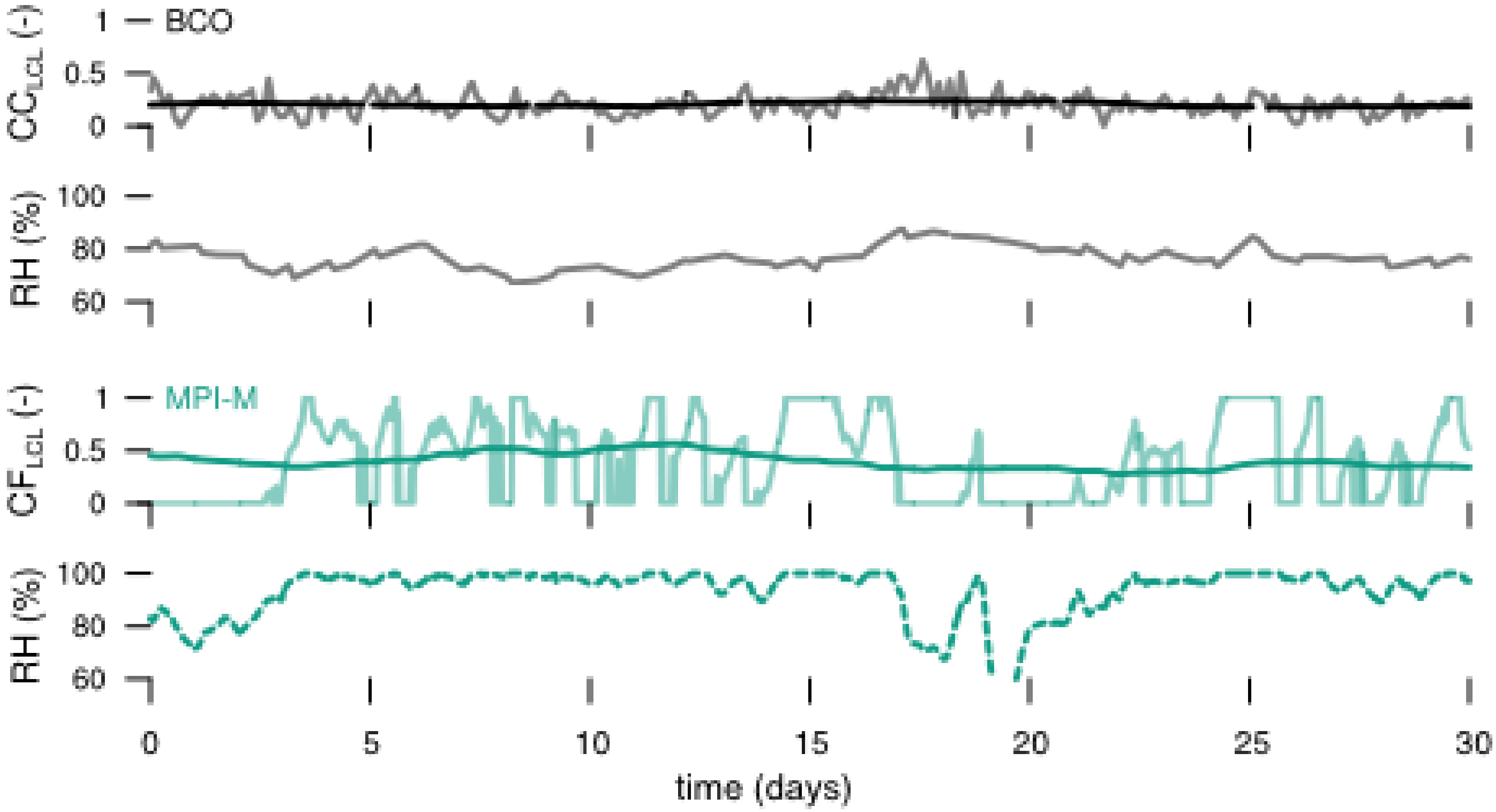
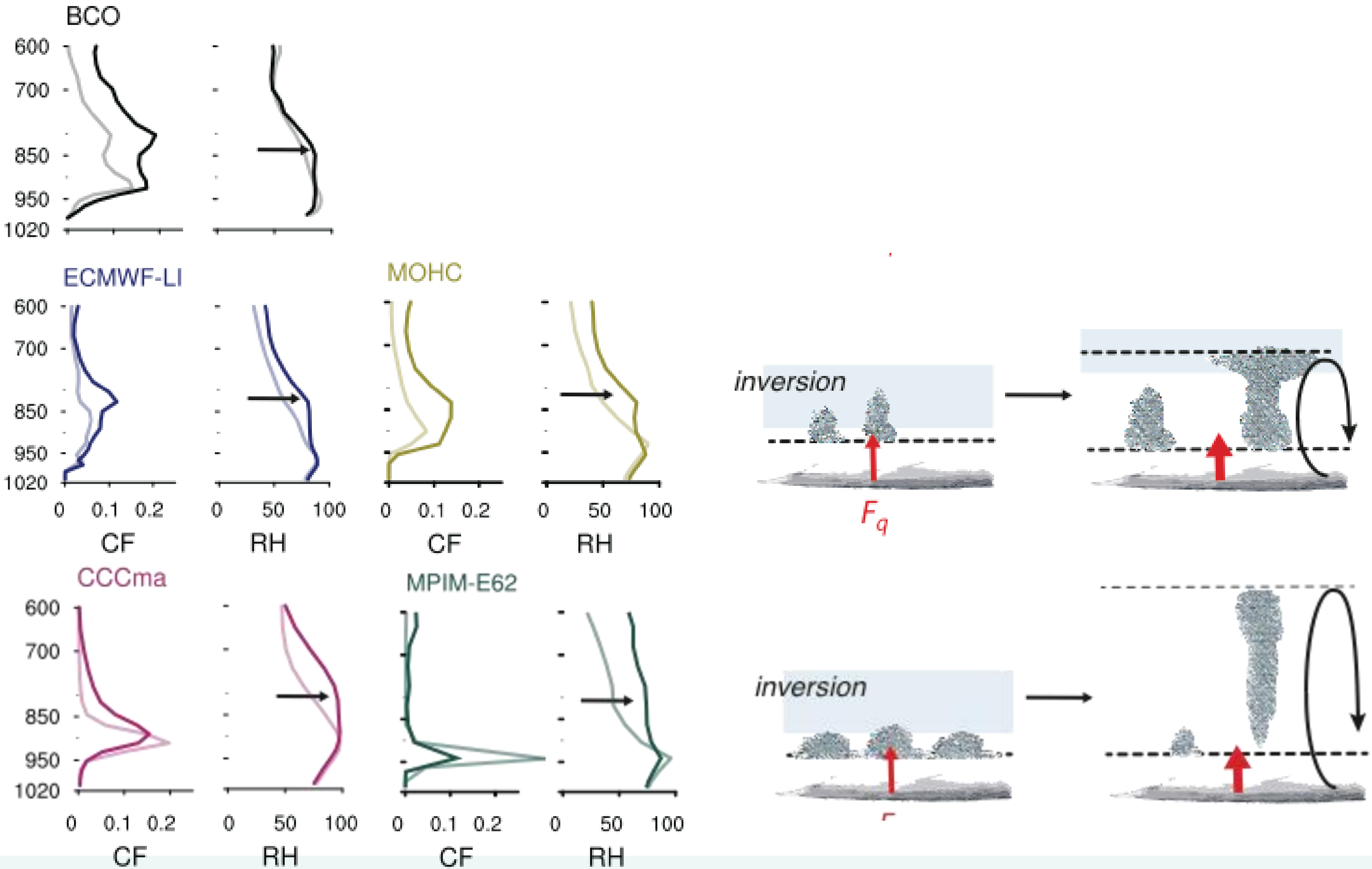


Nuijens et al (2015)

Some models effectively reduce cloud near cloud base as more cloud forms further aloft (and moisture is mixed across a deeper layer)



Nuijens et al (2015)

Concluding remarks

- ✧ Behind modeled behavior appear to linger relationships between low-level cloudiness, relative humidity, the stability of the lower atmosphere and the large-scale vertical velocity, which separate zonal patterns of cloudiness and inspired early cloud parameterizations.

- ✧ Because these parameters do not reflect the dominant mechanisms that control cloudiness on short time scales, they might lead to overly strong dependencies on the large-scale flow.

- ✧ The larger variance in models on short-time scales has implications for the calculation of radiative fluxes and heating rates.

- ✧ **Observations are needed as (quantitative) input and validation for models, but can also be used to inspire models, or for finding evidence for modeled behavior in nature**