Convection III

(Coupling to larger scales)

Steve Sherwood

Cargese Summer School 2009

Climate Change Research Centre

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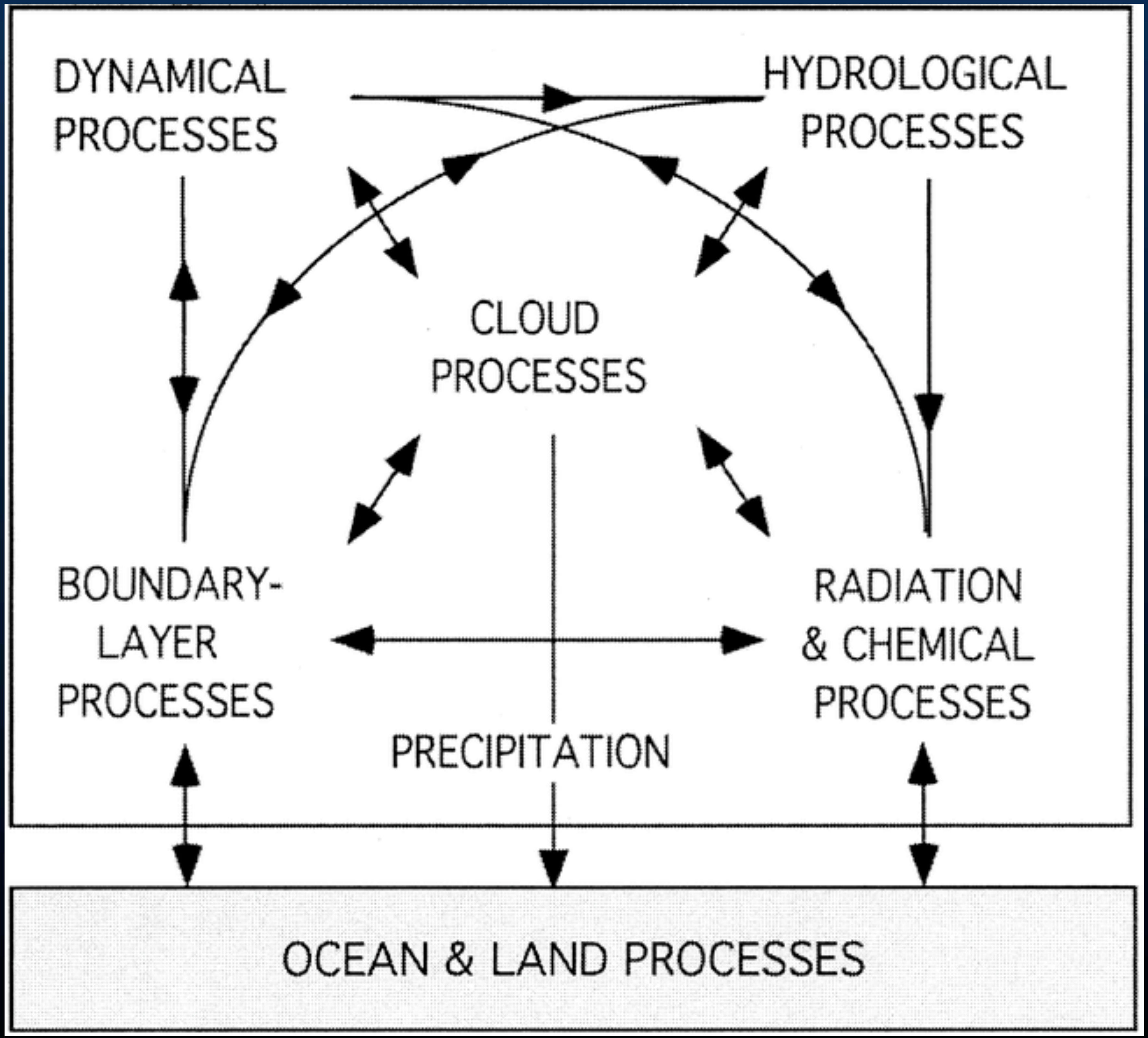
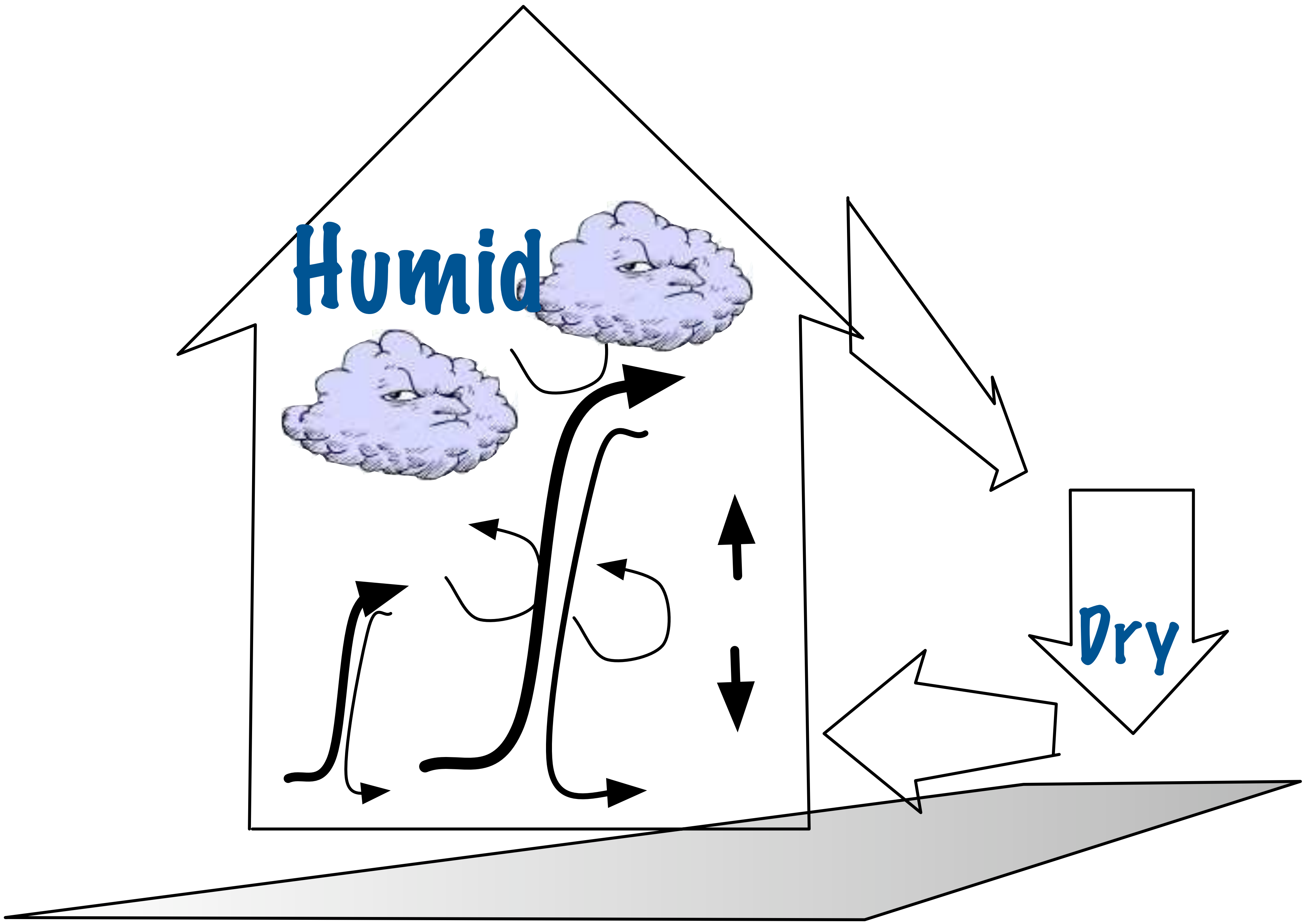
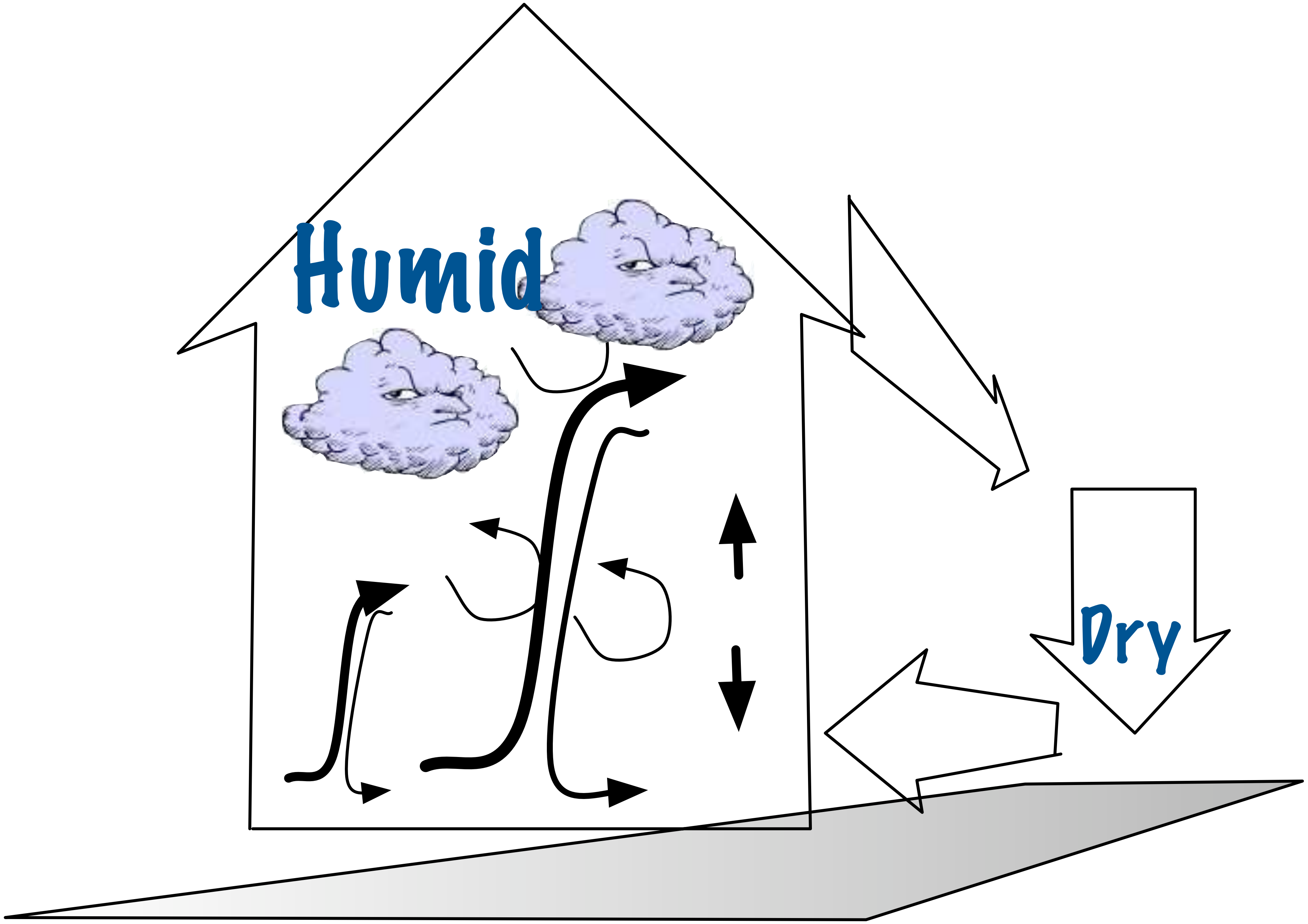


Arakawa, 2004

Strong coupling of convection to the large-scale flow

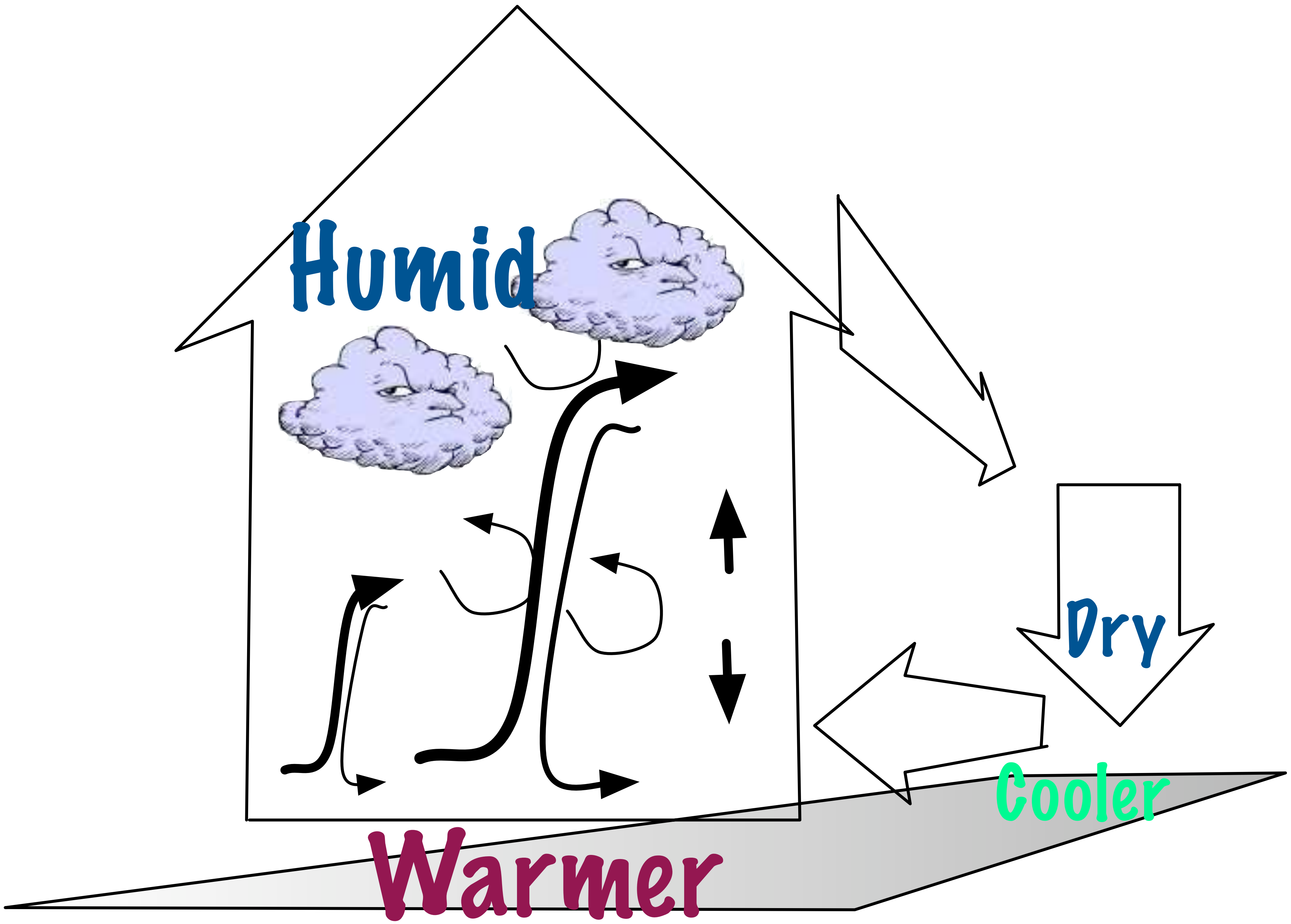


Strong coupling of convection to the large-scale flow



- Caution in interpreting correlations in data
- Caution in blaming model problems on particular model components

Strong coupling of convection to the large-scale flow



- Caution in interpreting correlations in data
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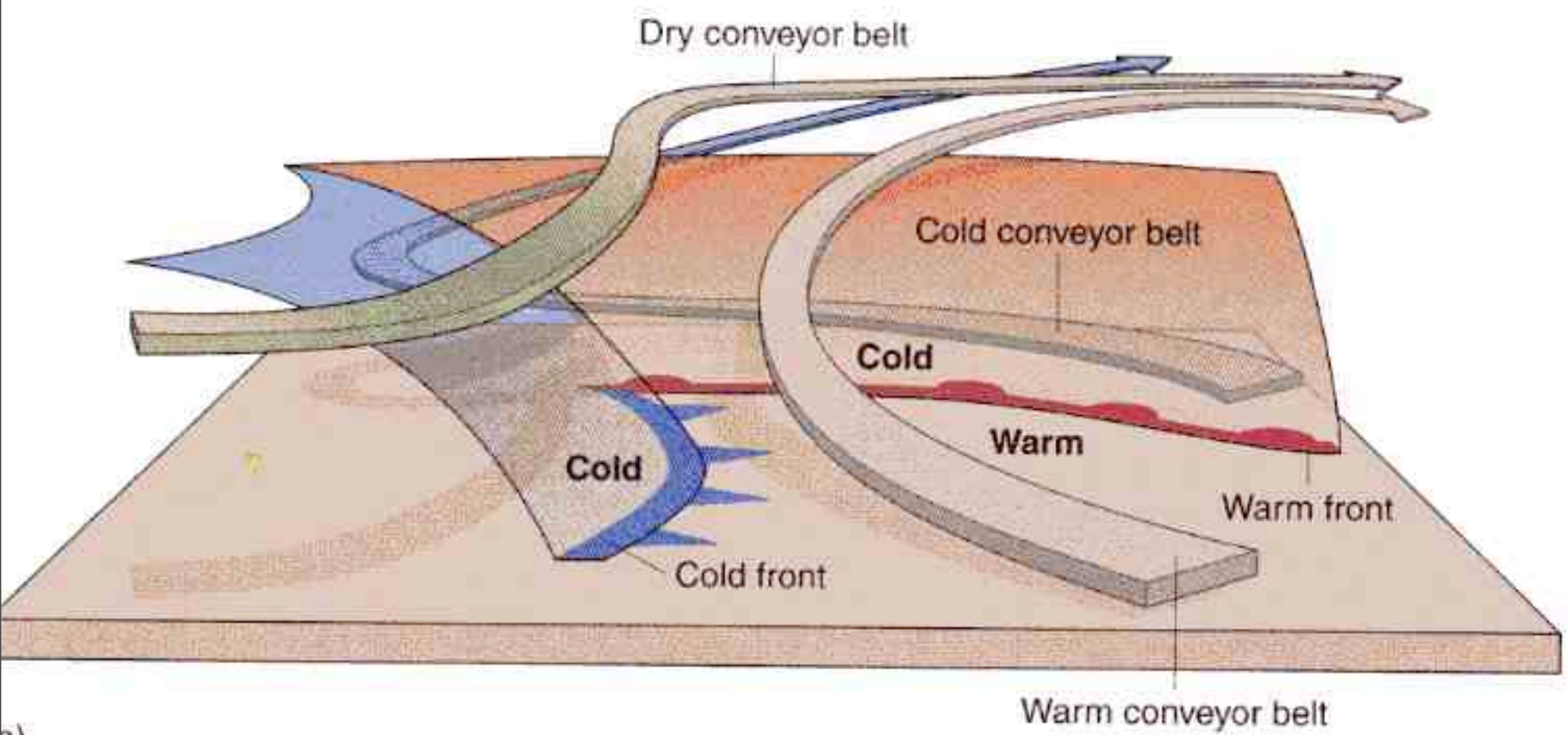
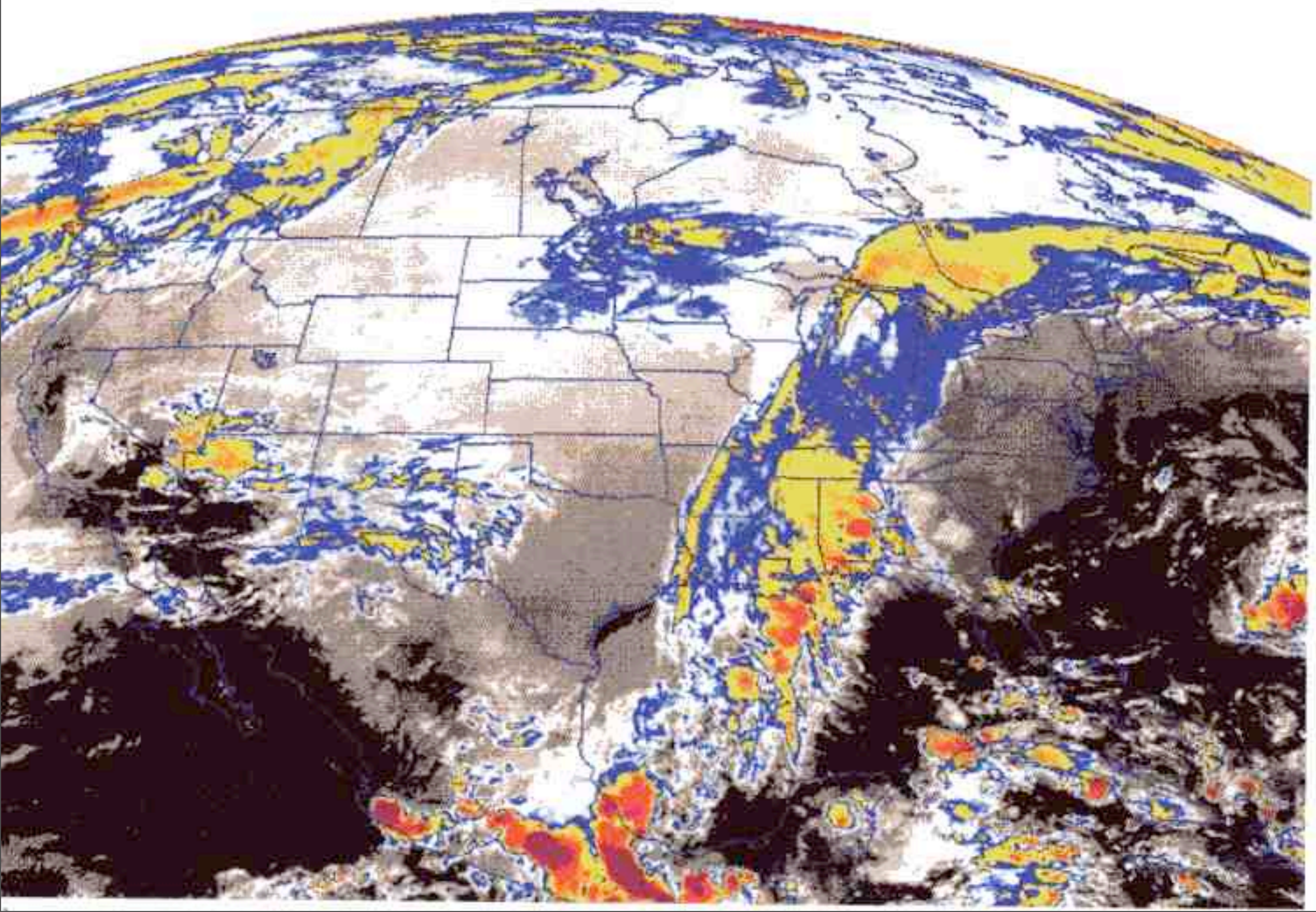


a)

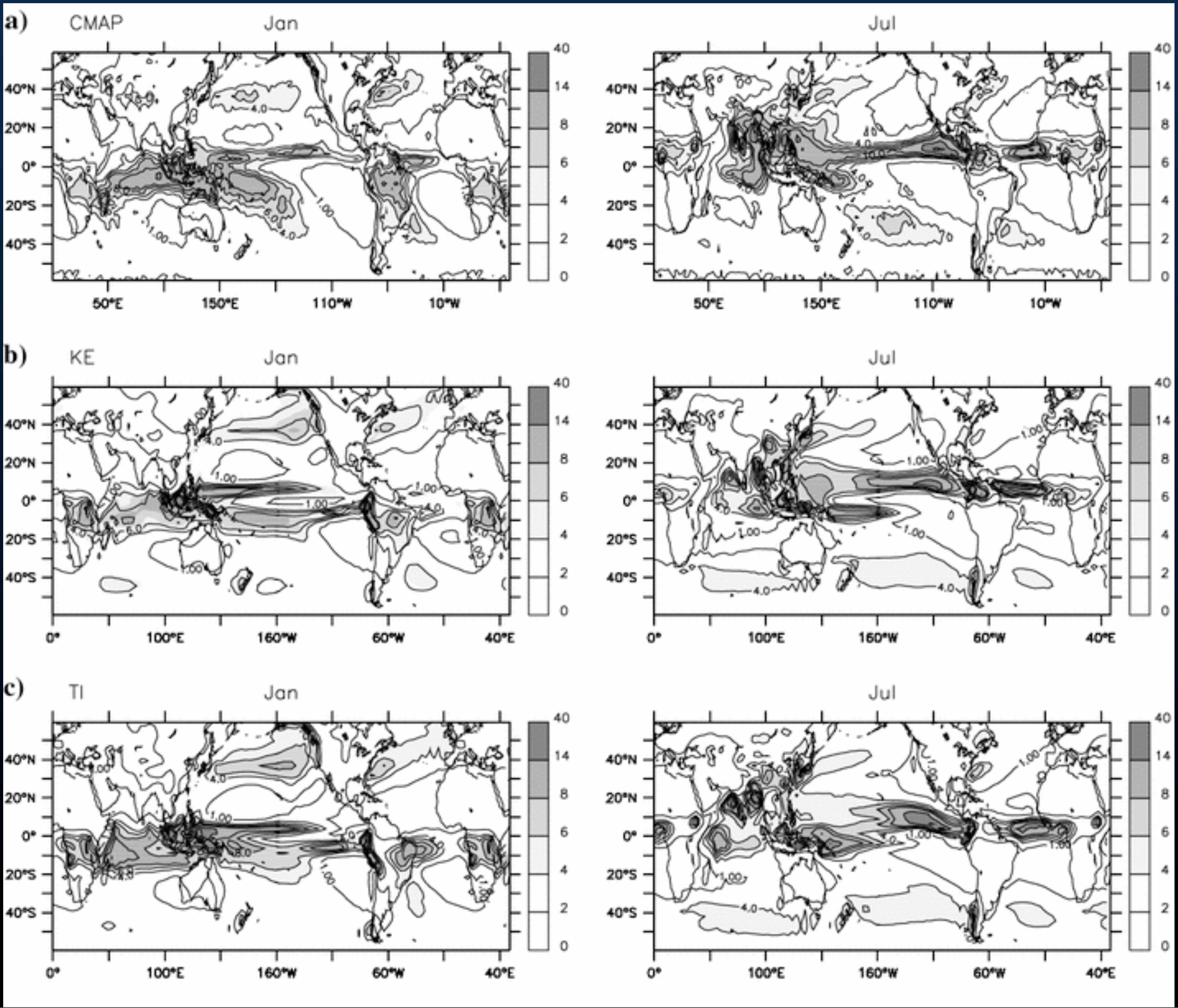


Midlatitude convection is largely slaved to synoptic dynamics, which can be predicted to leading order without explicit consideration of convective physics.

Convective coupling to the circulation more active in the tropics

ITCZ sensitive to cumulus scheme

Braconnot et al 2007



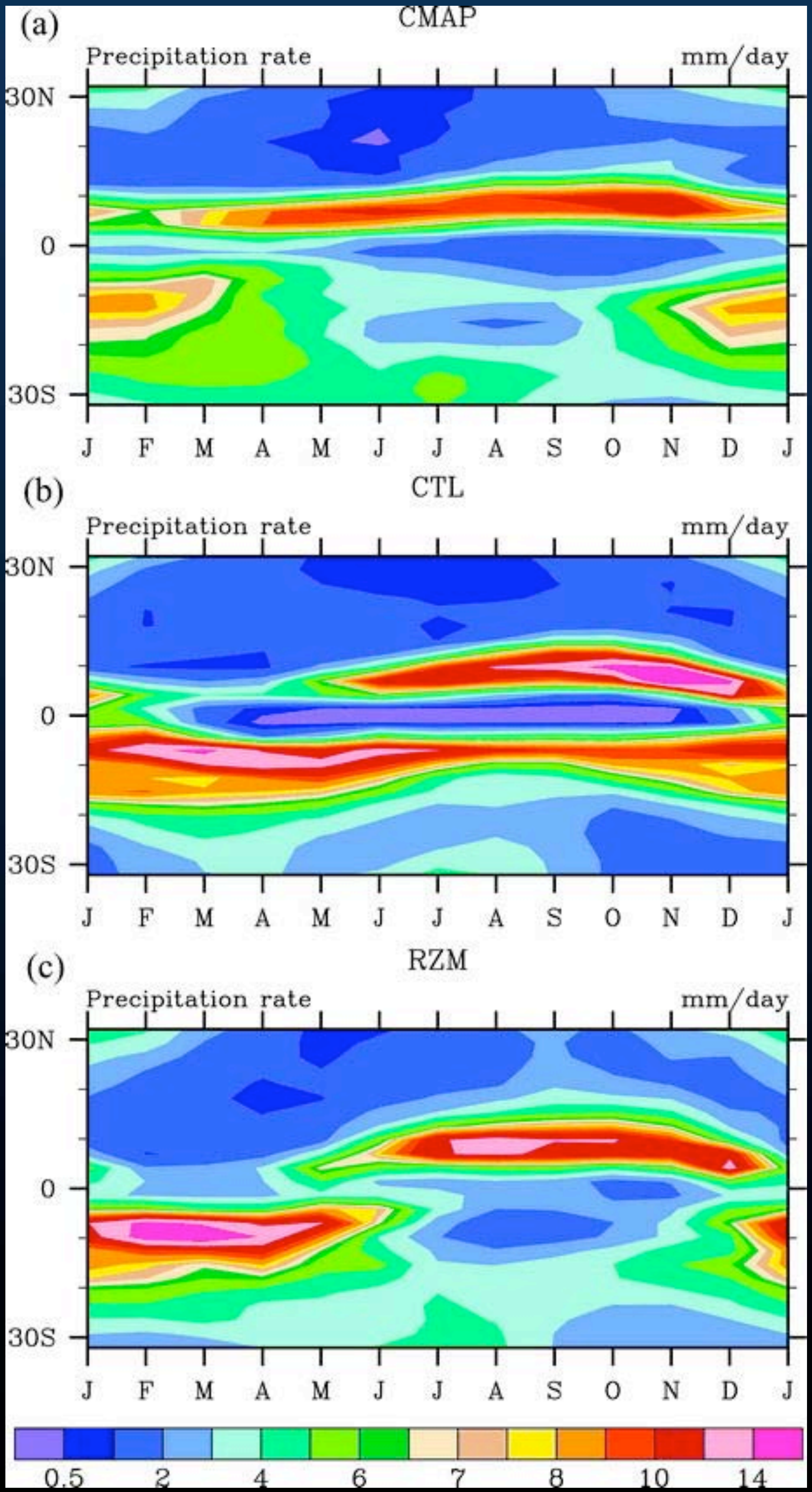
a) Observations

b) Emanuel

c) Tiedke

Another example

Song and Zhang 2009



a) Observations

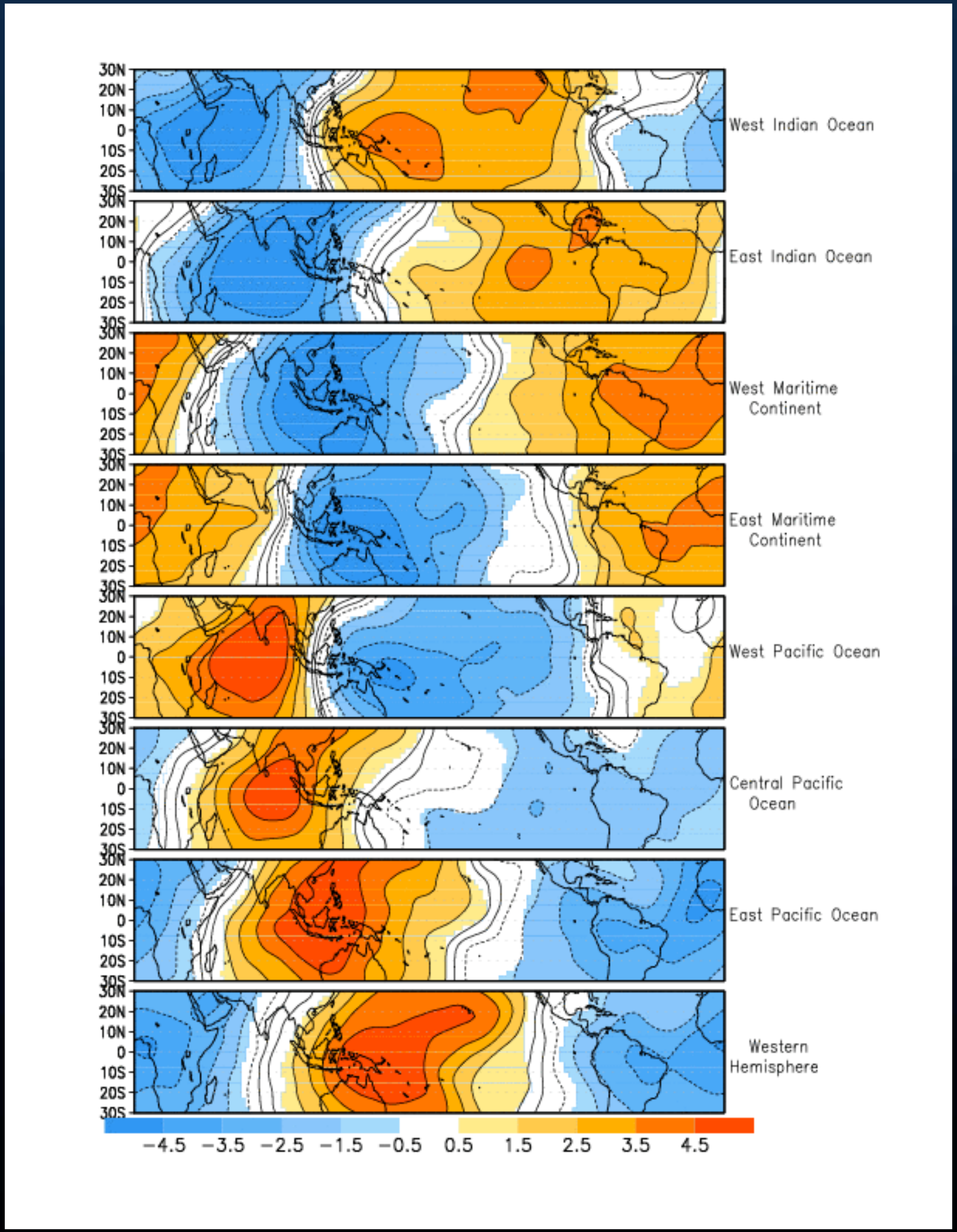
b) Original Z-M scheme

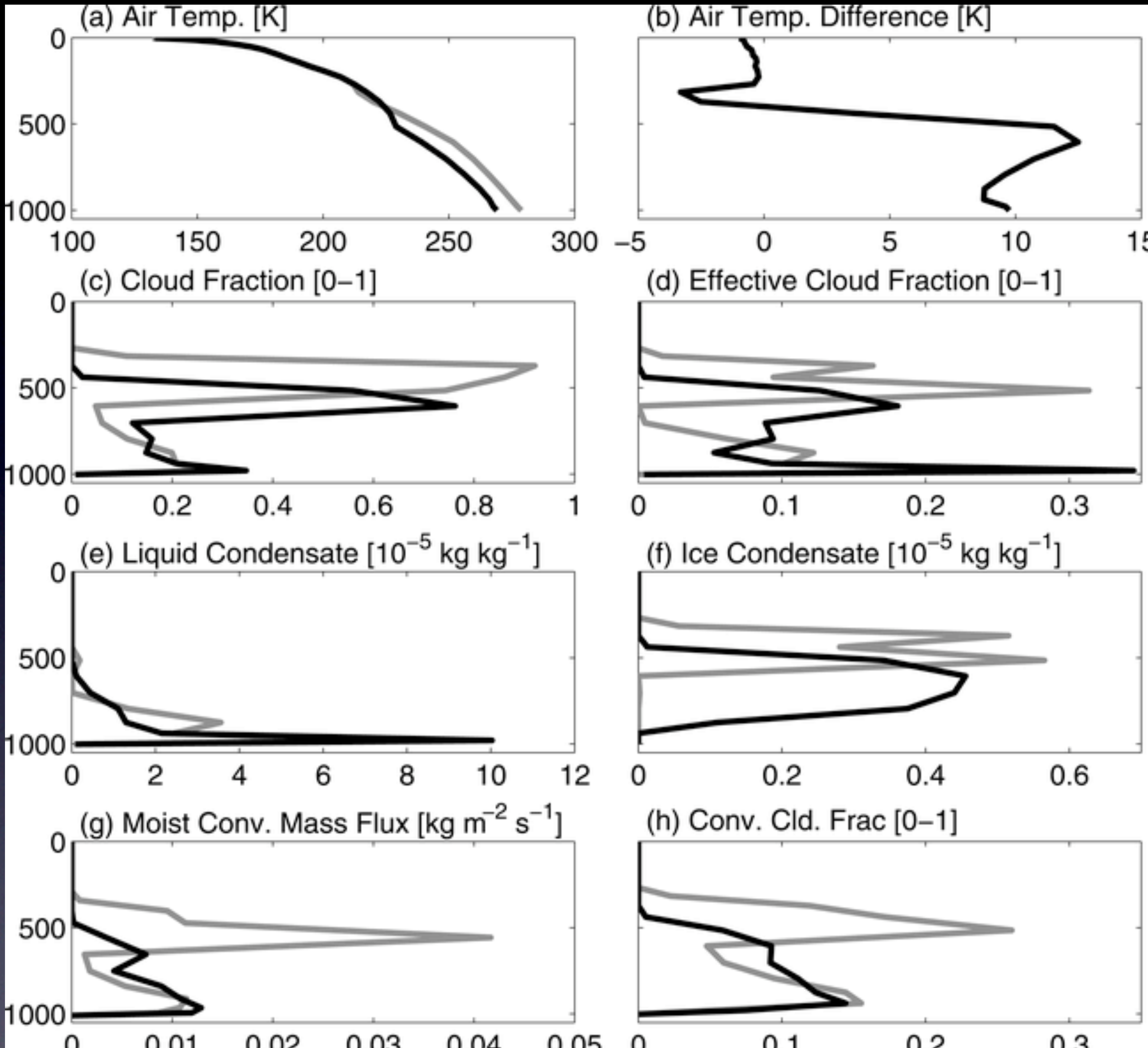
c) Modified

Convection also important to:

- a raft of studies show that the Madden Julian oscillation (MJO) in the Indo-Pacific is sensitive to cumulus parameterization (at least three in 2009 alone)

- Cumulus entrainment parameter is the most important single parameter to the climate sensitivity of the HadCM model (Rougier et al. 2009)





Possible change in the role of convection in a warmer climate?

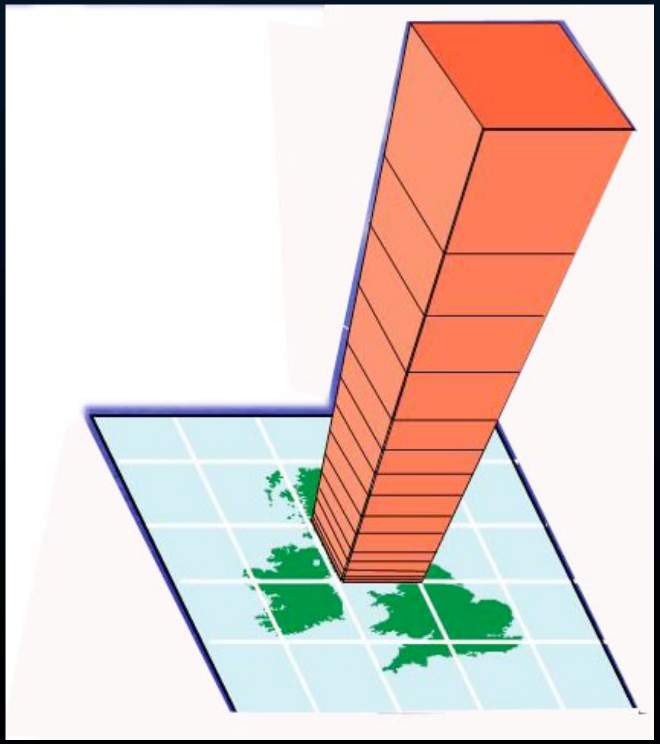
Simulated high-latitude cloud properties:

Today
Eocene

Abbot and Tziperman 2009

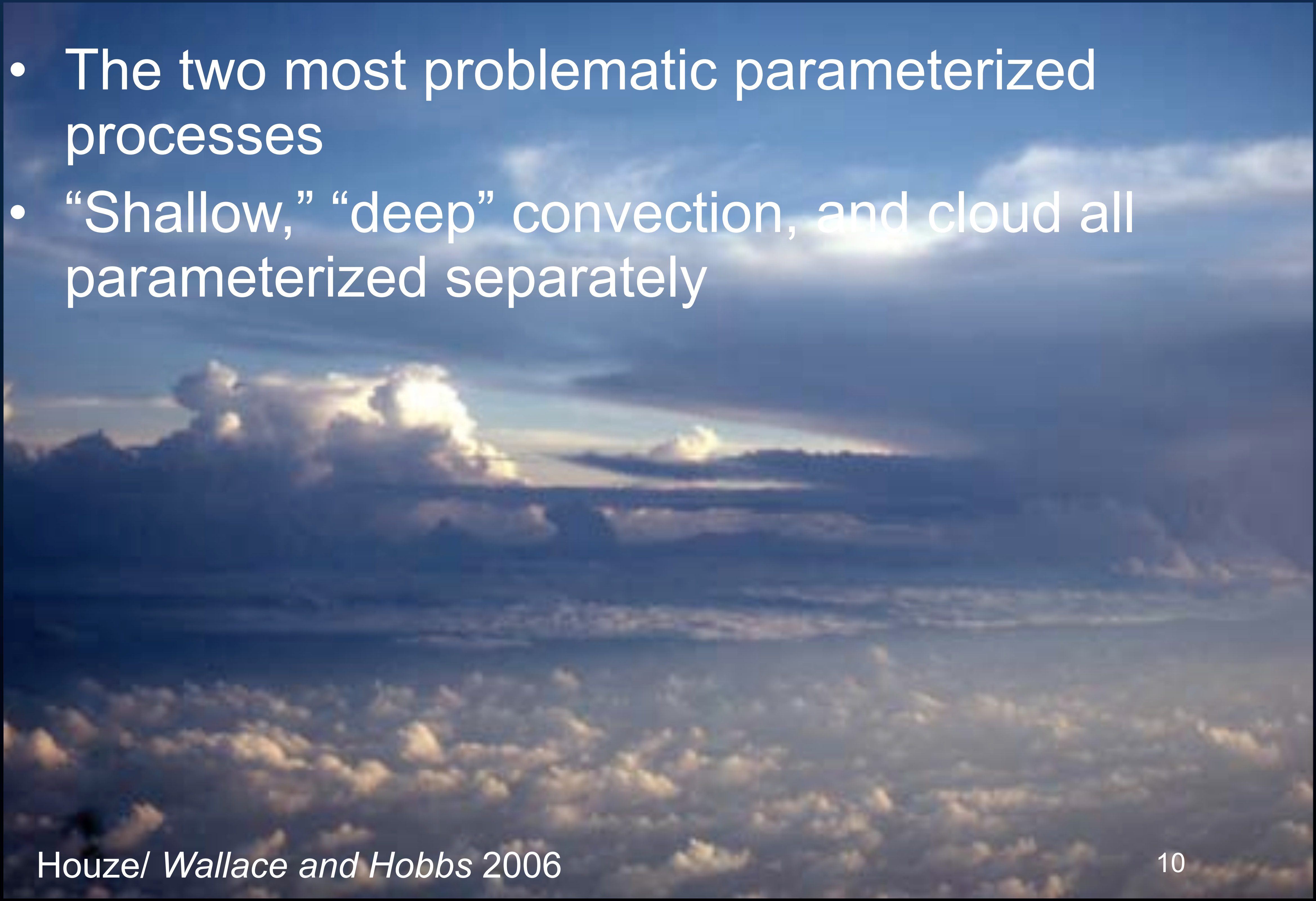
What is a numerical climate model (AGCM)?

- Start with simplified version of the Navier-Stokes +continuity+heat equations on a sphere; add rotation and truncate
- Devise “parameterizations” for unresolved sources of heat, momentum, and water due to:
  - horizontal and vertical mixing
  - phase changes of water, precipitation
  - cloud formation and dissipation
  - radiative transfer
  - surface evaporation
  - others



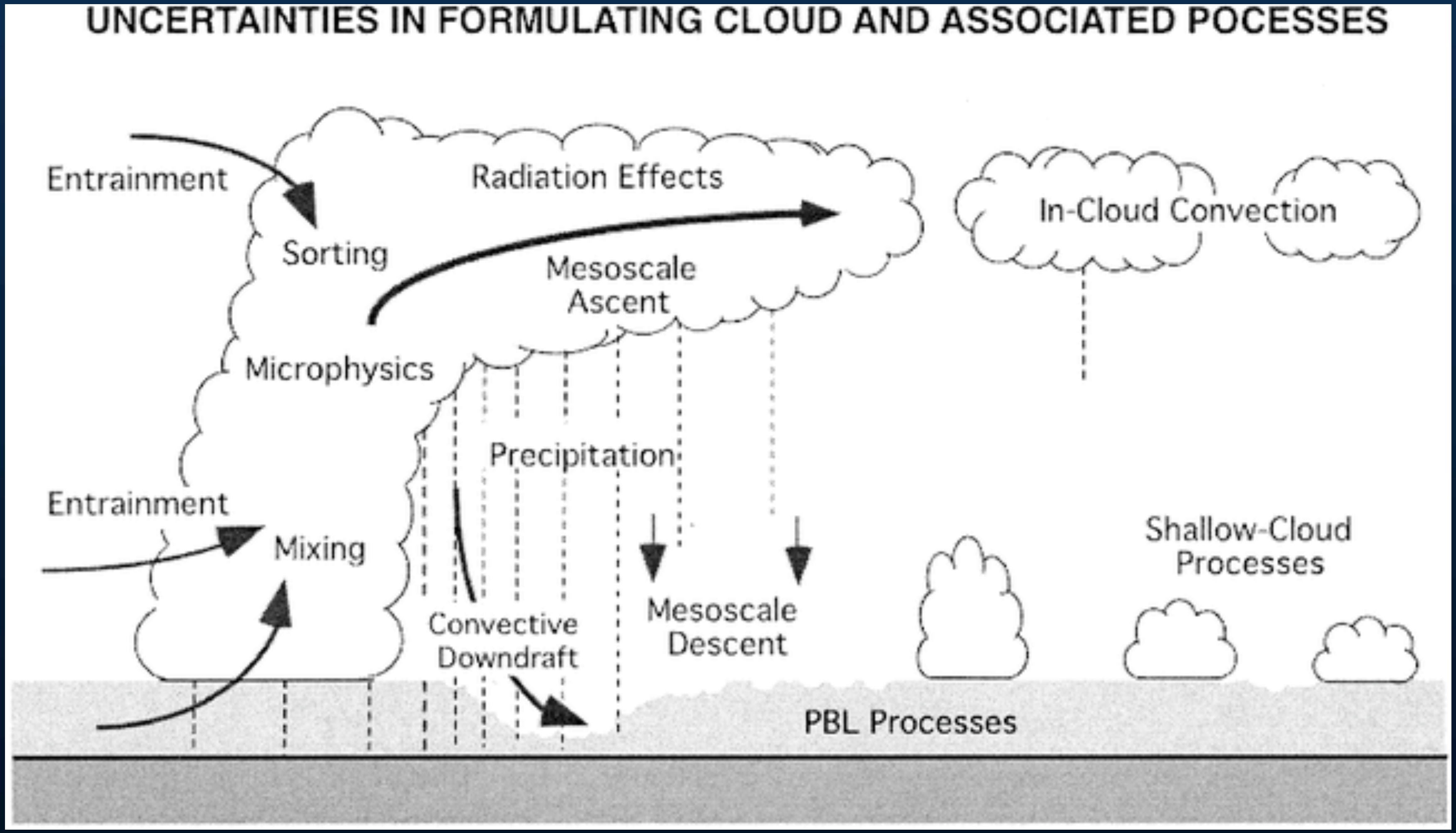
Convection/cloud

- The two most problematic parameterized processes
- “Shallow,” “deep” convection, and cloud all parameterized separately



Houze/ *Wallace and Hobbs* 2006

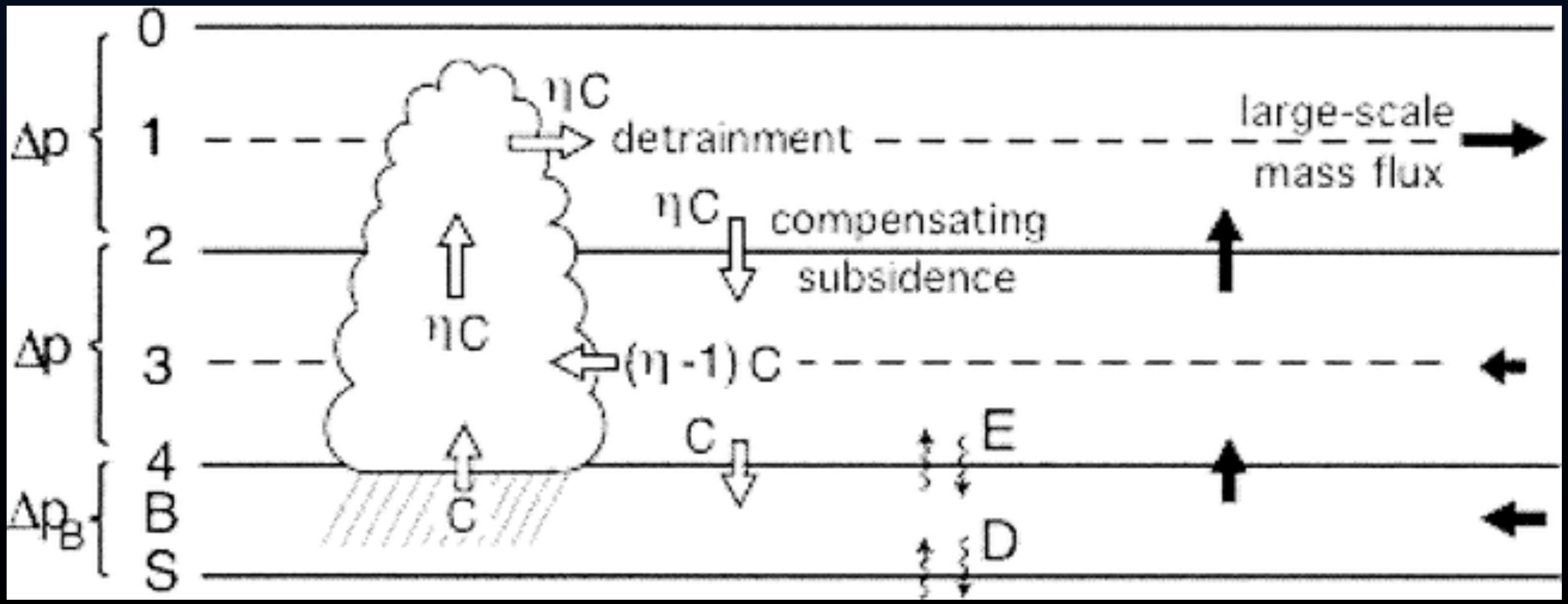
Parameterization



Need to predict:
$Q_1(z)$: effective heat source
$Q_2(z)$: L*effective vapor sink
$\int Q_1 dz = \int Q_2 dz = LC$

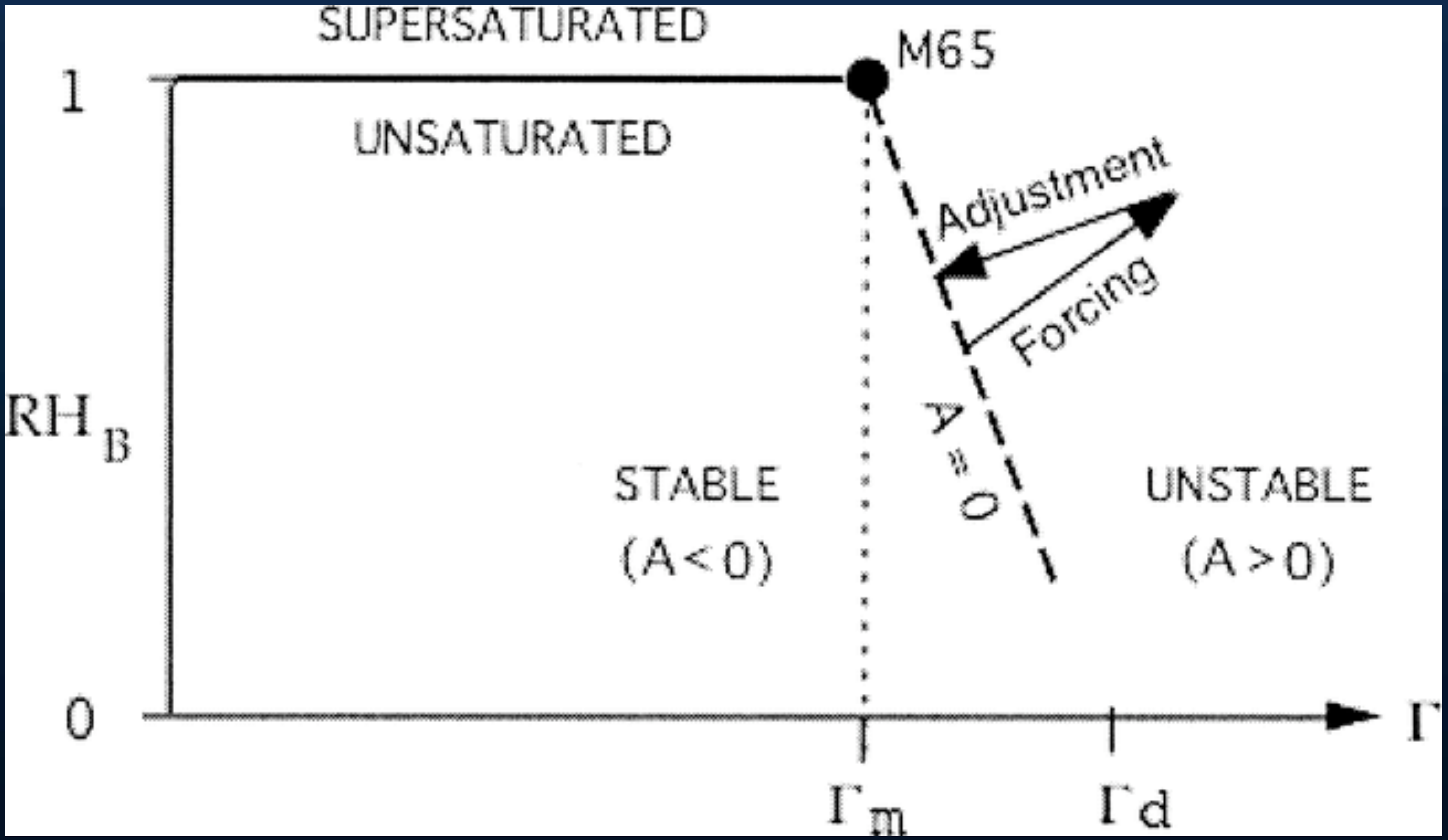
P/C = "precipitation efficiency" (in crude model, might be assumed unity)

From *Arakawa* (2004)



Parameterization

Boundary-layer moisture -->

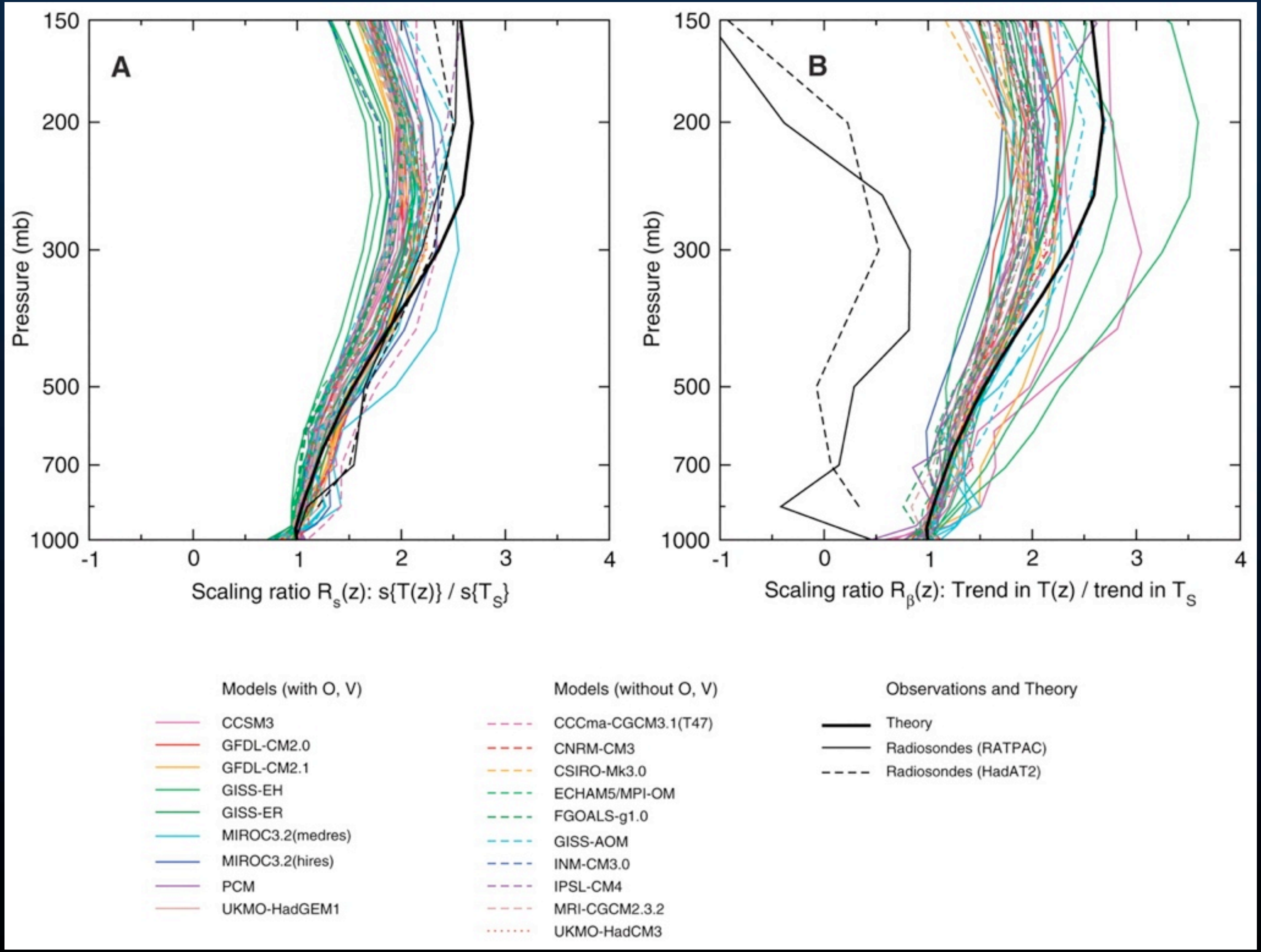


Lapse rate

From *Arakawa* (200

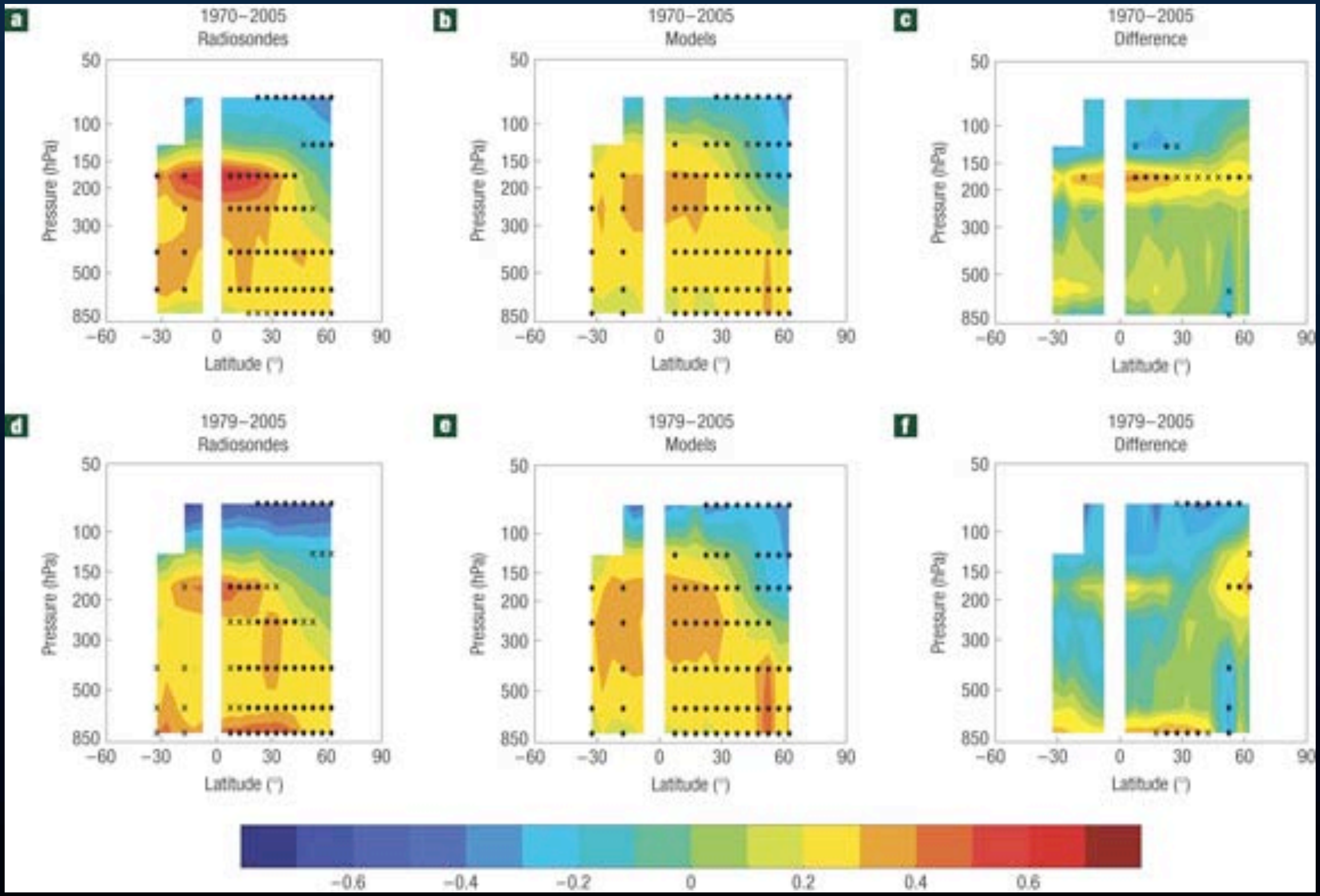
Fundamental idea: force atmosphere toward moist neutrality (e.g., small CAPE) with respect to specified perturbations (parcel lifting)

Evidence that convective influence on temperature extends higher in reality than in GCMs



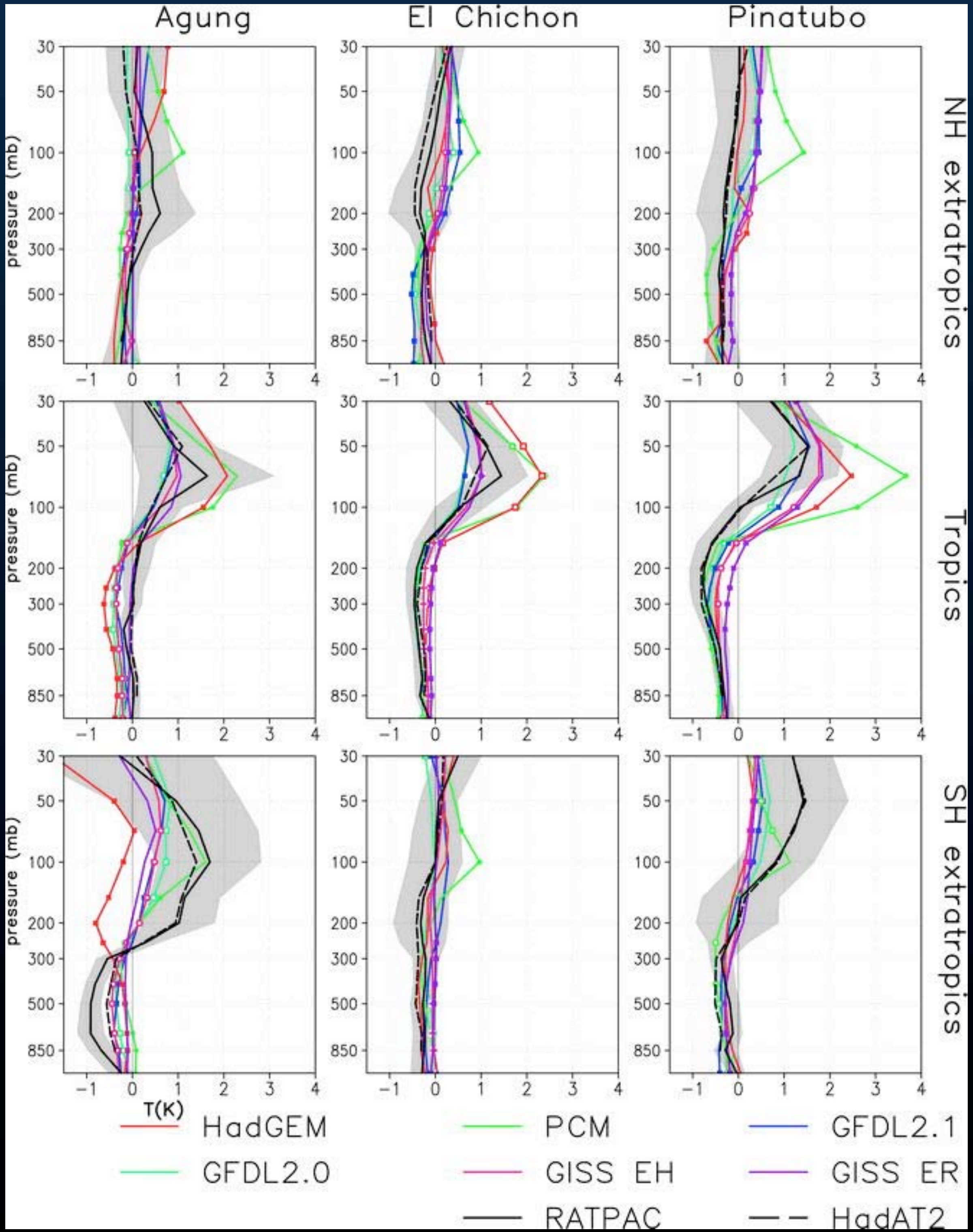
Santer et al. 2005

Evidence that convective influence on temperature extends higher in reality than in GCMs



Allen and Sherwood 2008

Evidence that convective influence on temperature extends higher in reality than in GCMs



Delta-T, after eruption

Black: obs
Colors: various GCMs

Lanzante and Free 2009

GATE phase III results (1974)

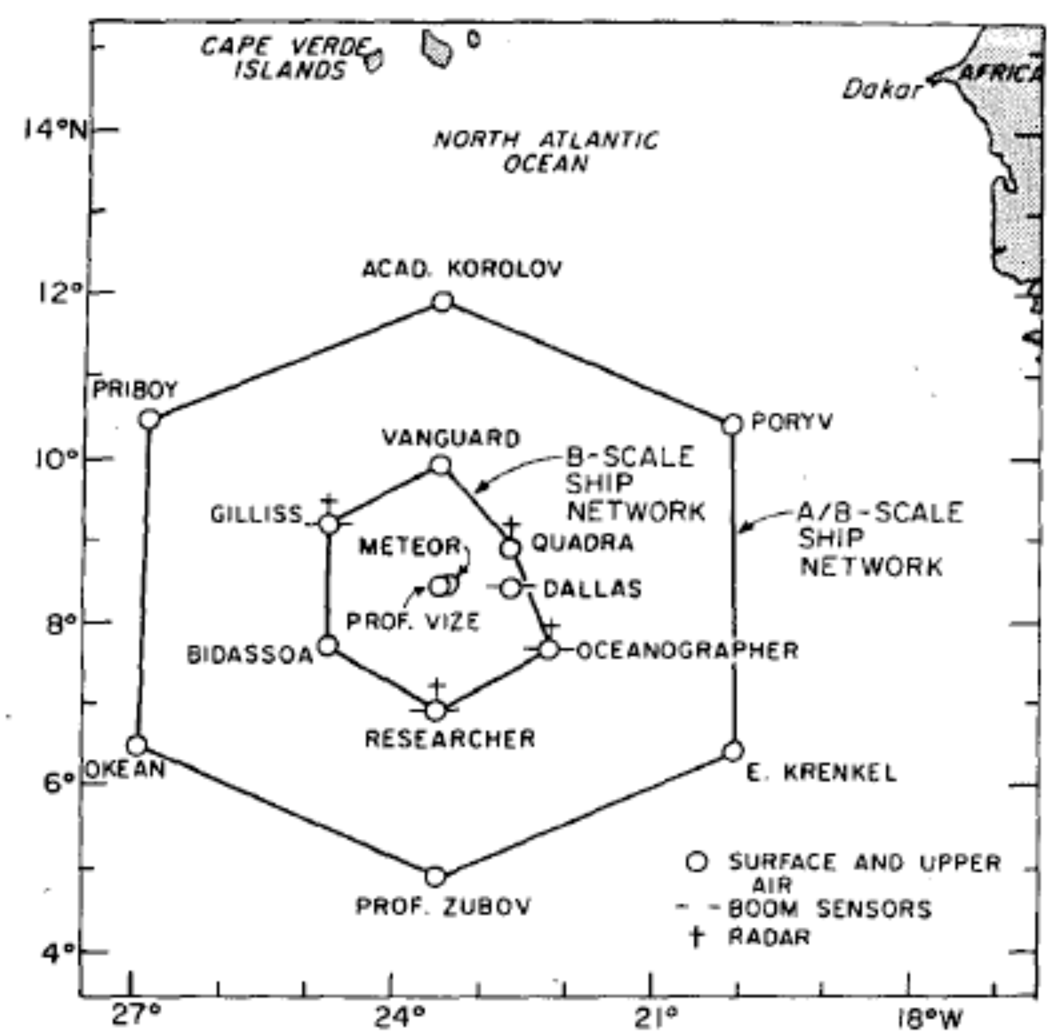


FIG. 1. Network of ship observations. Types of observations utilized in the present study are indicated by code.

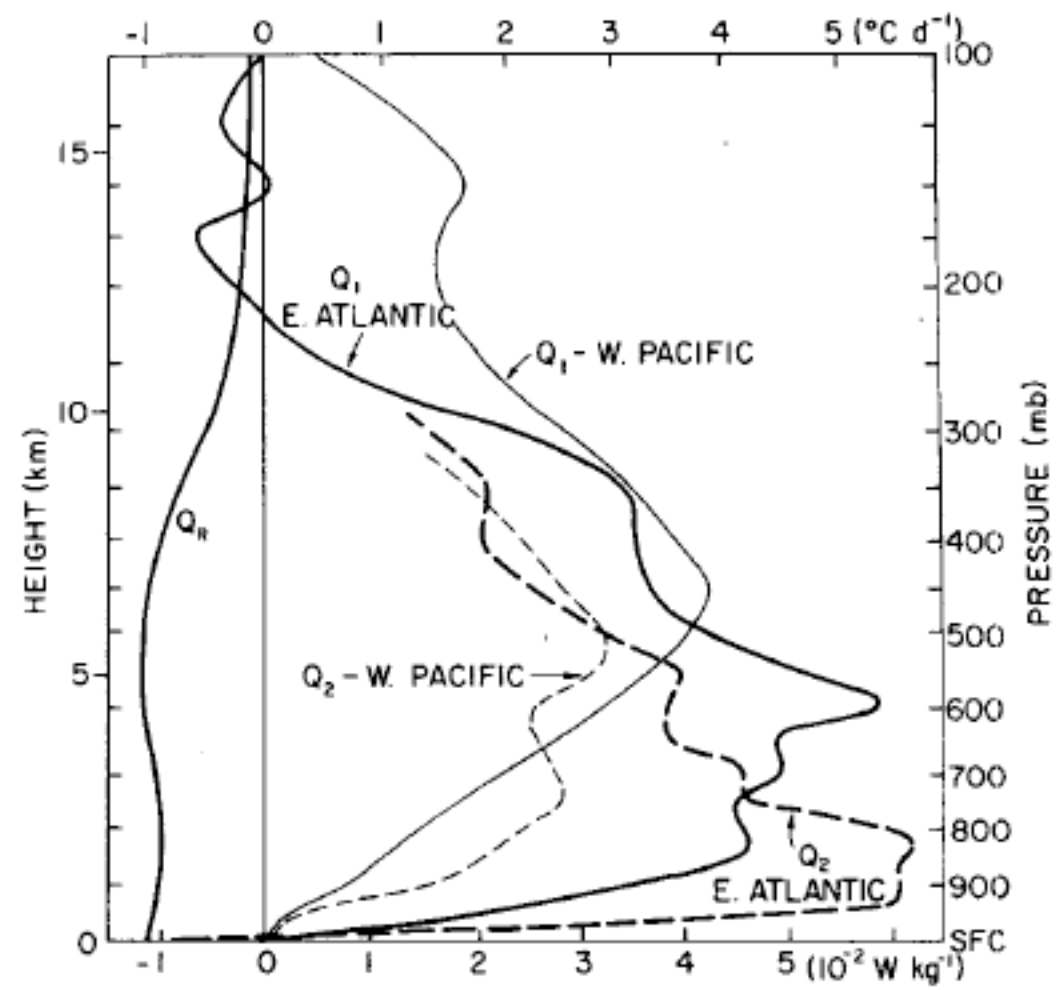


FIG. 8. Variation with height of the apparent sensible heat source Q_1 and apparent latent heat sink Q_2 for the B-scale area and KEP triangle. Also shown is the profile of mean radiational heating Q_R for the B-scale area (see text).

GATE concept: measure the inputs and predictands of a cumulus scheme

Thompson et al., 1979

GATE phase III results (1974)

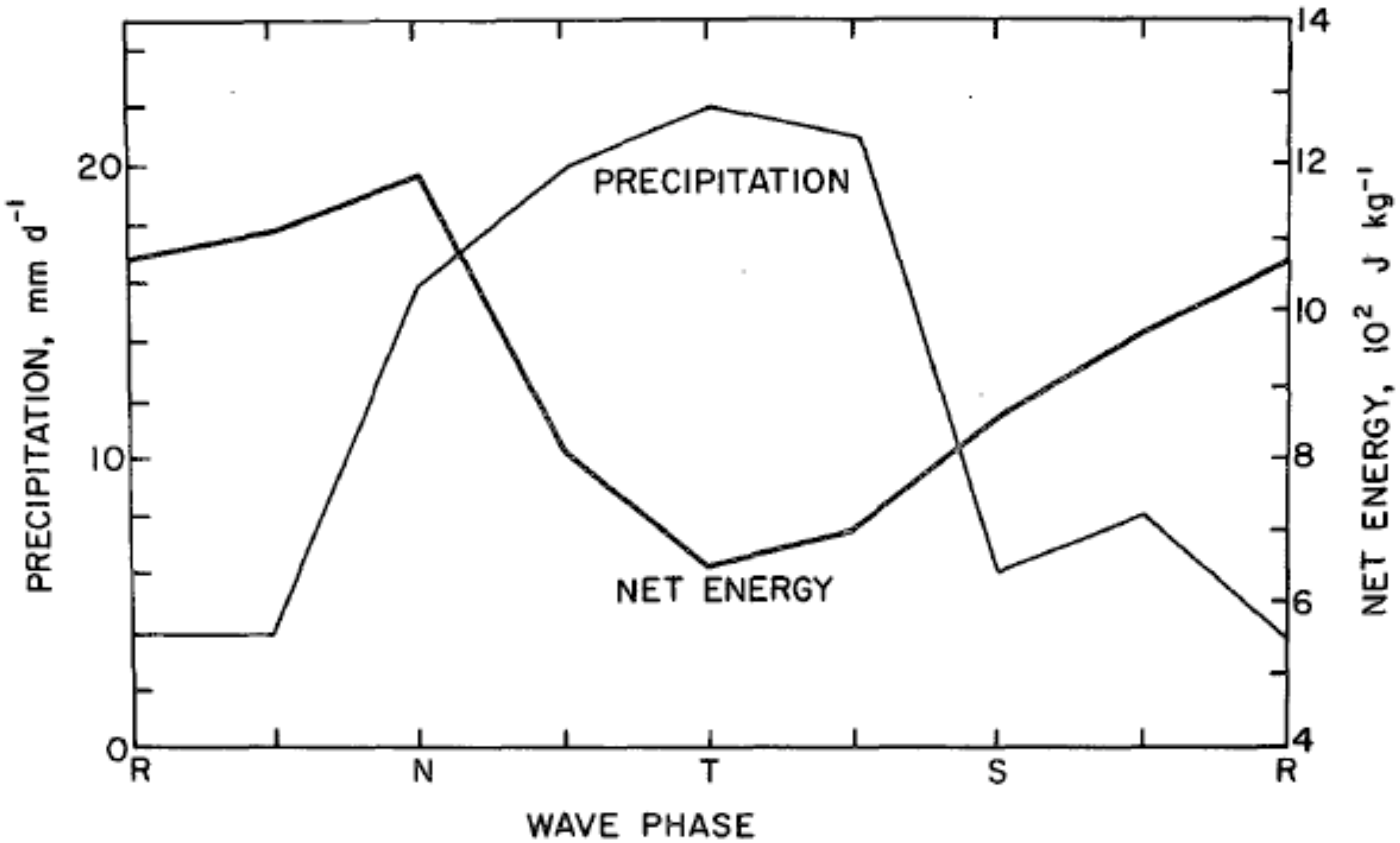


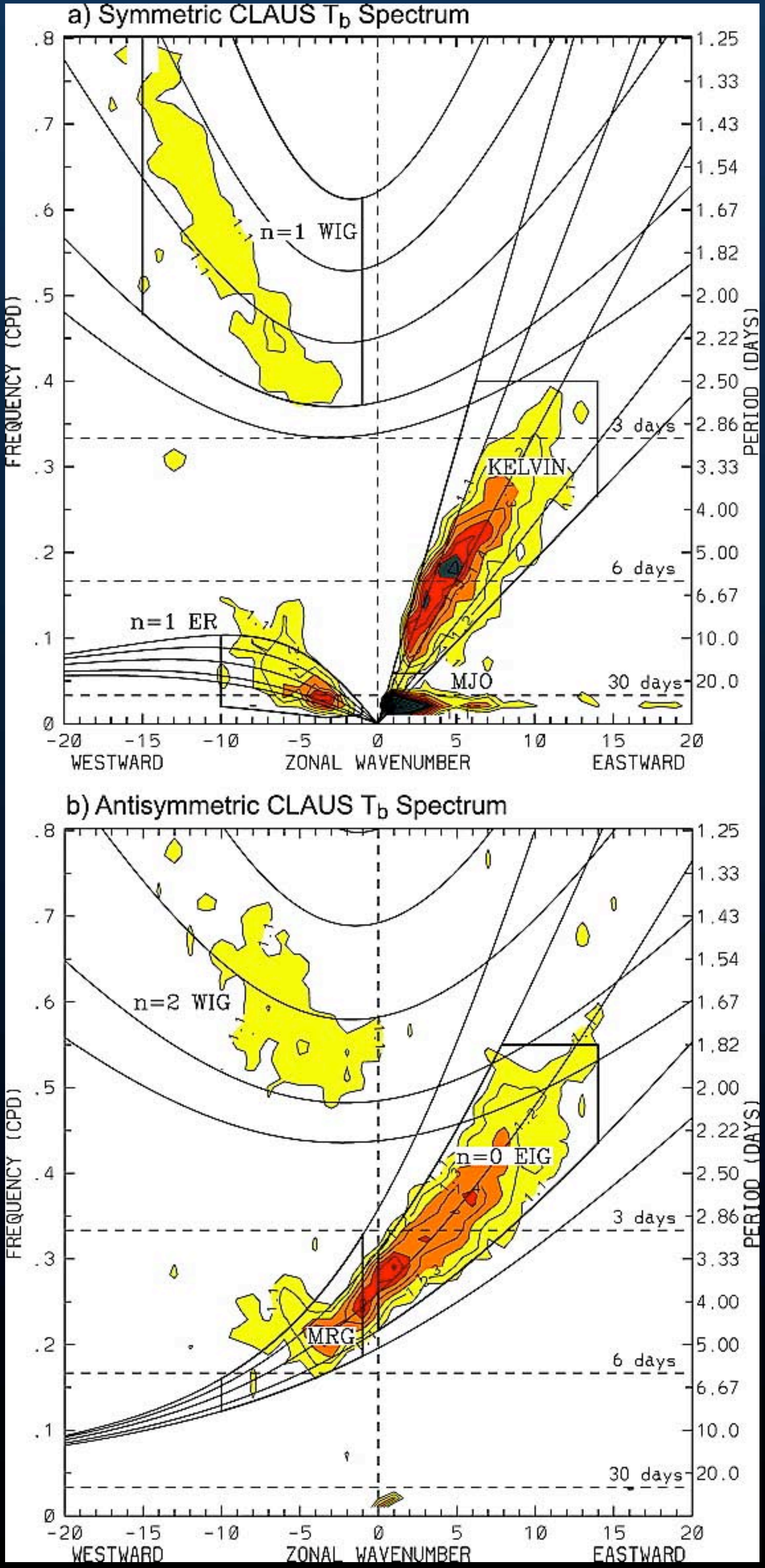
FIG. 19. Precipitation rate (thin) and net energy released in lifting undilute parcel from 1000 mb to the level of zero buoyancy (heavy) as functions of wave position.

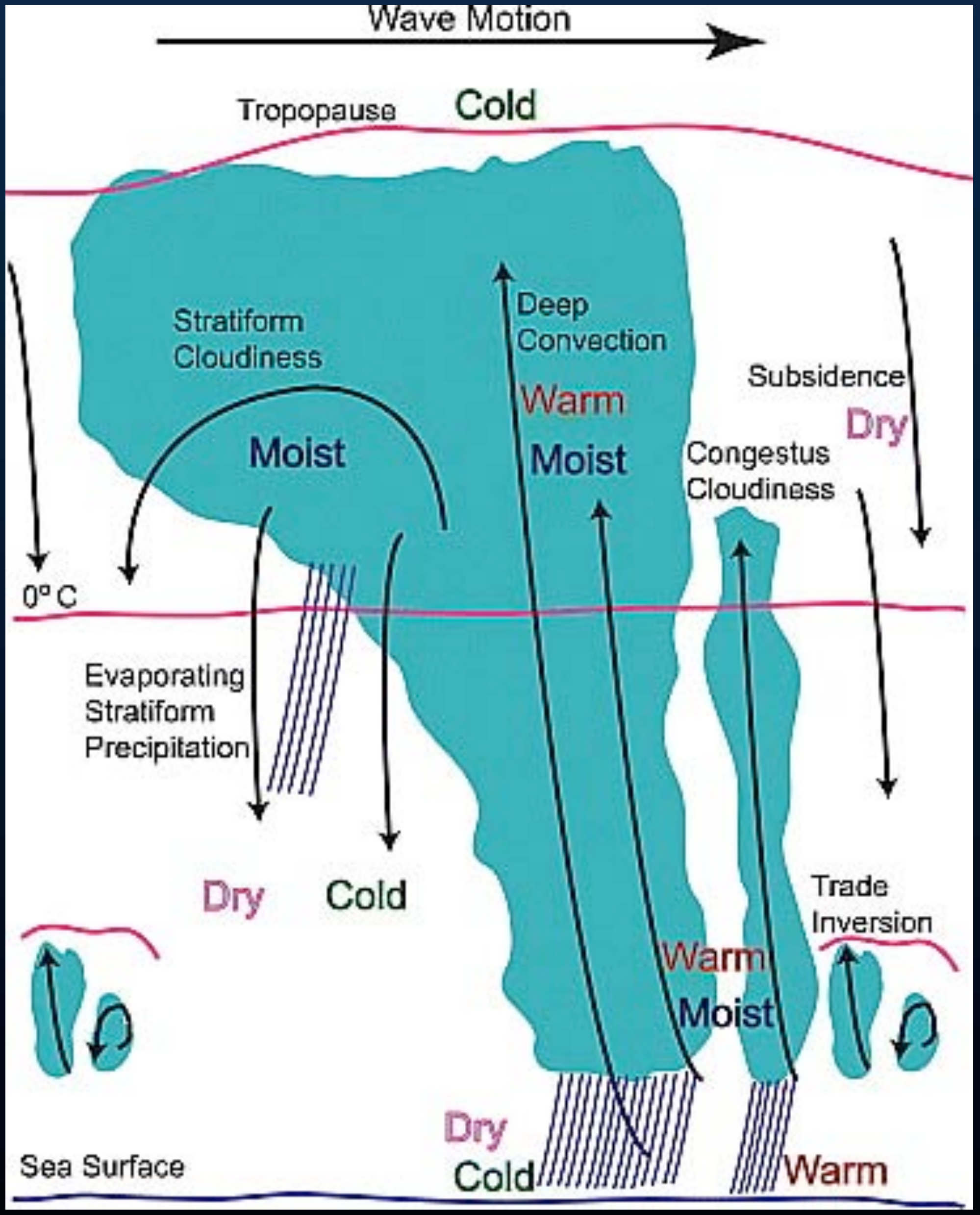
CAPE

Compositing: waves coupled to the convection

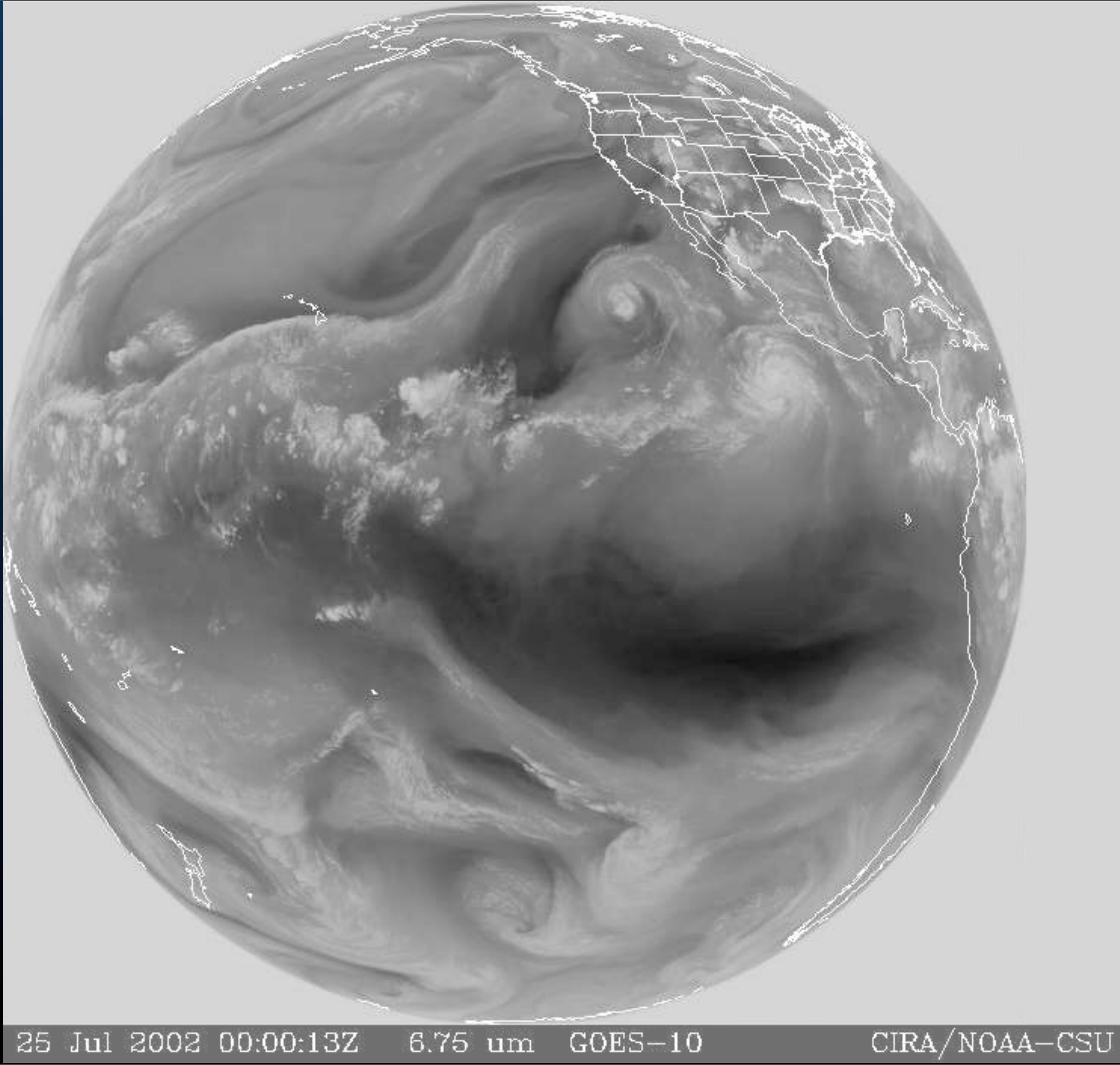
Thompson et al., 1979

Observed convectively-coupled waves





Kiladis et al. 2008


25 Jul 2002 00:00:13Z 6.75 um GOES-10 CIRA/NOAA-CSU

Cloud clustering

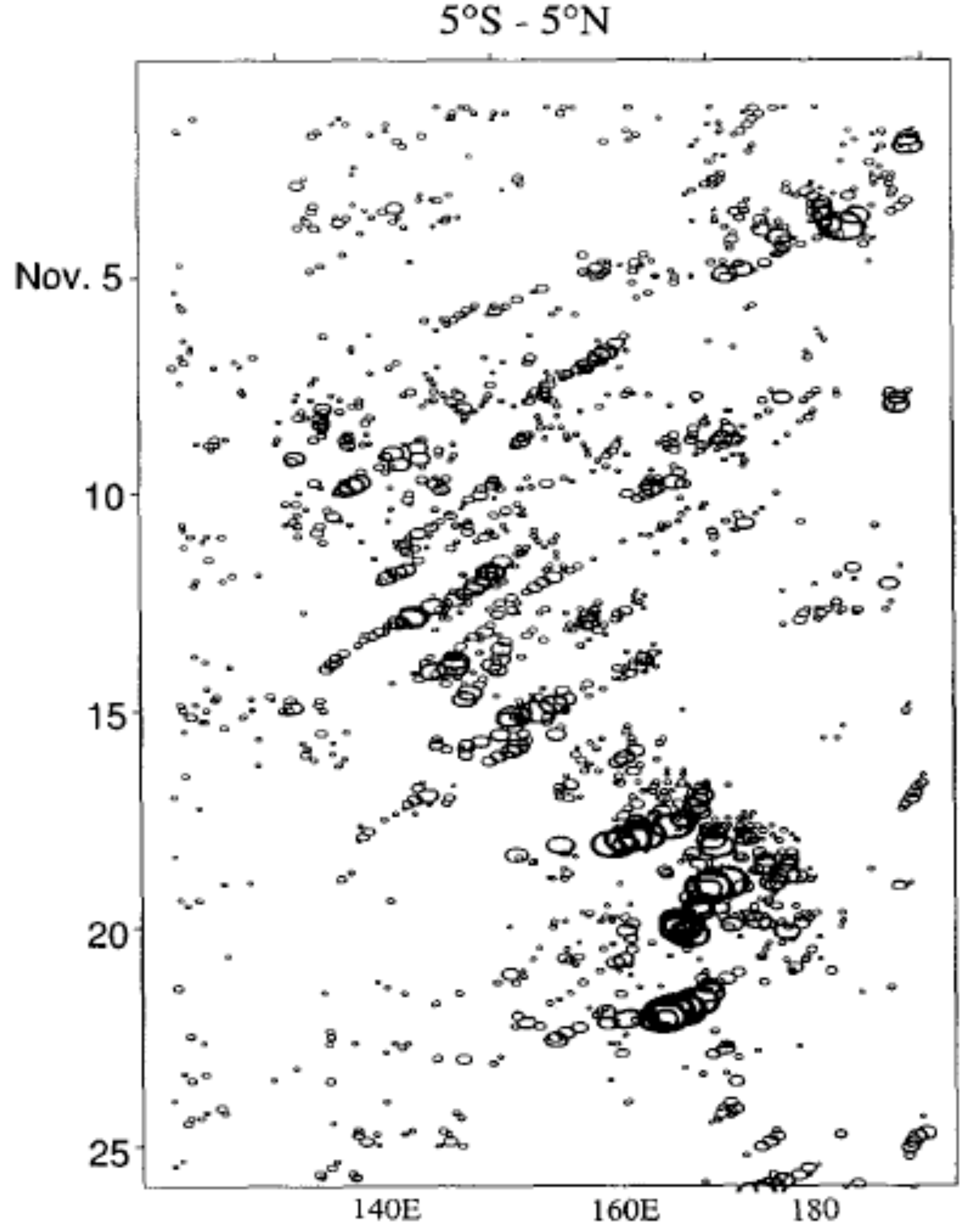
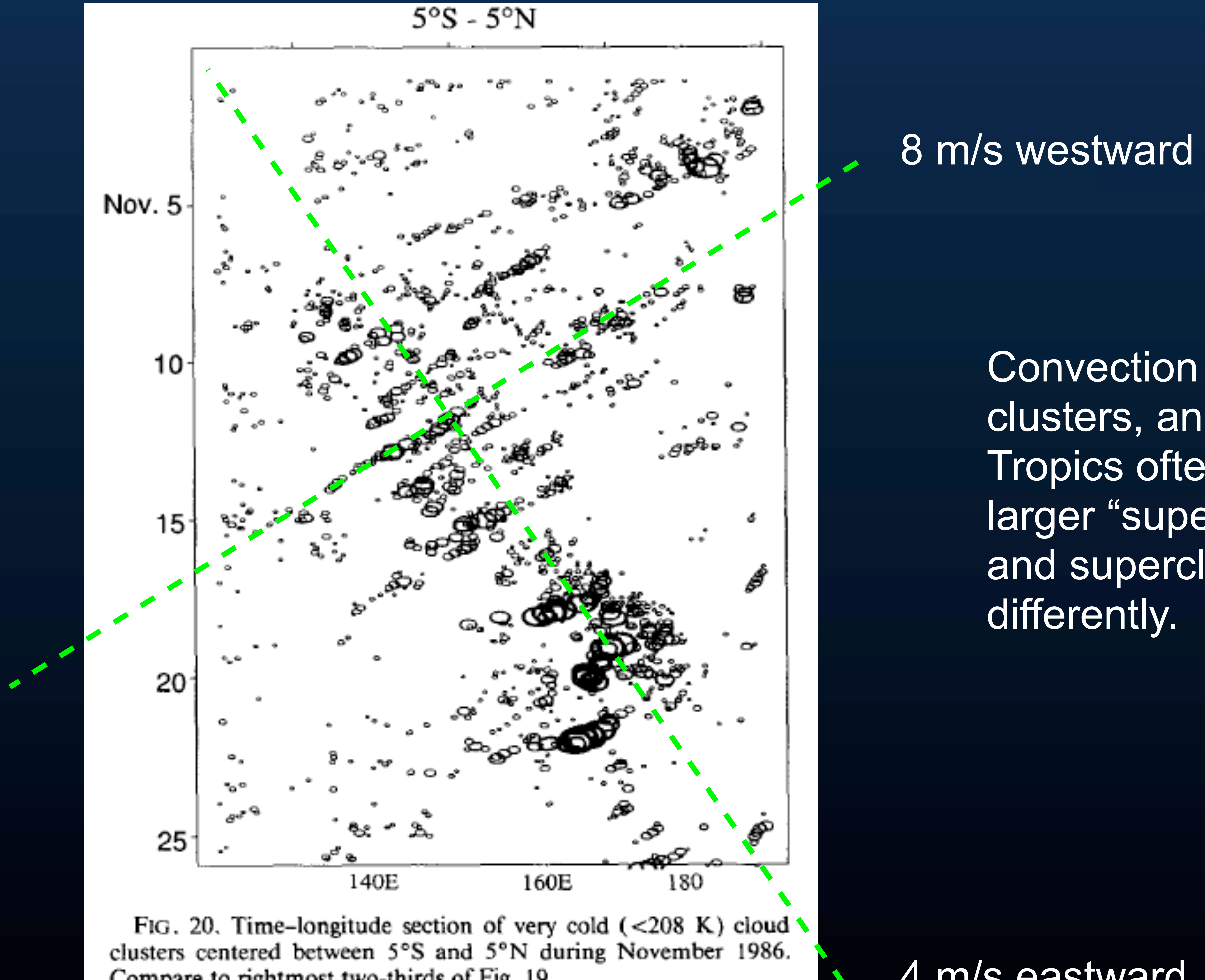


FIG. 20. Time–longitude section of very cold (<208 K) cloud clusters centered between 5°S and 5°N during November 1986. Compare to rightmost two-thirds of Fig. 19.

Convection tends to occur in clusters, and small clusters in the Tropics often occur together in larger "superclusters." The clusters and superclusters can propagate differently.

Mapes and Houze 1993

Cloud clustering



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Mapes and Houze 1993

Can waves organize convection more generally?

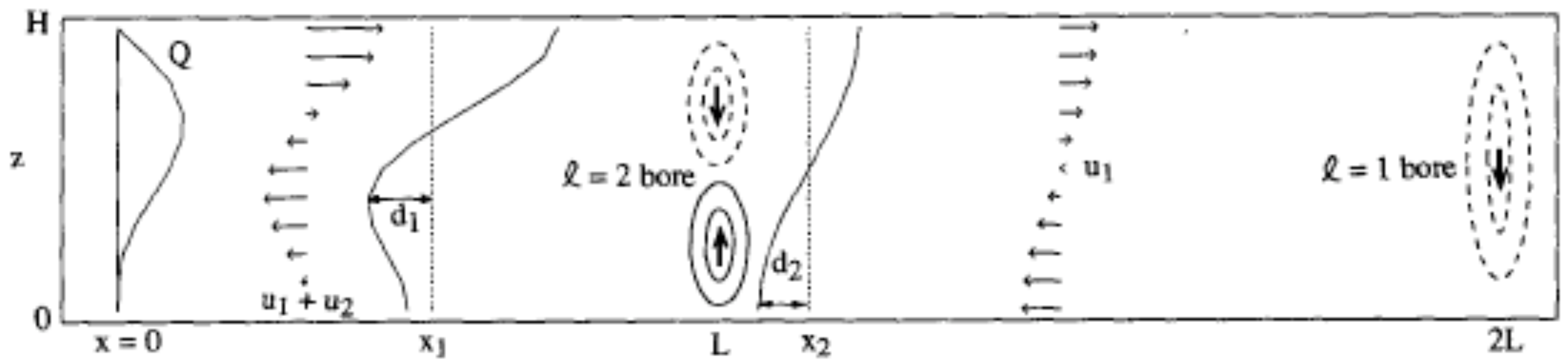
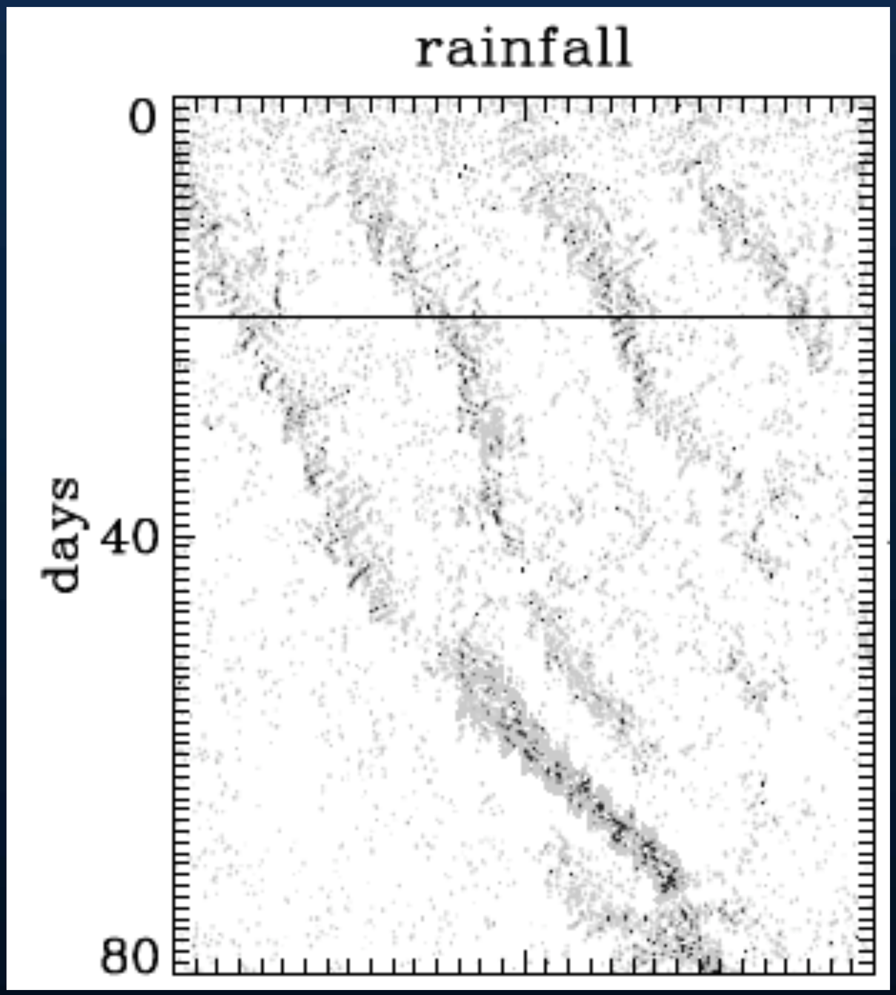


FIG. 3. Schematic of the buoyancy bores, horizontal winds, and integrated displacements of material lines (solid) relative to their initial positions (vertical dashed lines) a time τ after the initiation of the slab-symmetric heat source $Q(z)$ near $x = 0$. The two buoyancy bores have reached L and $2L$, where $L = NH\tau/2\pi$. Note that the material lines have moved closer together at low levels, indicating area contraction remote from the heated region. Adapted from Fig. 5 of NPC.

Mapes 1993: Tropical convection "gregarious" because of wave dynamics, and because the Q1 profile is top-heavy (most heating in upper half of the troposphere), exciting both the m=1 and m=2 vertical wave modes.

Phase speed of gravity wave ~ *N/m* in linear theory, so m=1 is twice as fast as m=2.

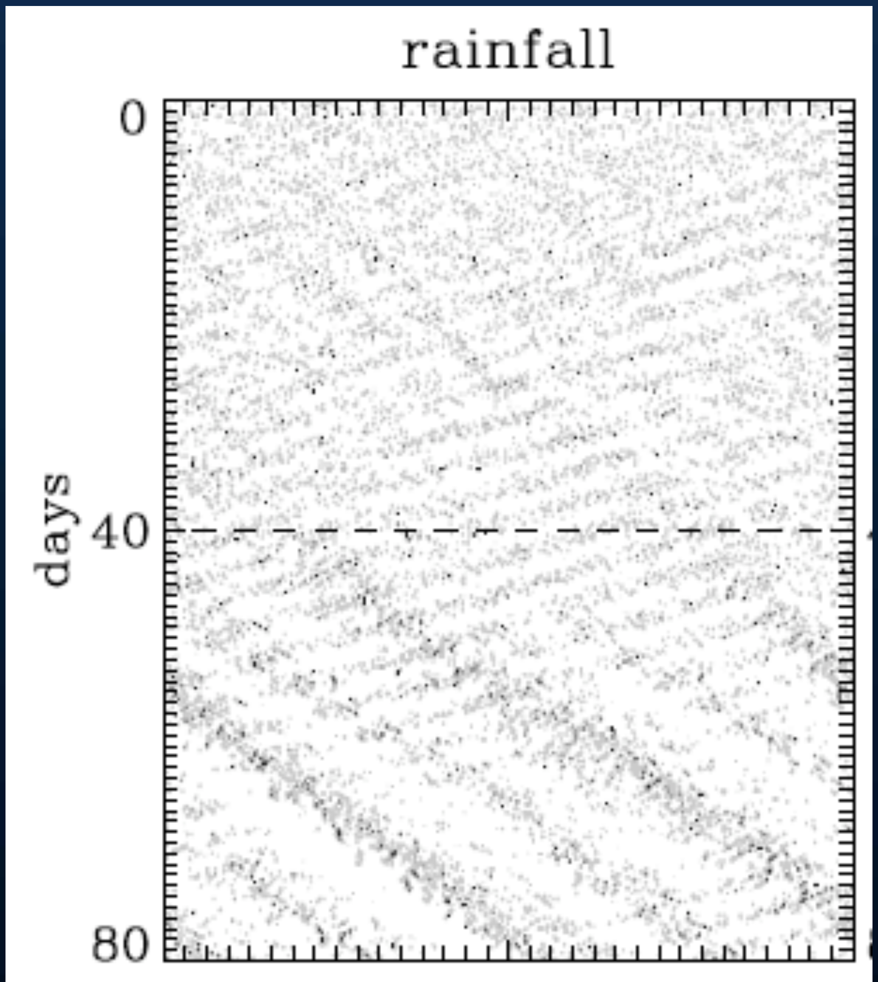
Organization by mid-level humidity



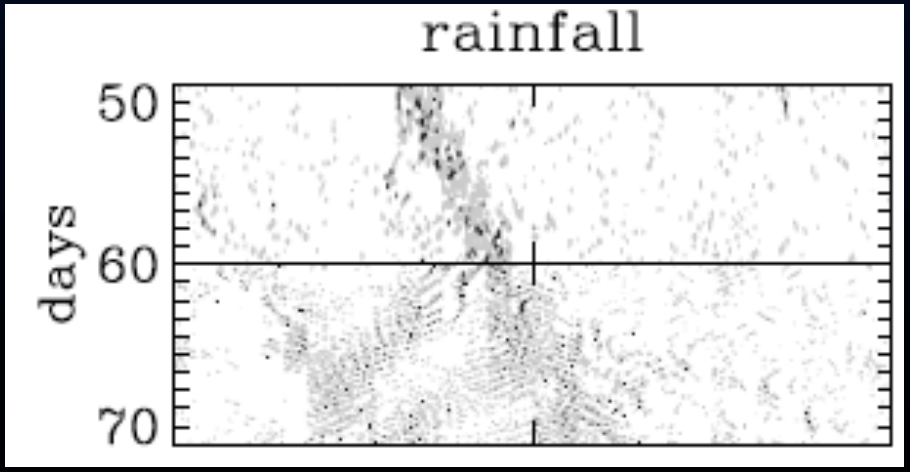
x

Control simulation (large area cloud-resolving simulation of tropical belt)

Simulation with redistribution of free-tropospheric water vapor



x



Stepwise imposition of redistribution

Grabowski and Moncrieff 2003

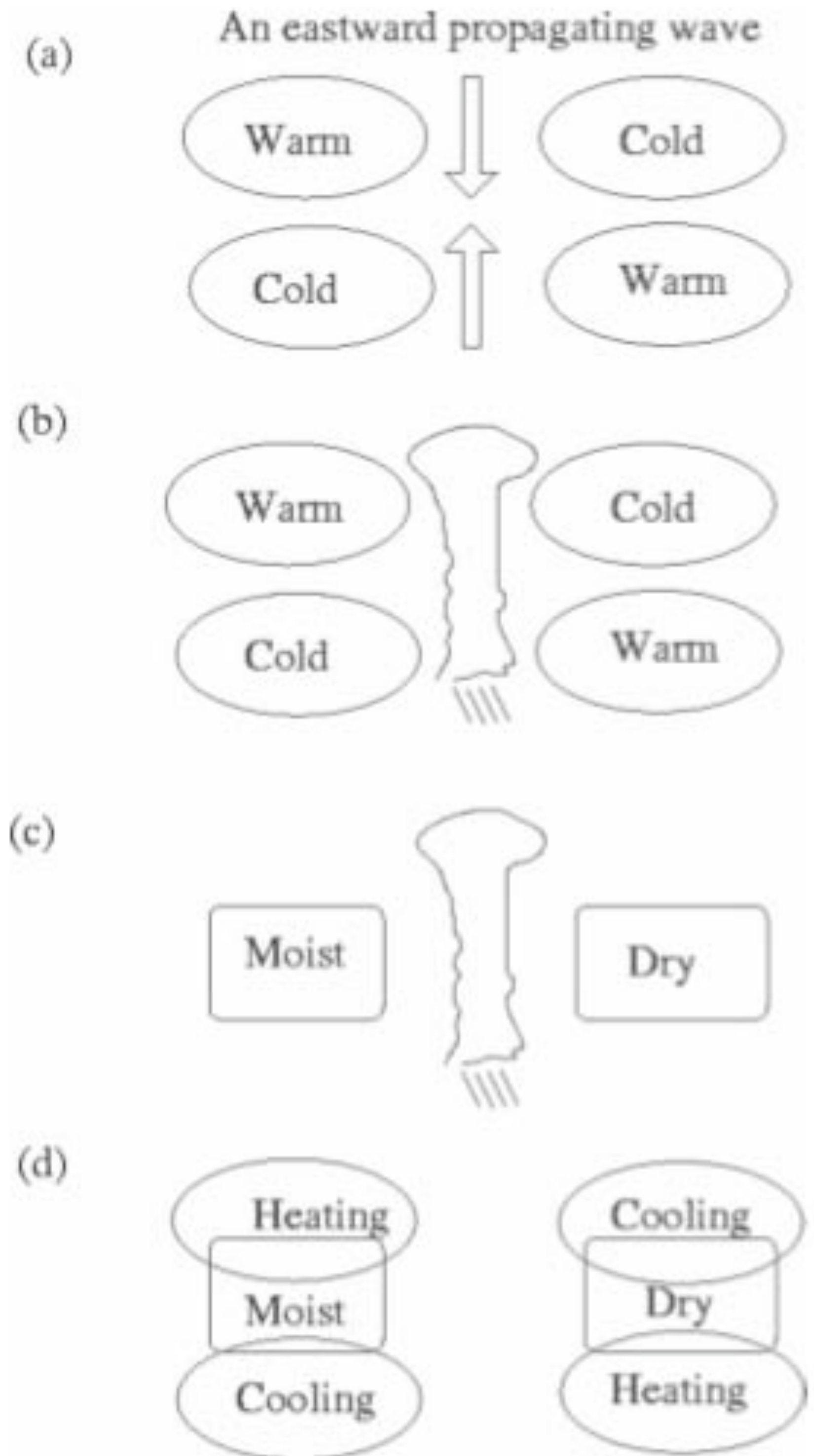


FIG. 11. A schematic of the moisture-stratiform instability, illustrated for an eastward-propagating wave viewed in a reference frame that follows the wave. All fields shown are anomalies. We start with (a) temperature and vertical velocity (arrows) anomalies associated with the wave. The large-scale lifting cools the lower troposphere as part of the wave signal. (b) This induces a positive deep convection anomaly, which cools the subcloud layer to maintain quasi equilibrium with the large-scale flow. (c) The deep convection anomaly also makes the midtroposphere more humid. (d) An anomalously moist midtroposphere allows convection to reach higher, while an anomalously dry one makes convection lower. This produces a convective heating anomaly pattern that is in phase with the original temperature anomaly and causes instability.

Idealized models of convectively coupled tropical waves

Convective quasi-equilibrium: idea that convective effects are in instantaneous near-equilibrium with some aspect of the large-scale forcing. Enables a closed set of equations for waves.

Kuang et al. 2008 one example (see also Khouder and Majda 2006,2007 etc., Fuchs and Raymond 2007 etc.) finding both the “Mapes” and “moisture” modes influencing predicted wave characteristics.

Kuang, 2008

A robust relationship between P and column water vapor

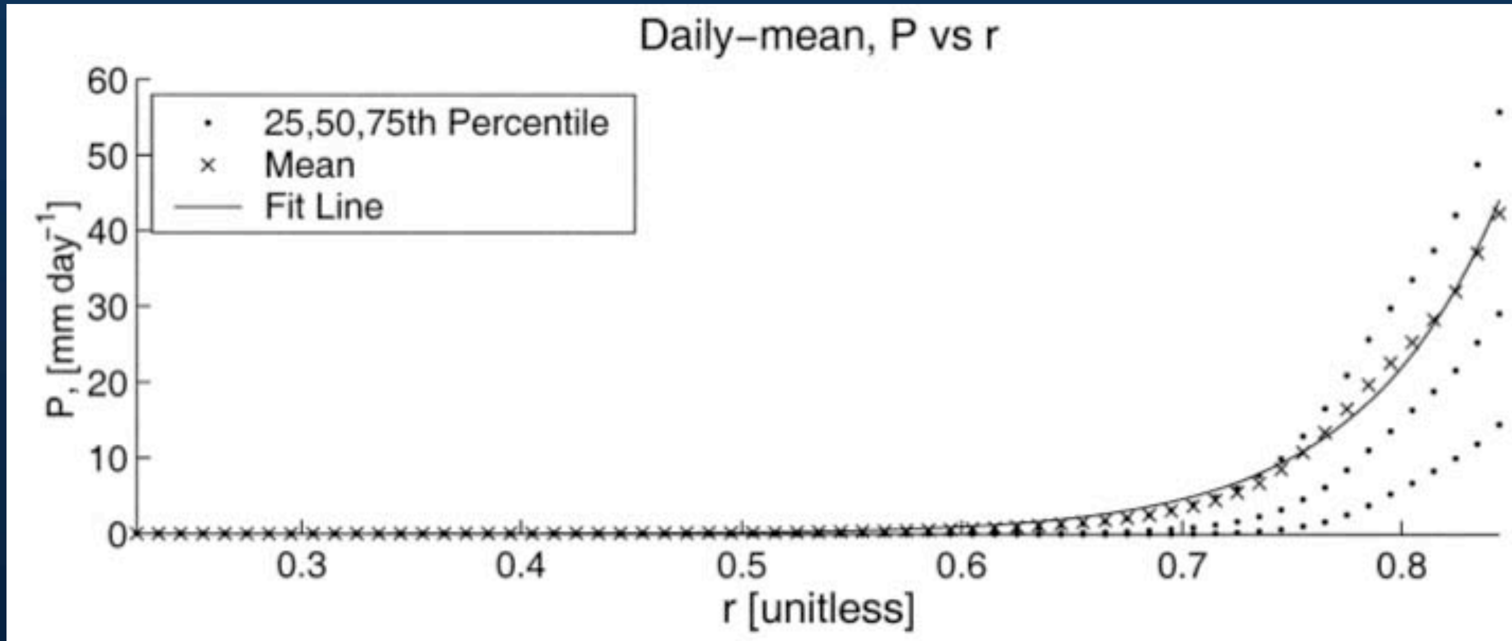
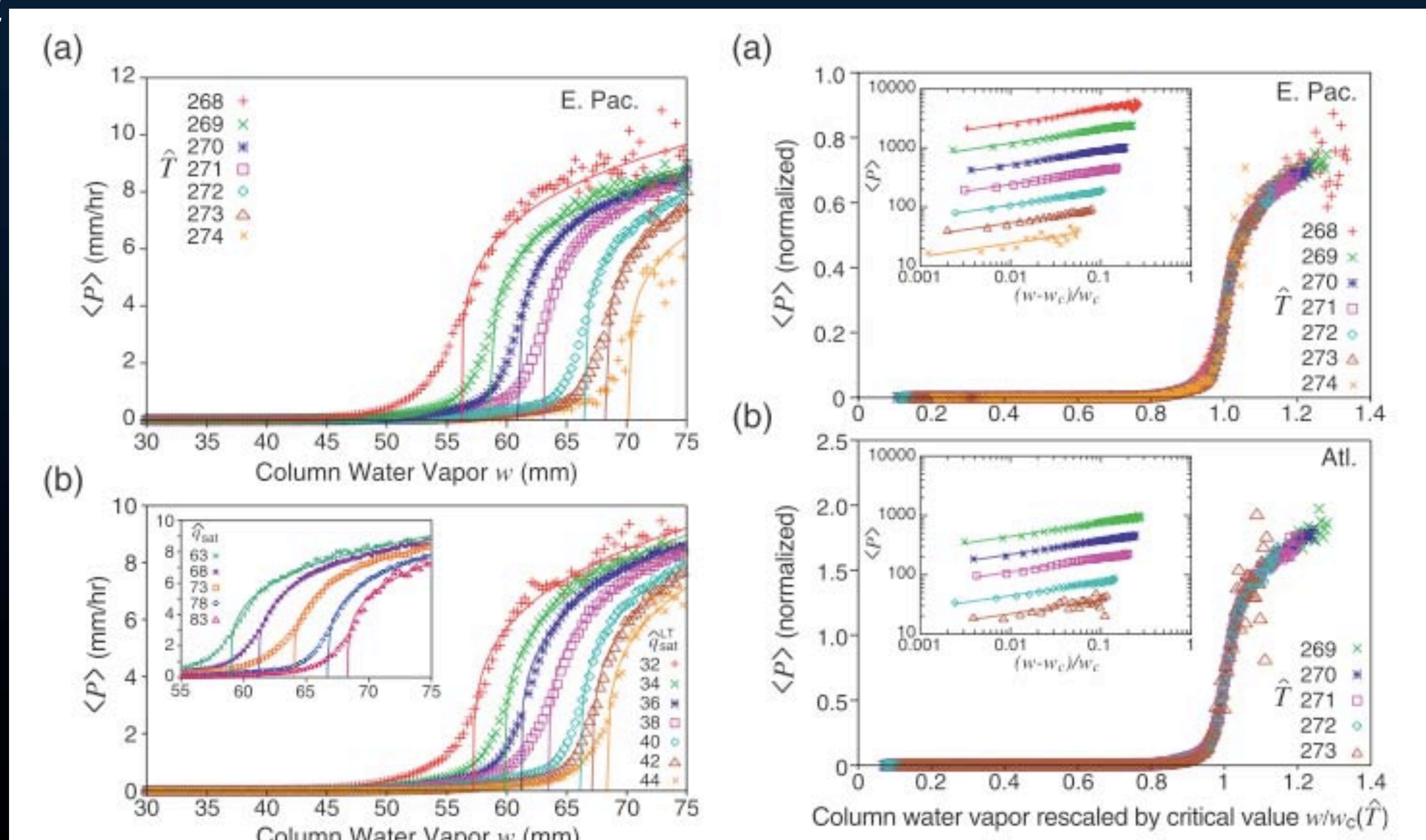


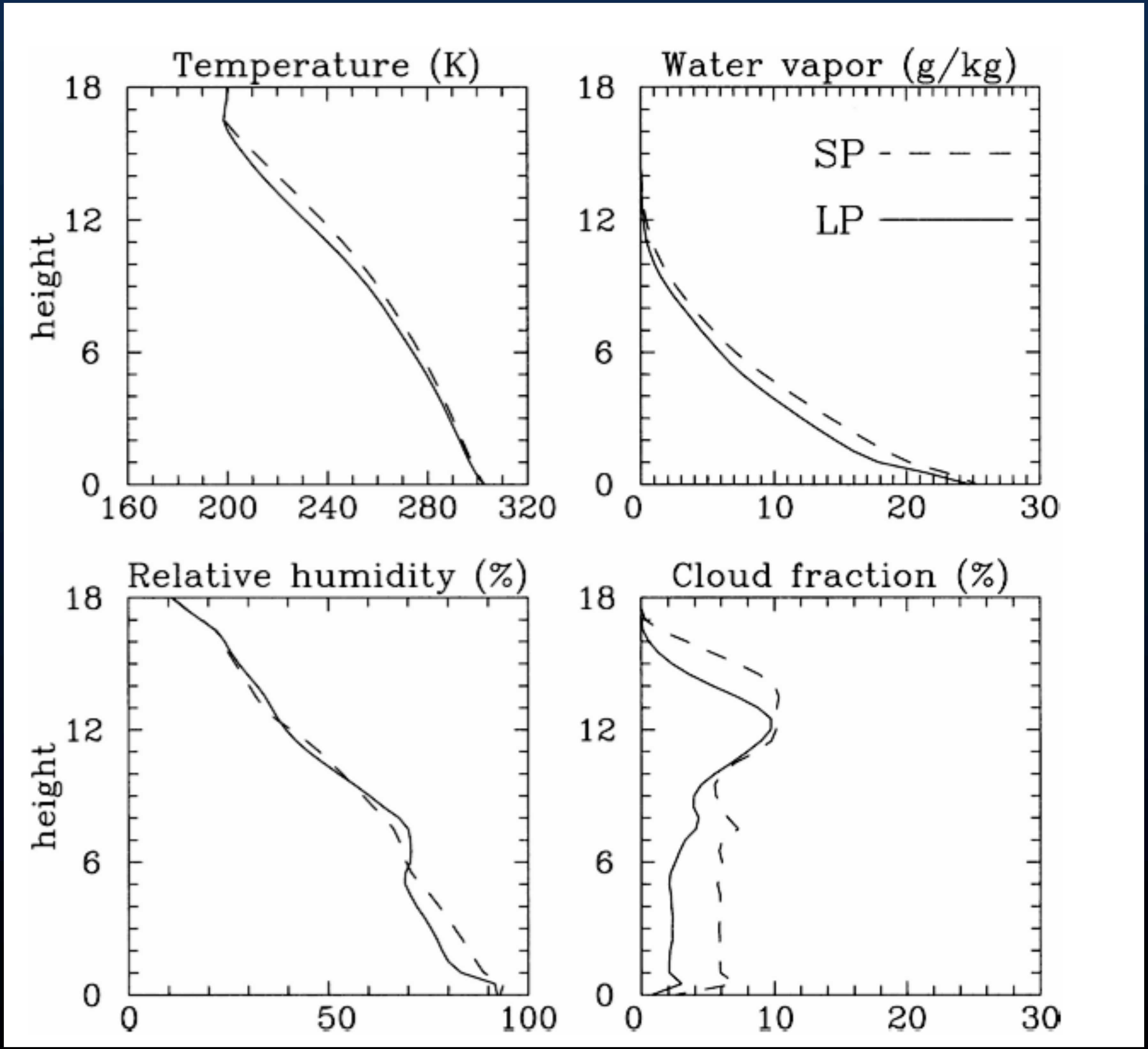
FIG. 4. Distribution of daily precipitation P in 1% bins of column-relative humidity r for all tropical ocean grid points in all months of 1998–2001. Dots show the 25th, 50th, and 75th percentiles of precipitation in each bin. The Xs show the bin-mean precipitation. The solid curve is the exponential fit (2).

Bretherton et al. 2004



Neelin et al 2009

Does all of this make it impossible for relative humidity in convective regions to change?



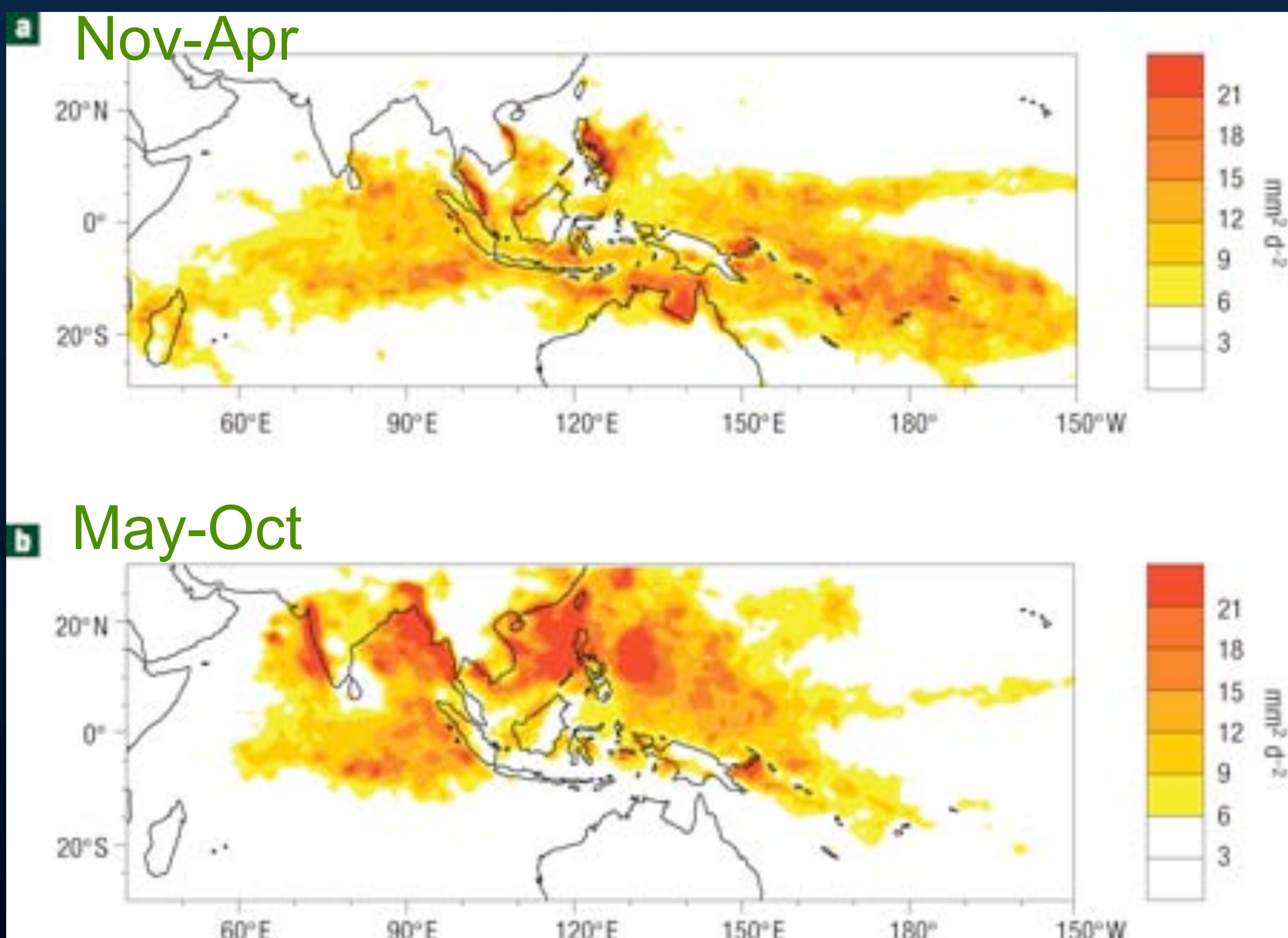
Two equilibrium cloud-resolving model simulations:

- SP small (slowly-falling) ice particles
- LP large (fast-falling) ice particles

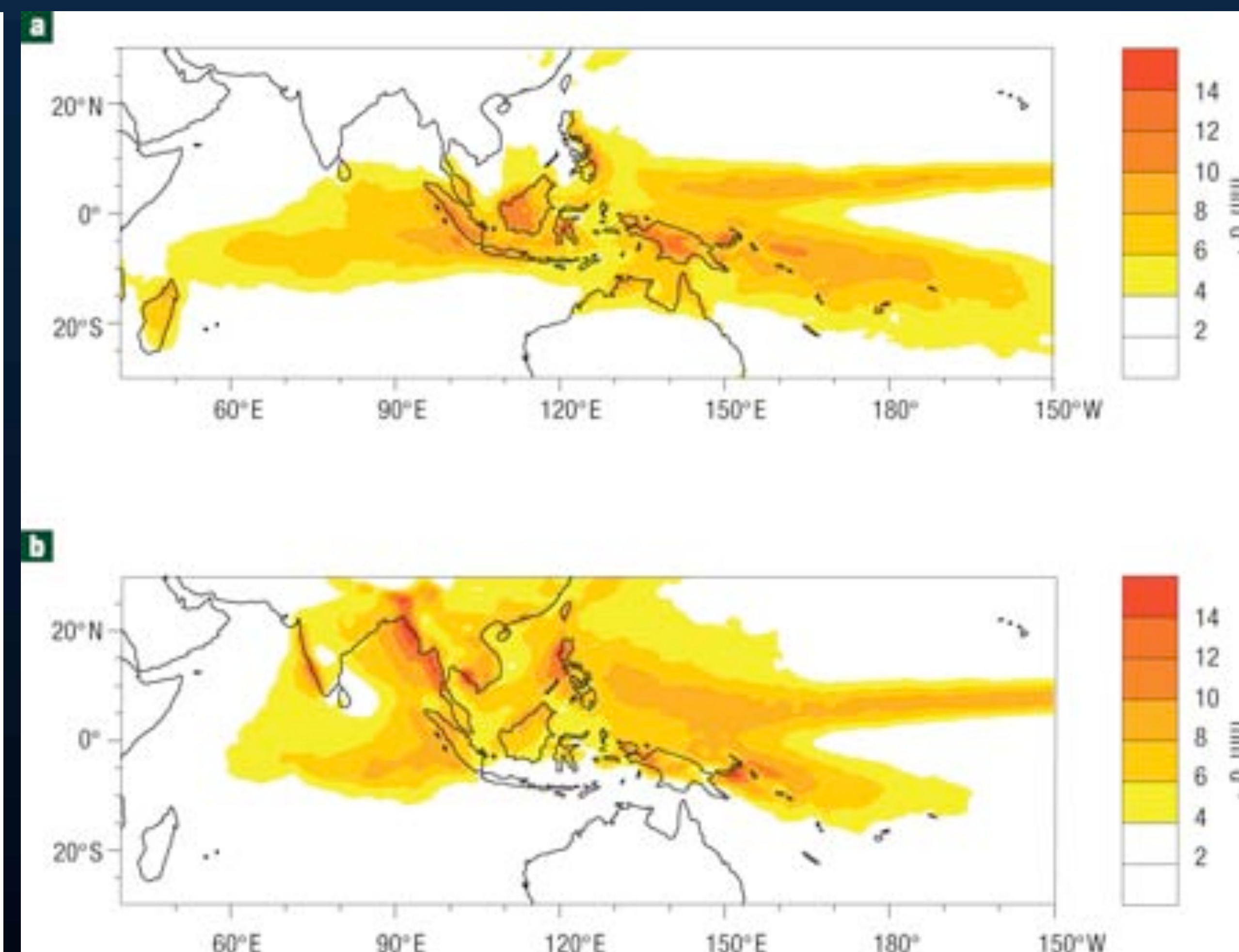
Grabowski 2003

Surface heat fluxes crucial drivers of precipitating convection

30-60 day filtered *P* variance



mean *P*

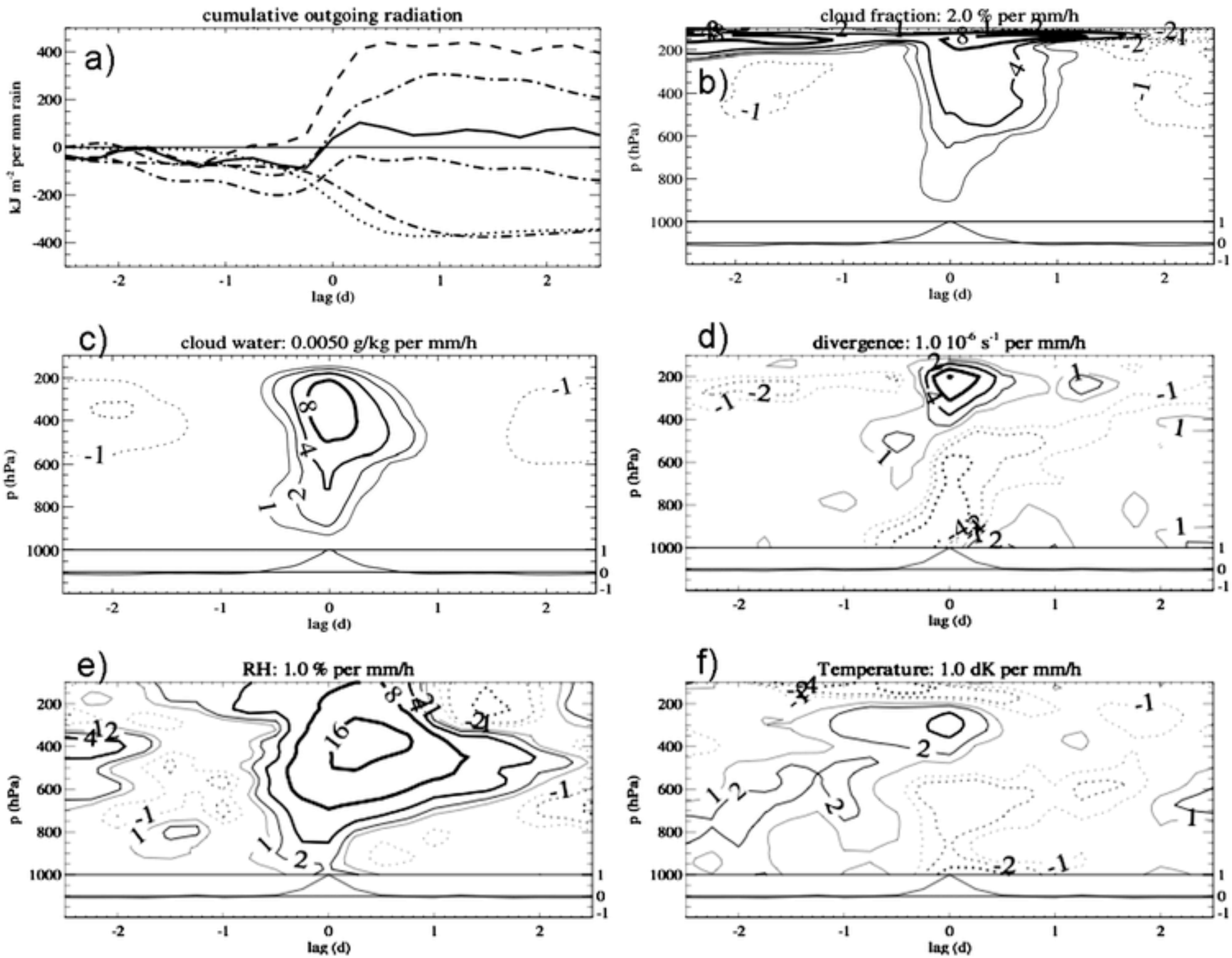


Sobel et al. 2008

Three random examples of process-based GCM tests

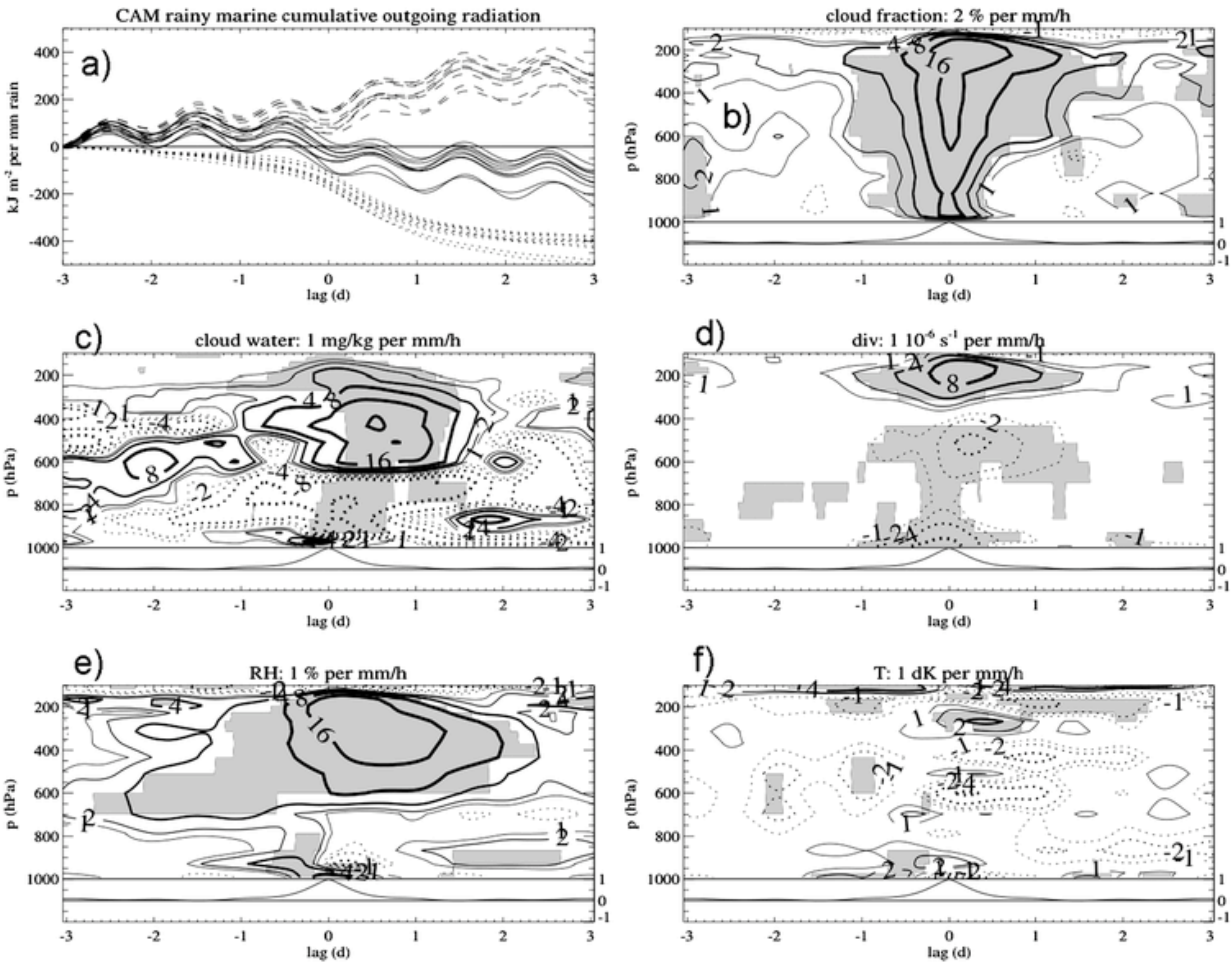
- “Virtual field campaigns” where composite storm events are compared in models and real field campaigns (Mapes et al 2009)
- Joint distributions of mean-state variables (Bennhold and Sherwood 2008)
- Systematic trends in observed vs. model cloud properties under reproducible conditions (Zhang et al. 2008)

Observations of six quantities from KWAJEX

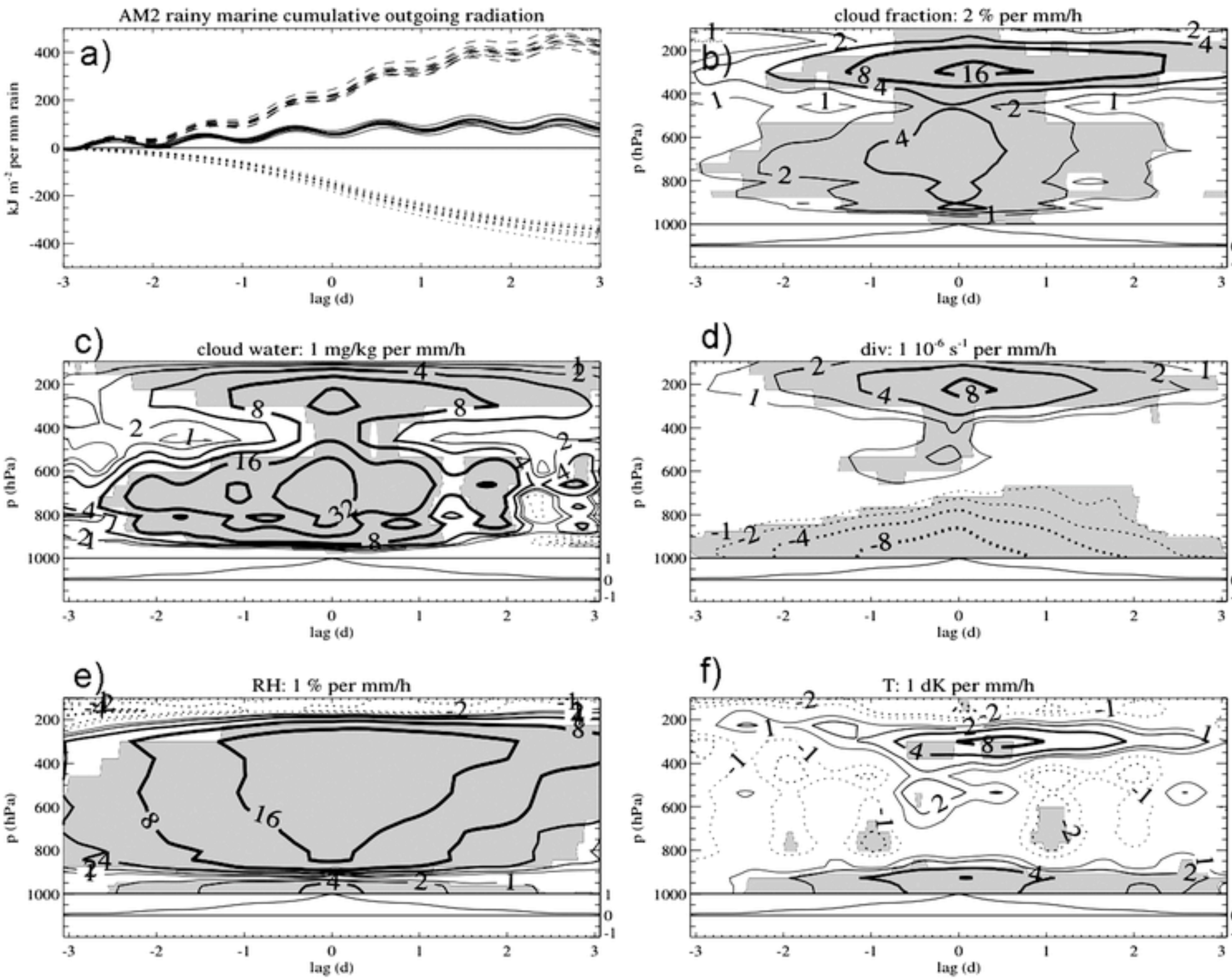


Mapes et al. 2009

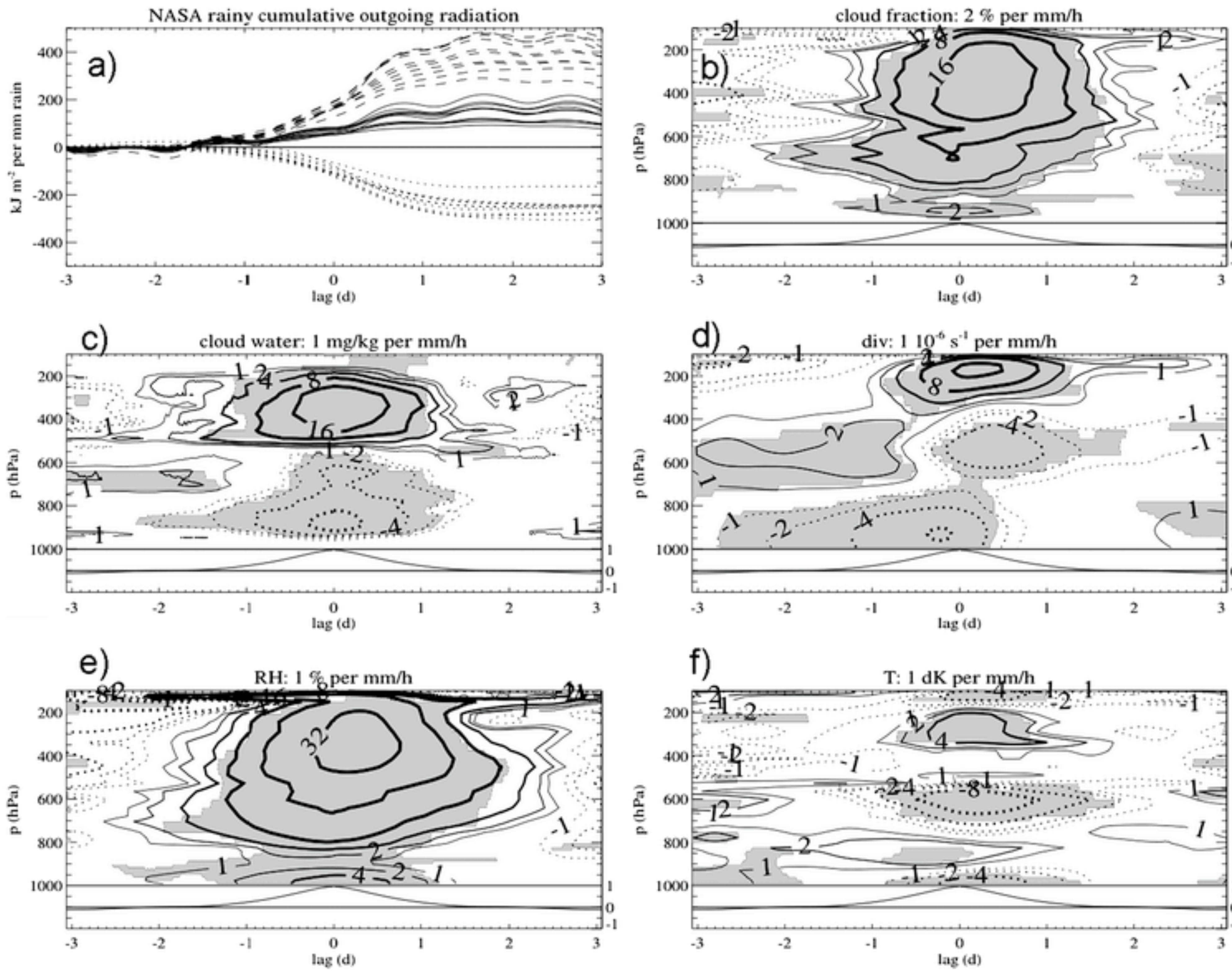
Simulation from CAM3 (NCAR)



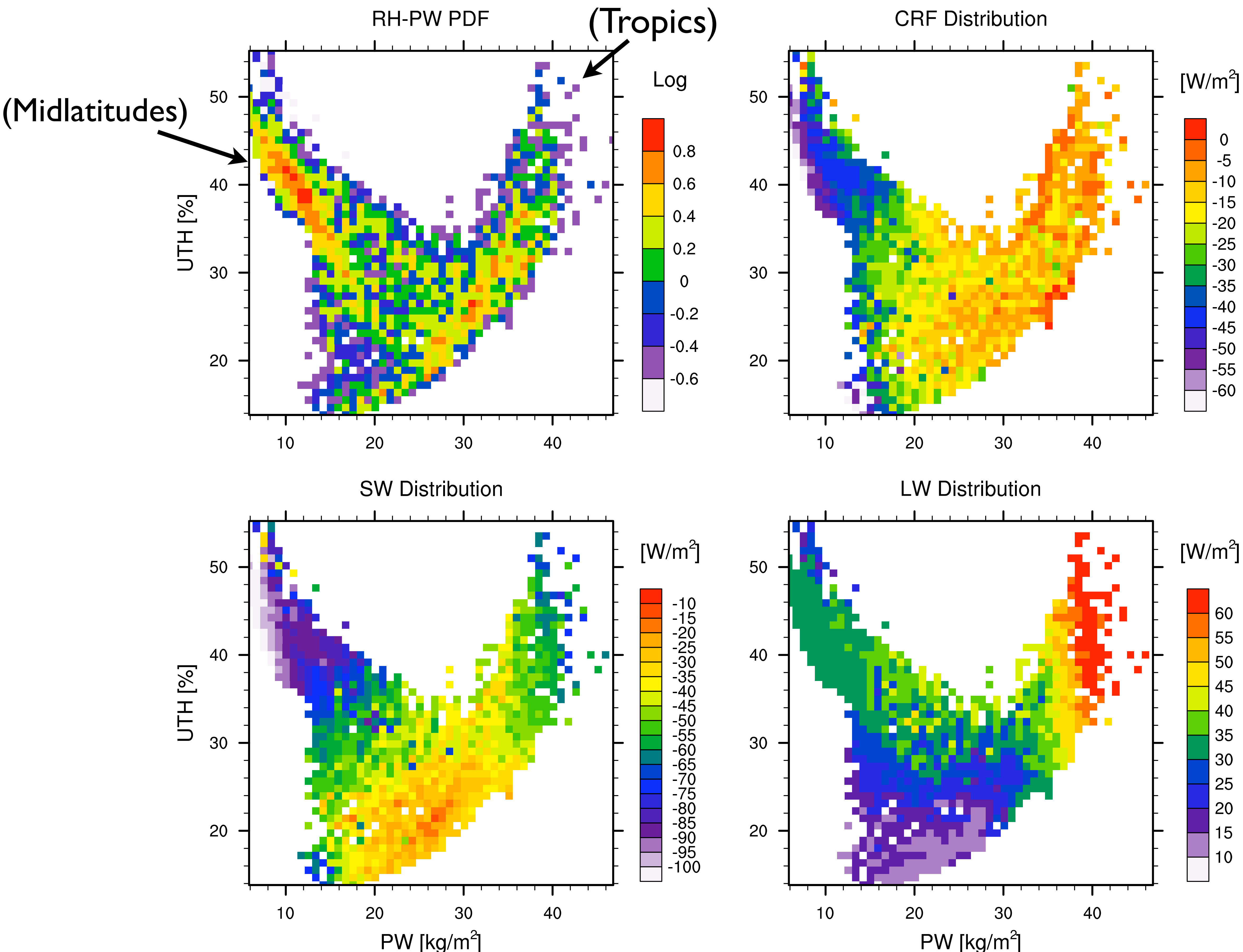
Simulations from AM2 (GFDL)



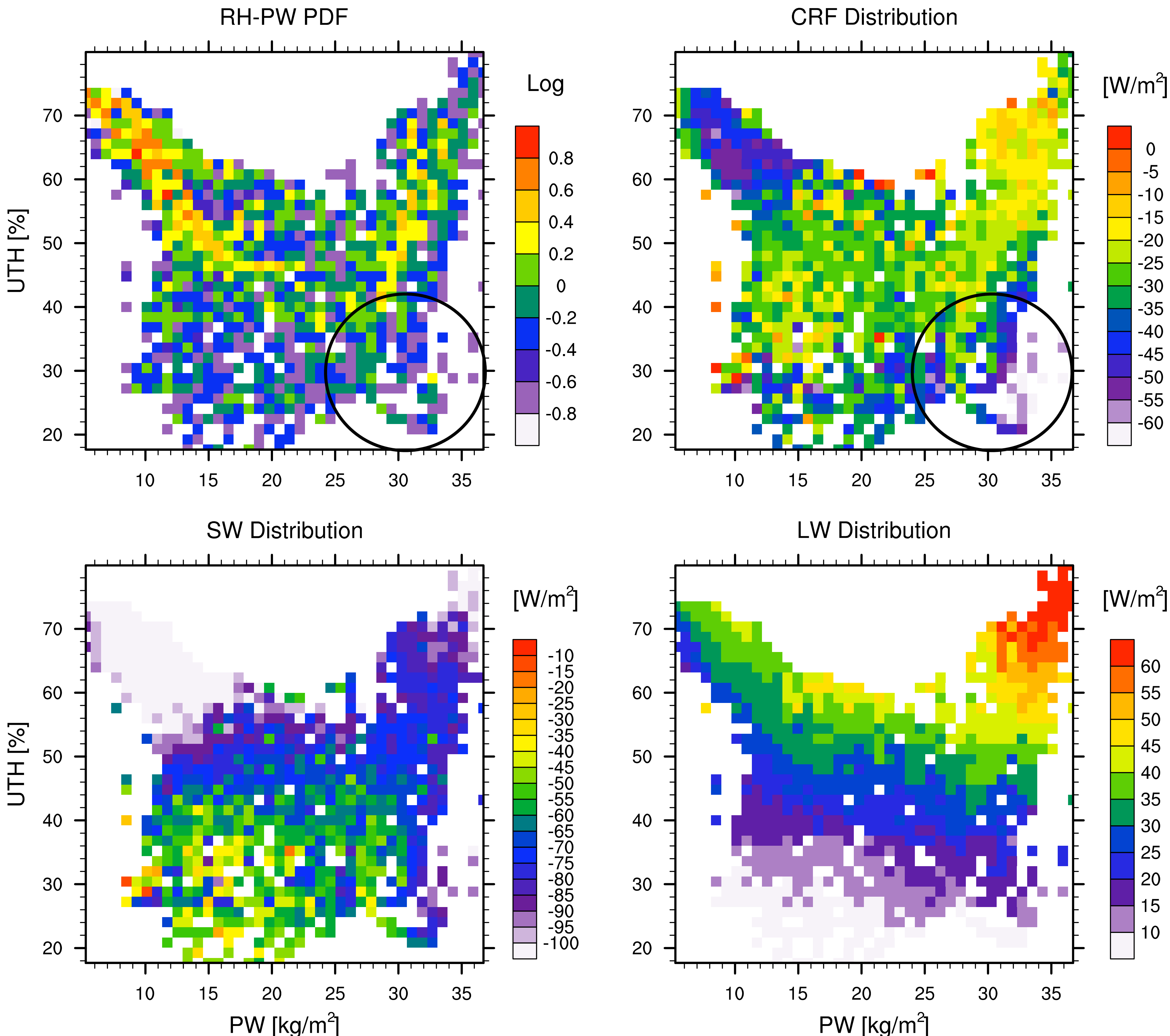
Simulation by NSIPP2 (new NASA model)



Observed RH/PW CRF regression

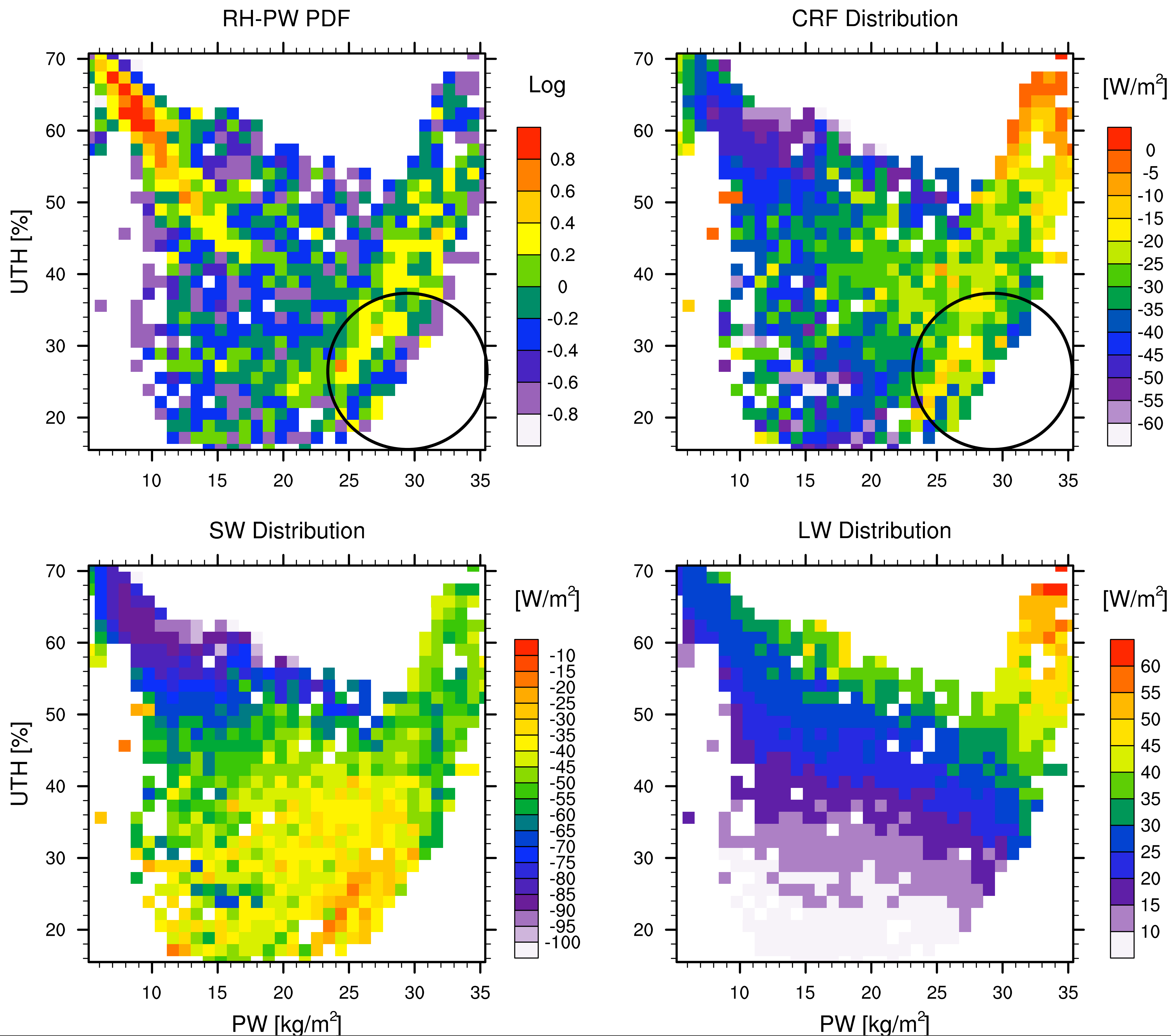


CCSM3 Model

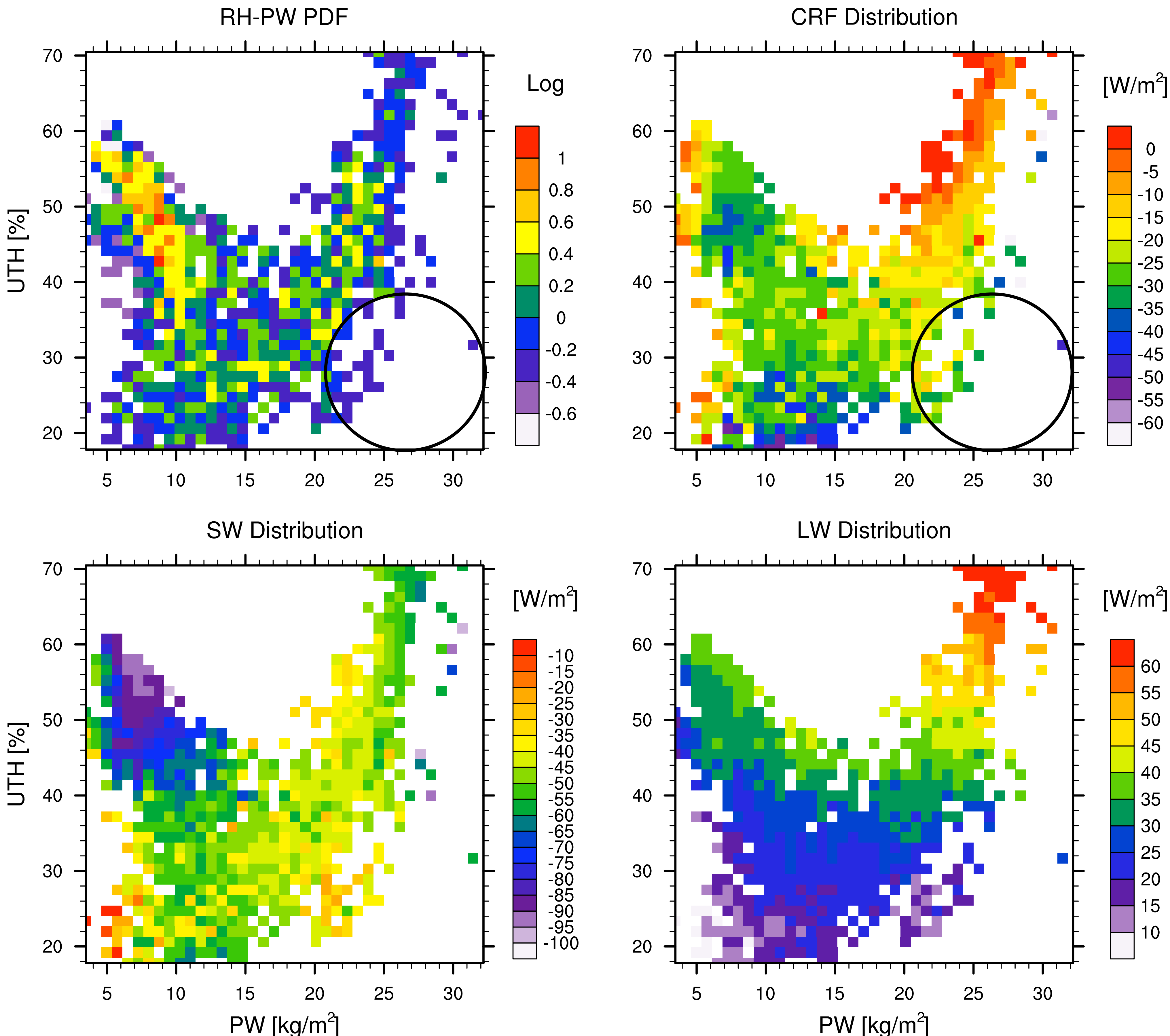


RH-PW PDF
Log
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
CRF Distribution
[W/m^2]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
SW Distribution
[W/m^2]
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
-95
-100
LW Distribution
[W/m^2]
60
55
50
45
40
35
30
25
20
15
10
UTH [%]
20
30
40
50
60
70
10
15
20
25
30
35
PW [kg/m^2]

HadCM3 Model



CCMA3 Model



RH-PW PDF
CRF Distribution
SW Distribution
LW Distribution
UTH [%]
PW [kg/m^2]
Log
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
[W/m^2]
0
-5
-10
-15
-20
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-40
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-15
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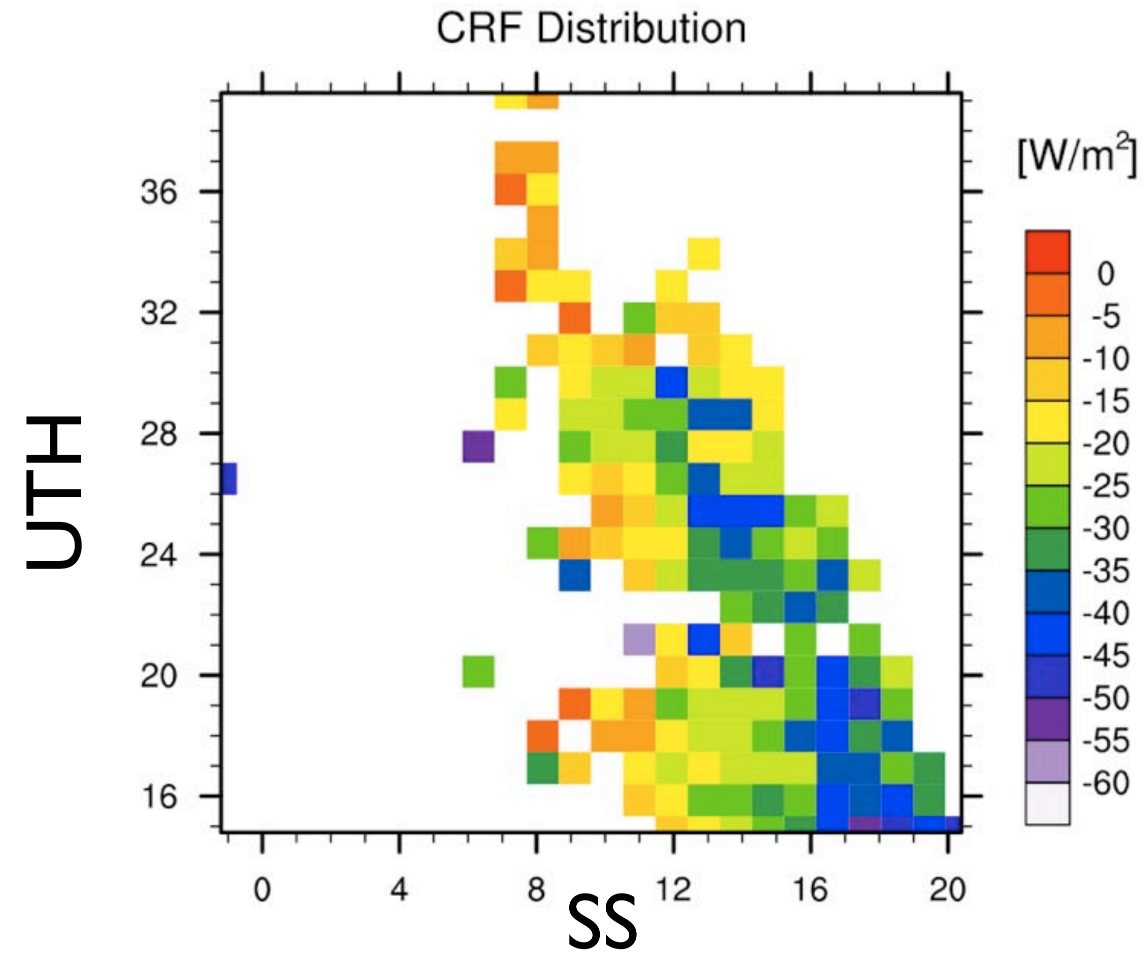
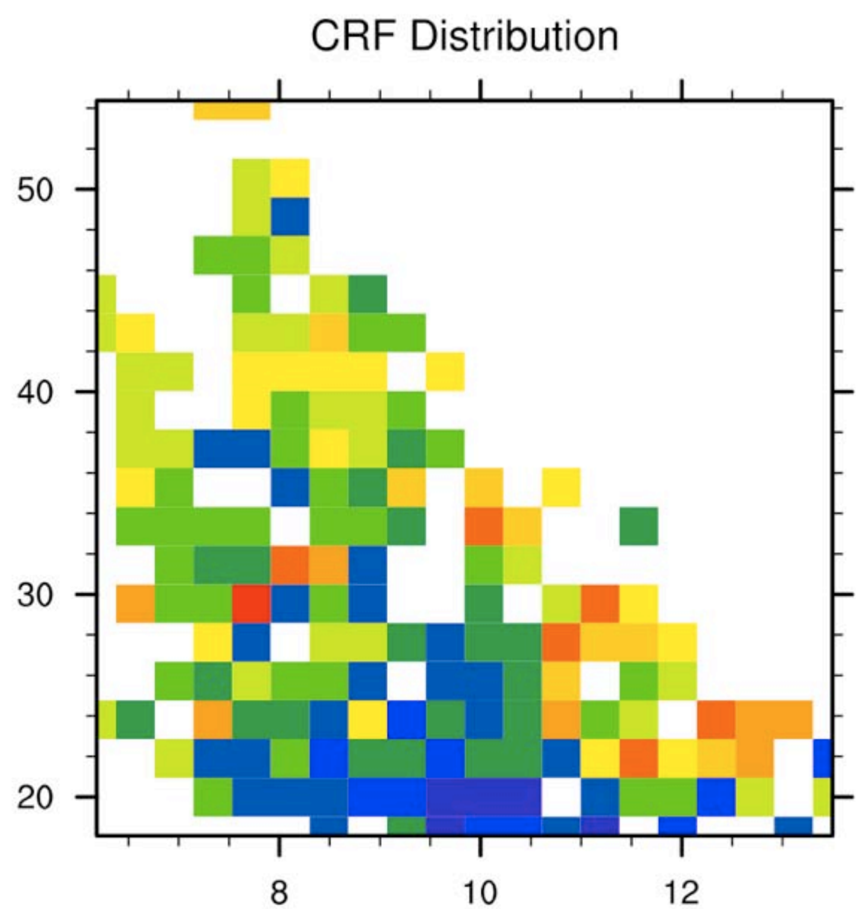
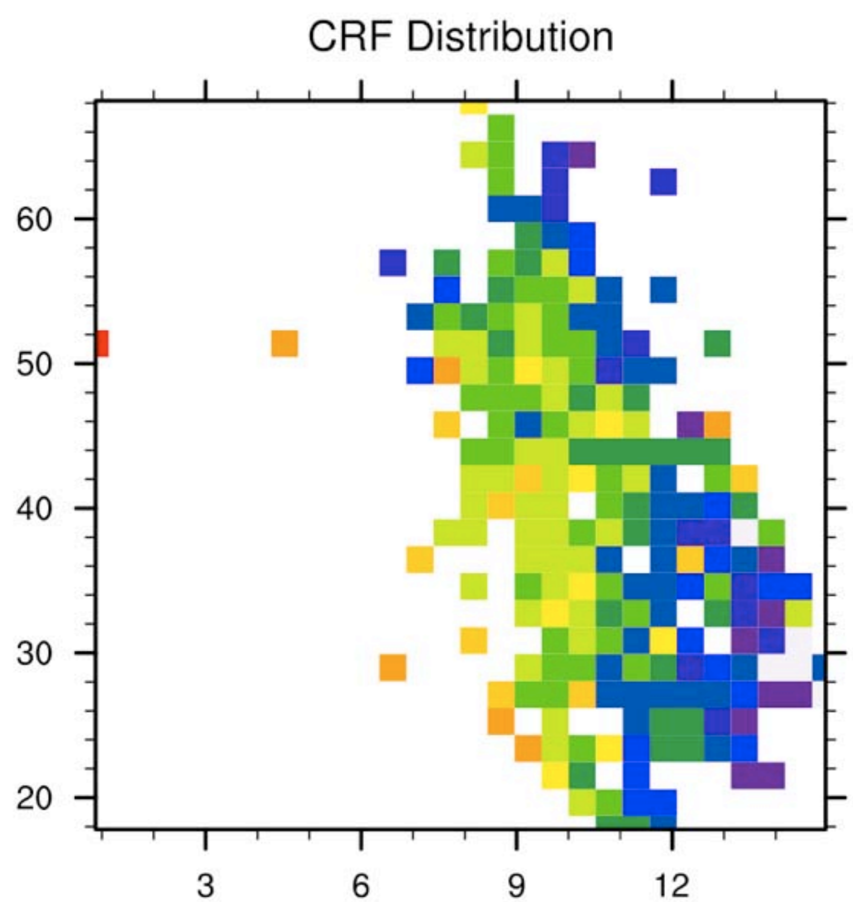
10

Marine Stratocumulus regions

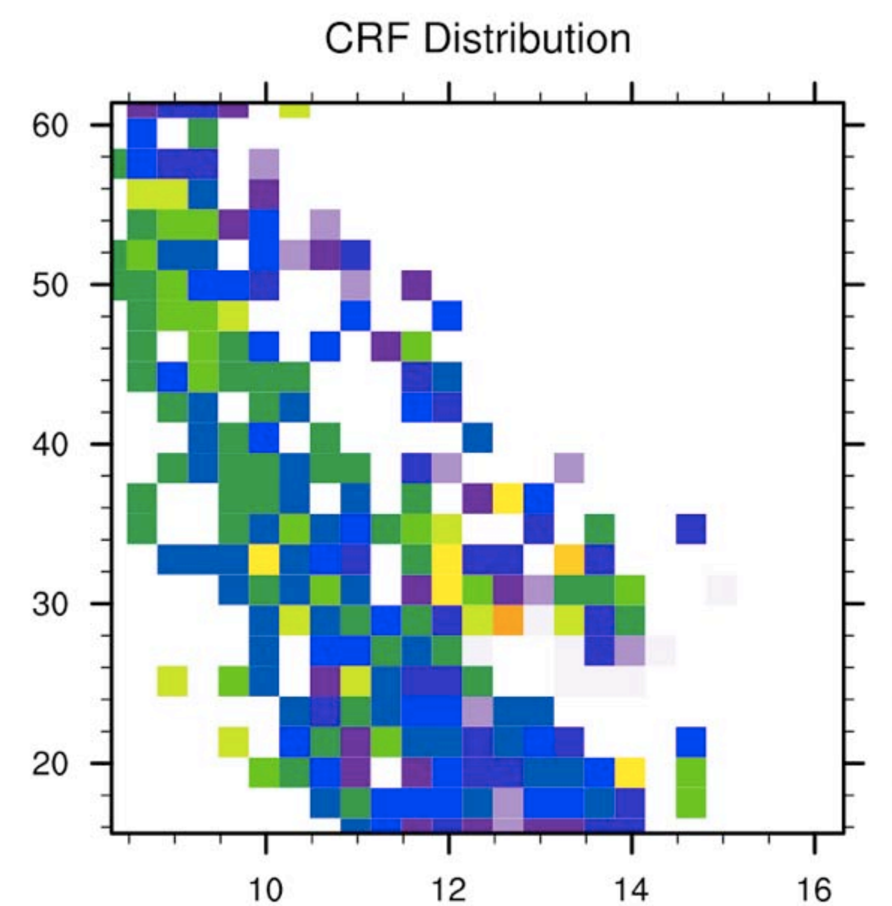




CCMA

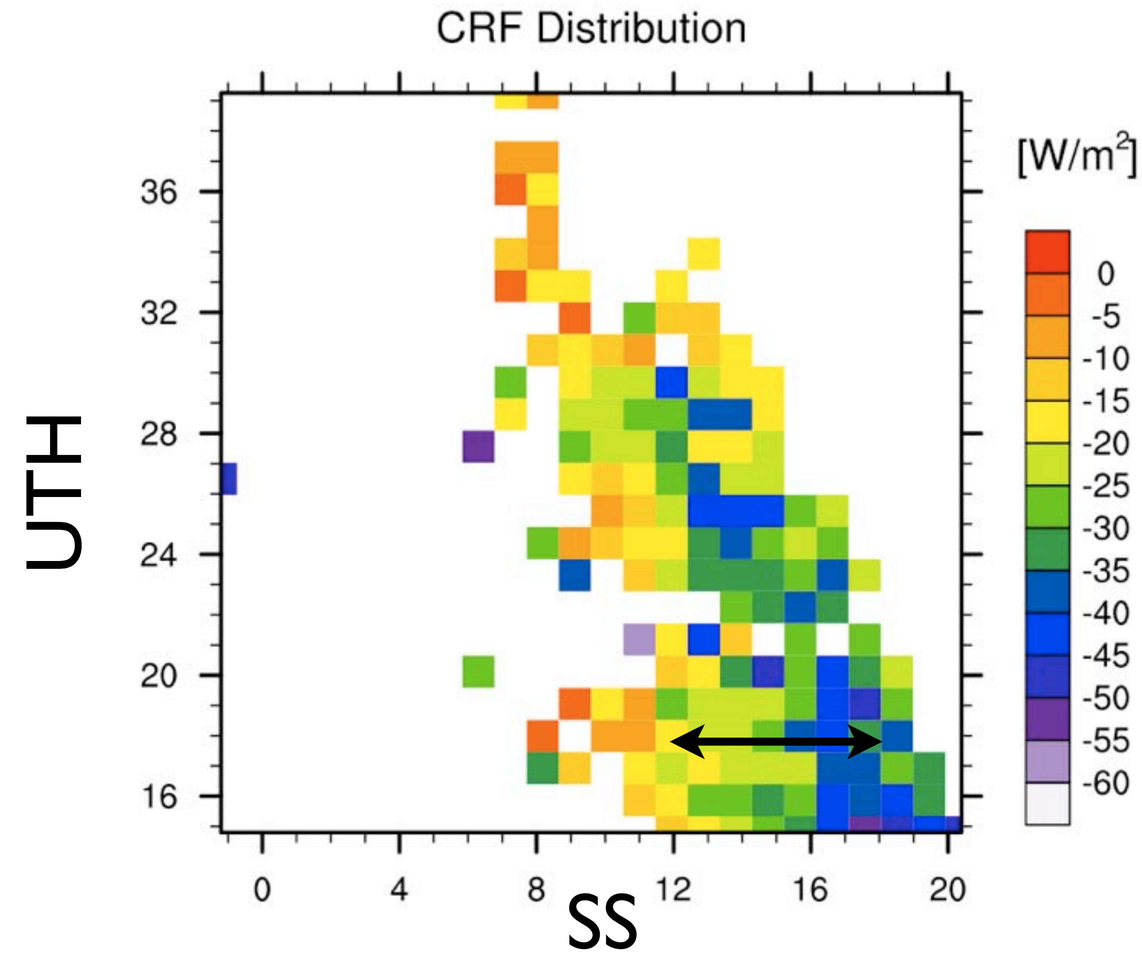


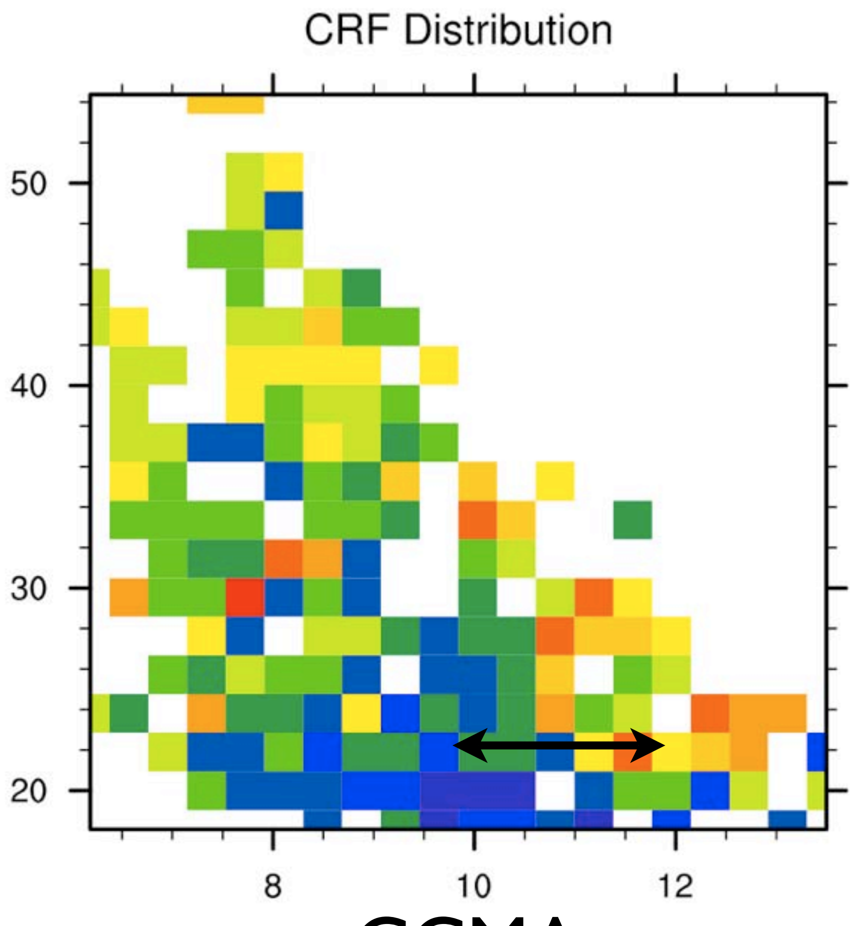
CCM3



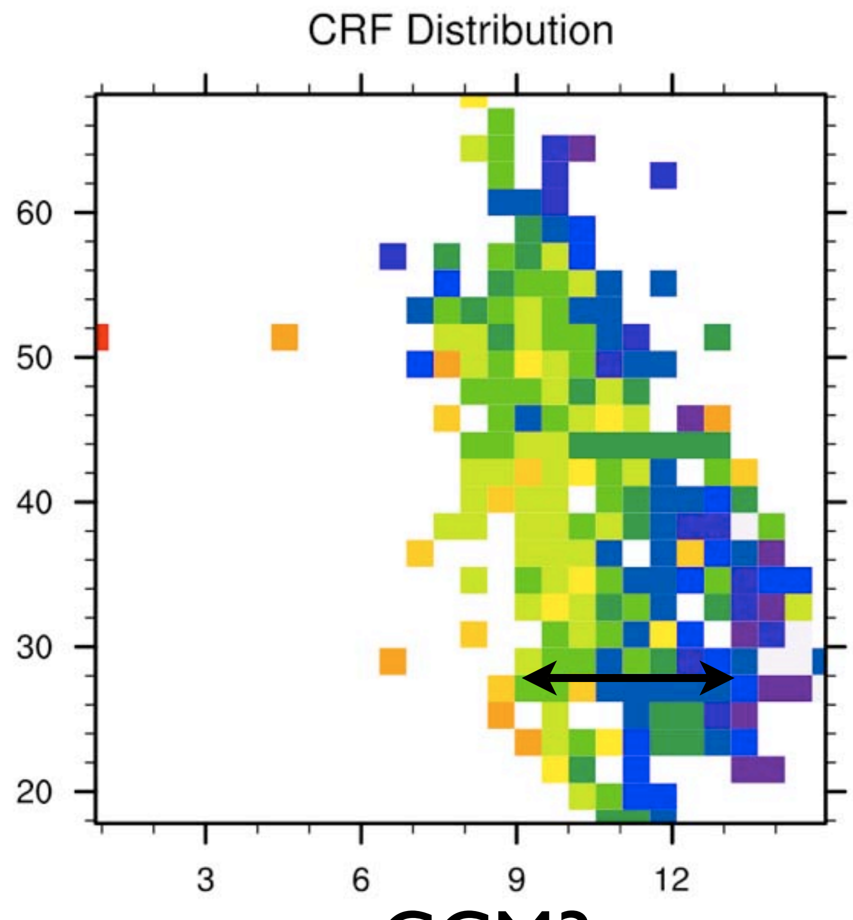
HadCM3

Marine Stratocumulus regions

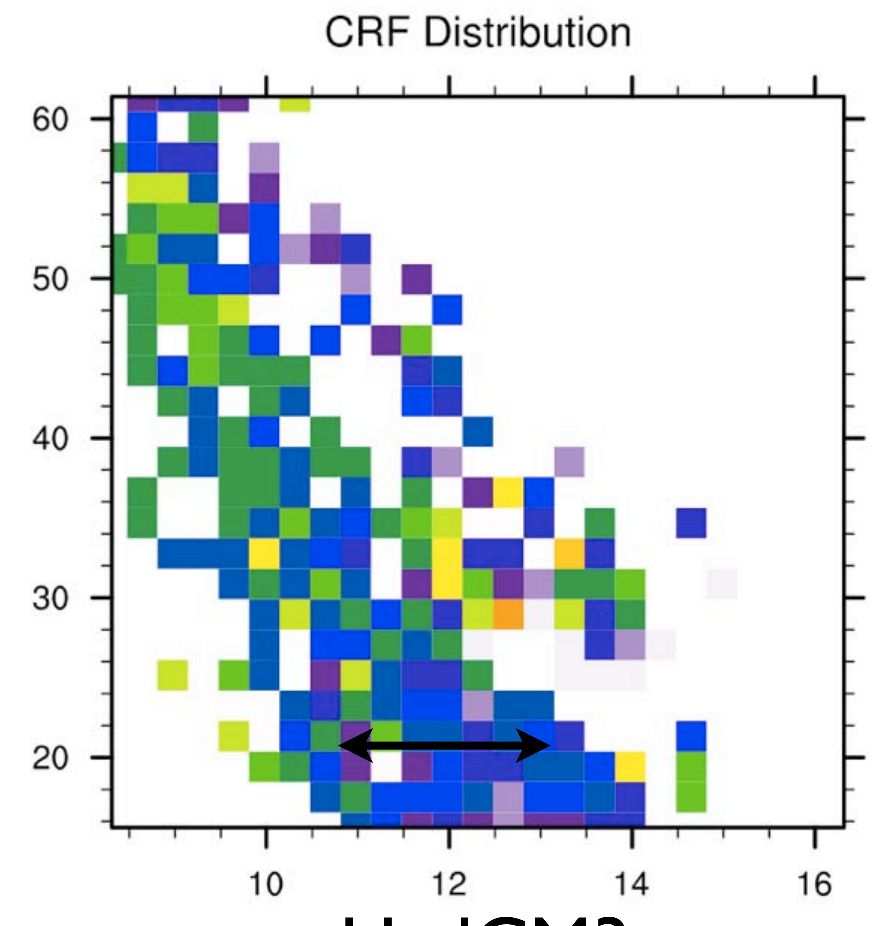




CCMA

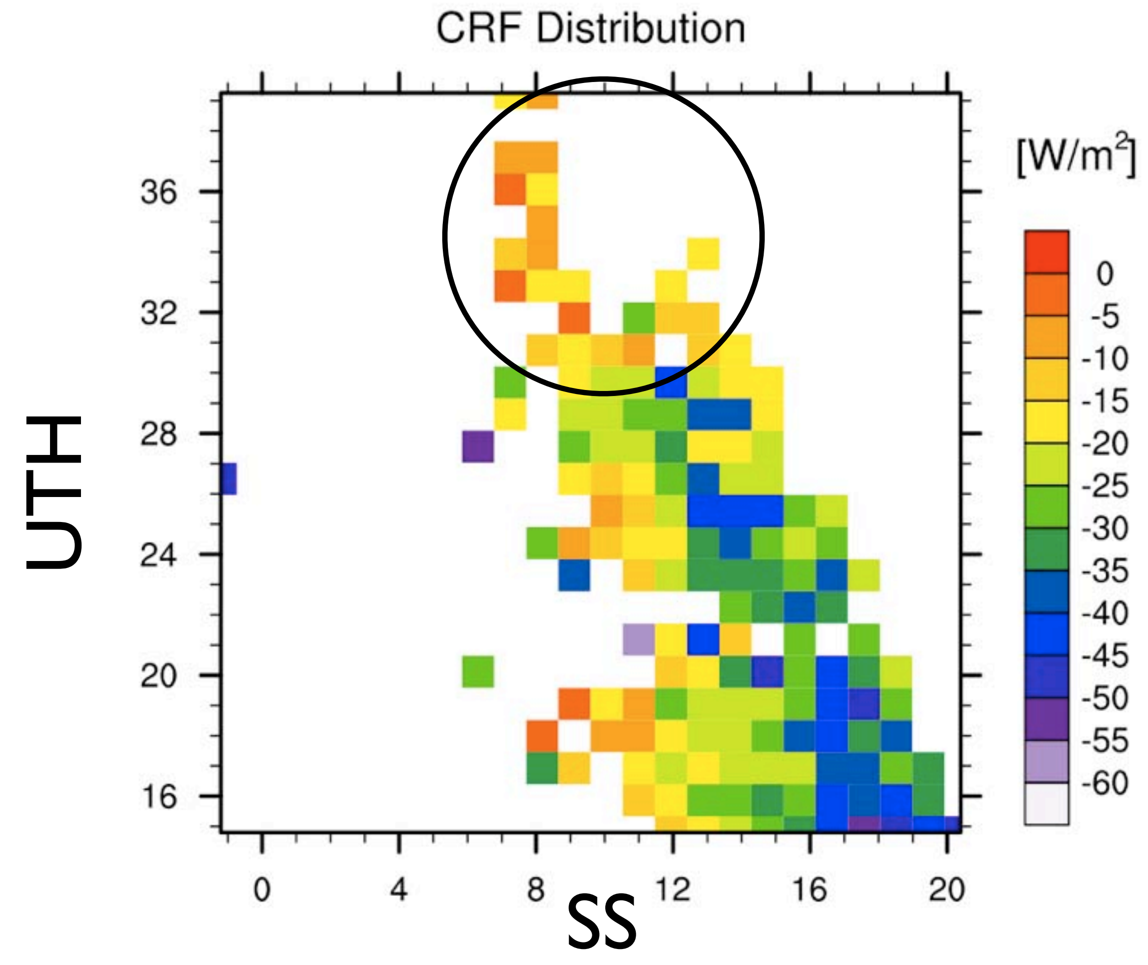


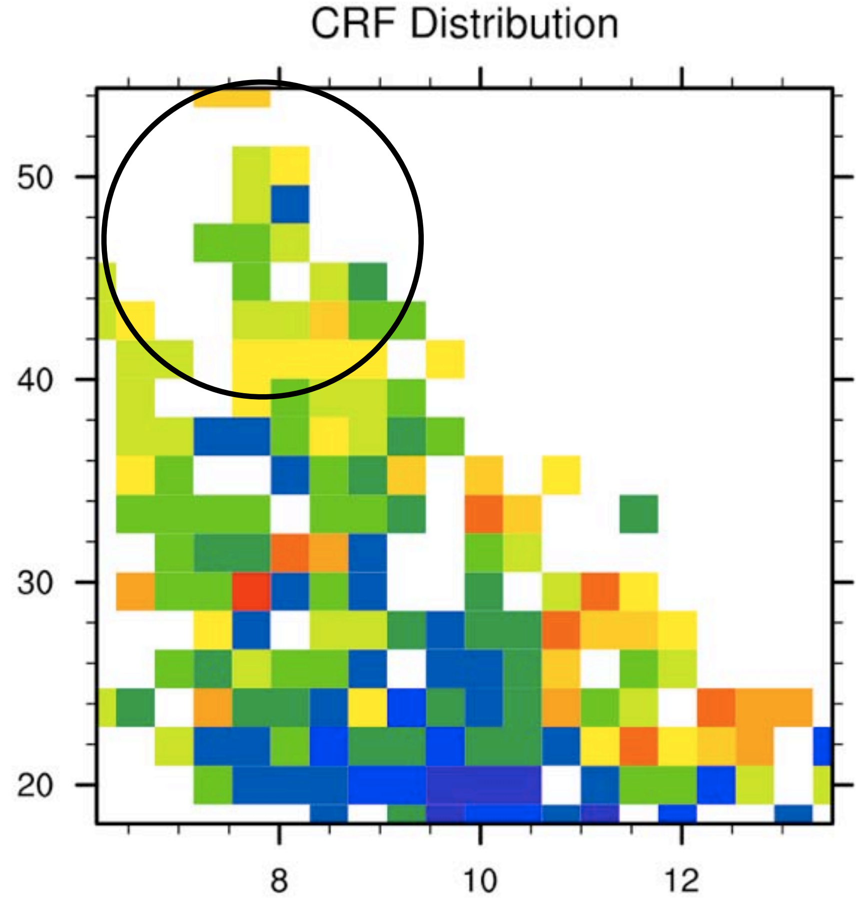
CCM3



HadCM3

Marine Stratocumulus regions





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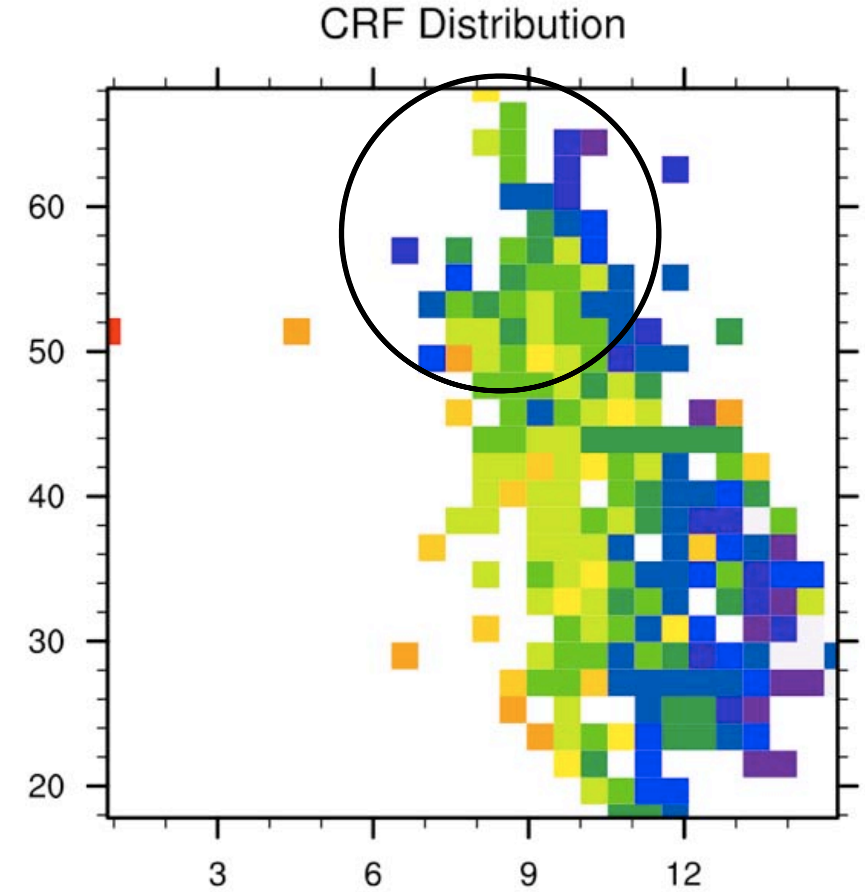

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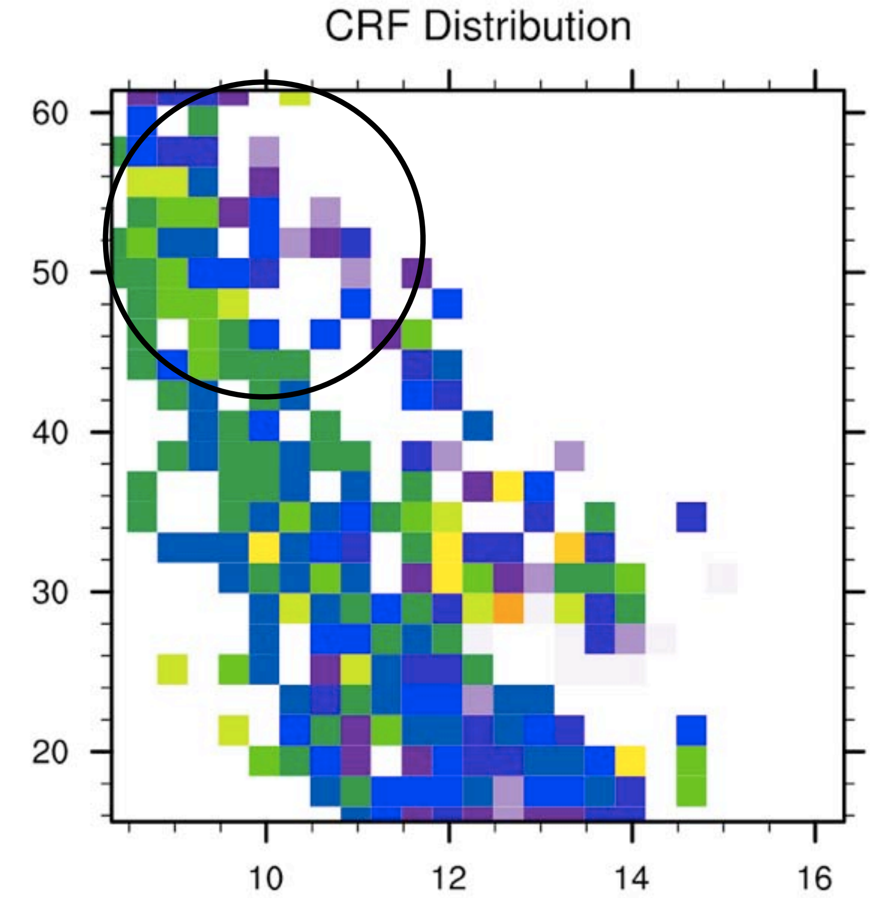
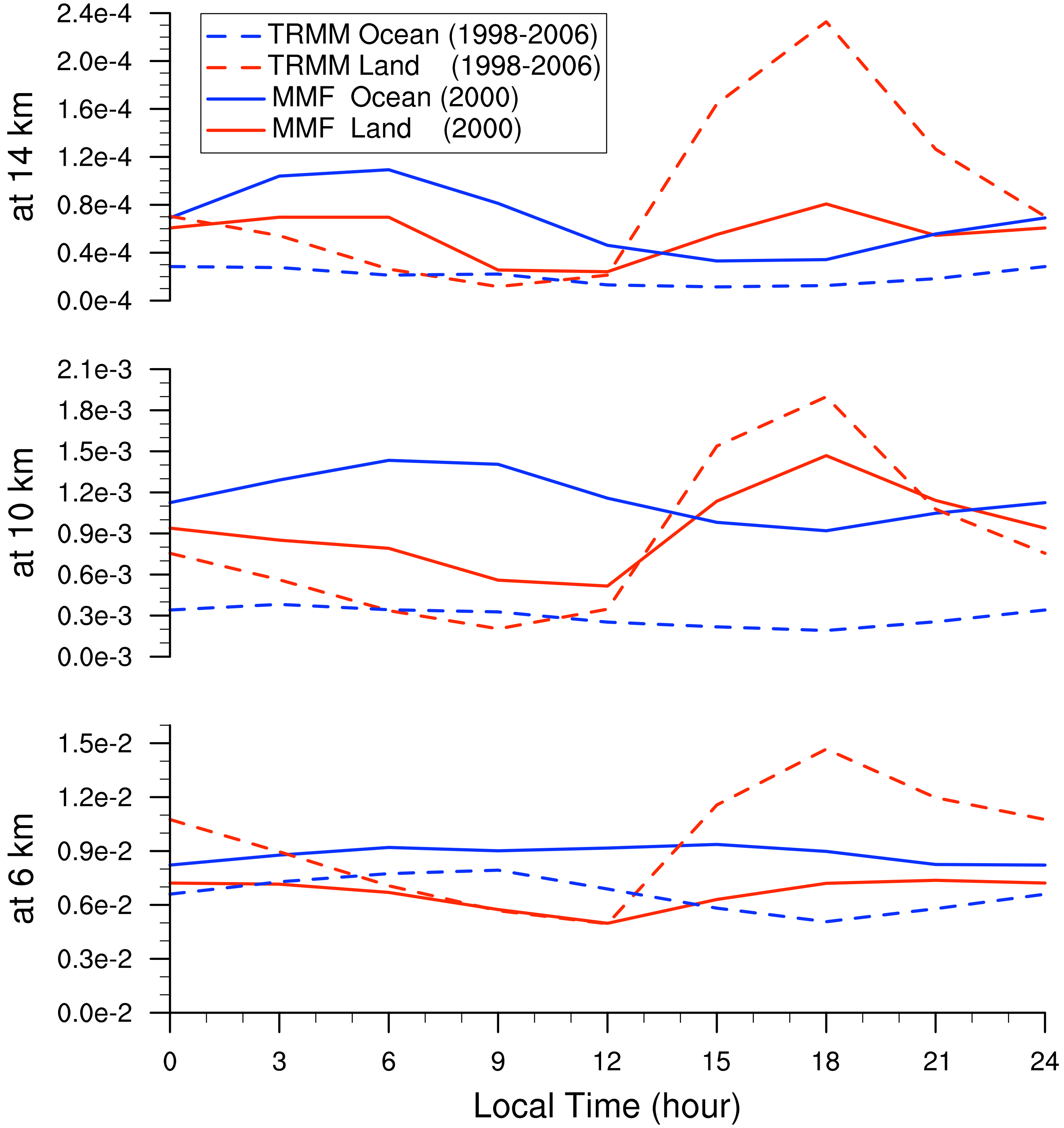


HadCM3

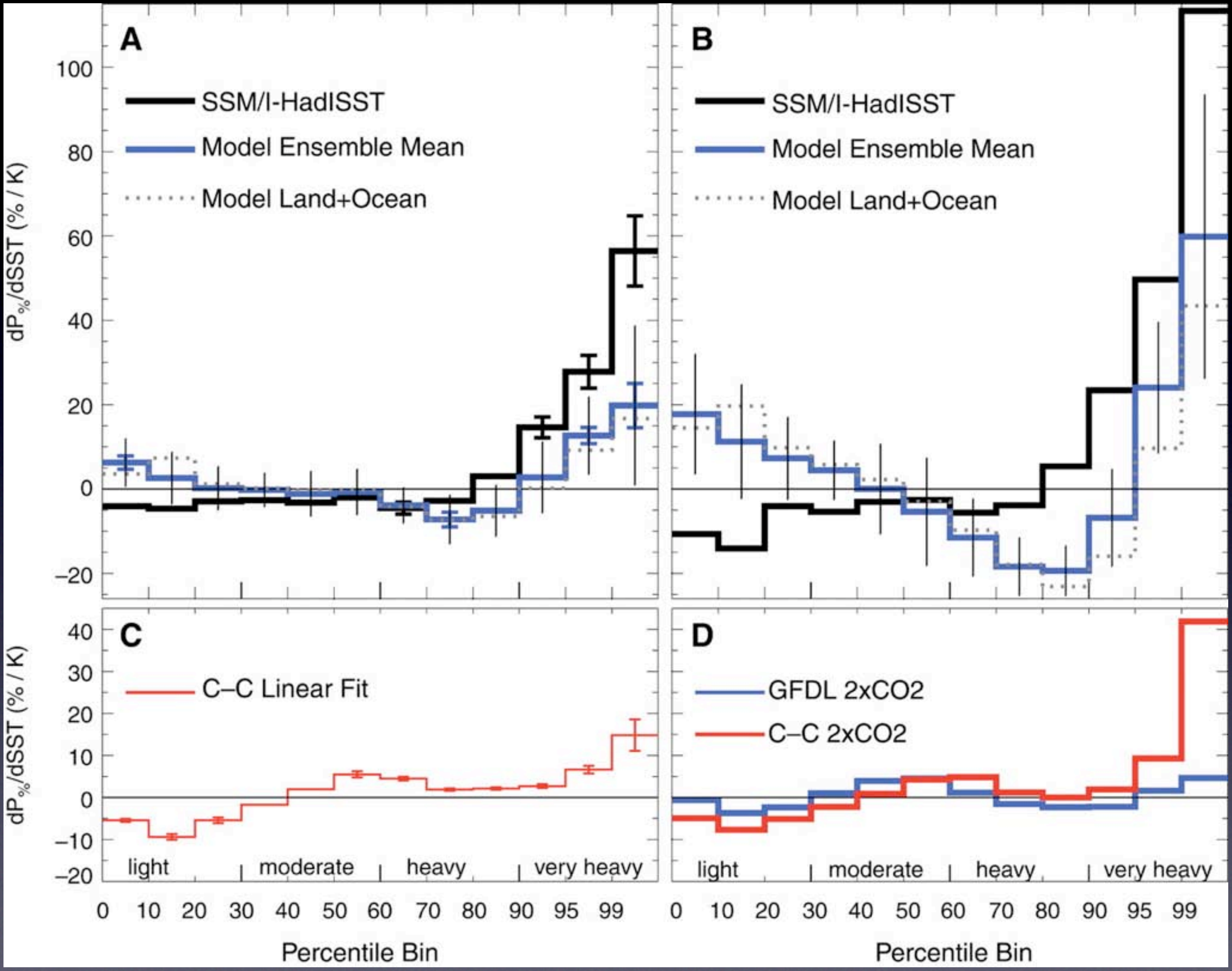
Diurnal cycle comparison between TRMM radar observations and those simulated from the MMF GCM



MMF = "Multiscale modeling framework" or superparameterisation, where a cloud-resolving model runs as the convection / cloud schemes.

Diurnal cycle is not significantly improved over base model (not shown).

Superparameterisation not a silver bullet (so far) and is very expensive.



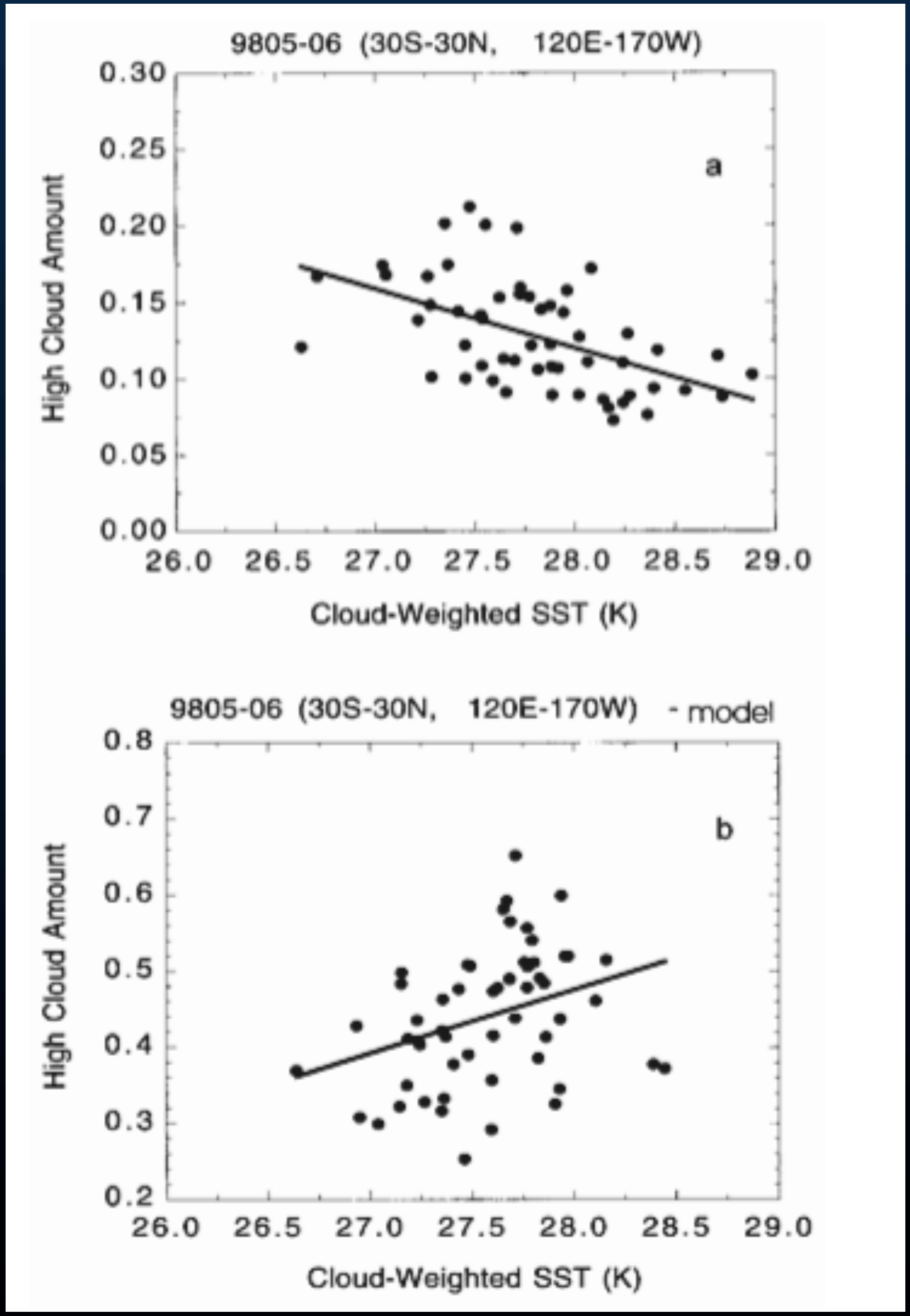
Allan and Soden 2008

Another observational challenge to models?

Atmosphere + ocean model (NCAR PCM)

Observed

Atmosphere model



Lindzen et al., 2001

Intriguing argument:

Precipitation efficiency will increase in a warmer climate due to larger drops. This will dry the troposphere and negate the water-vapor feedback.

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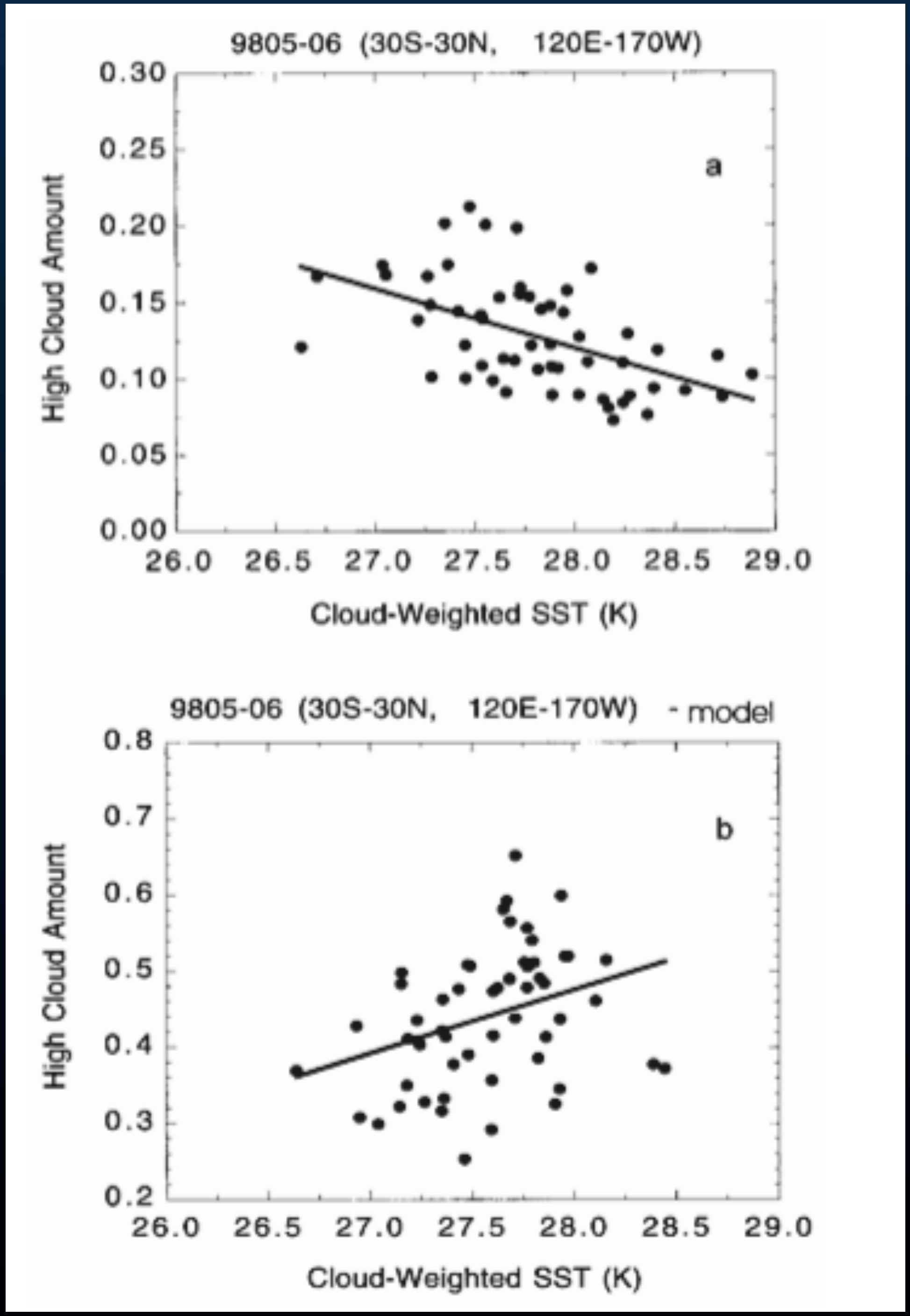

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Intriguing argument:

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Results from CRM simulations:

- The efficiency *decreases* in warmer atmosphere due to higher melting level, nonlinearity of Clausius-Clapeyron equation (Kirshbaum and Smith 2008)
- Depends mainly on rain rate (Sui et al 2007)

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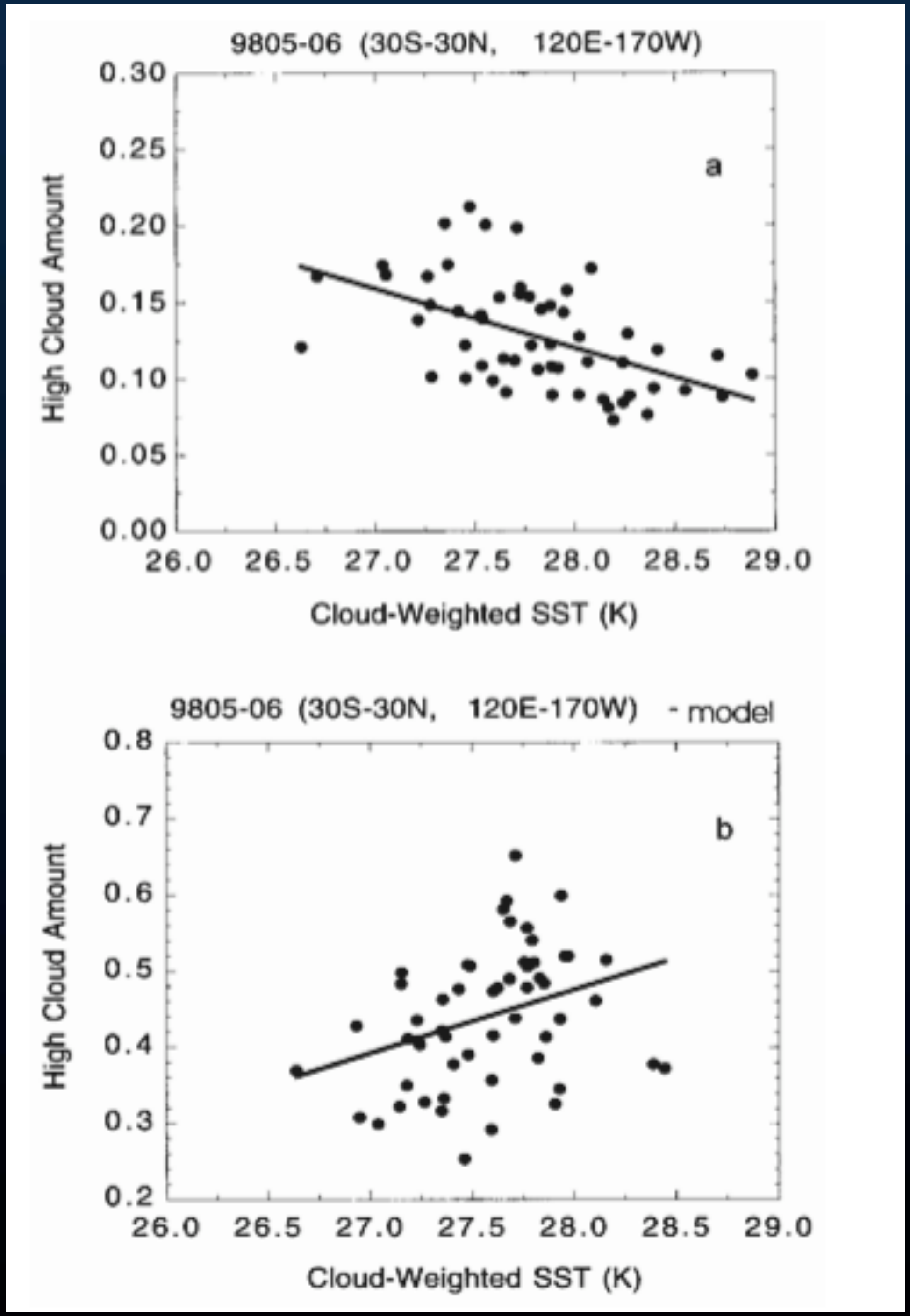
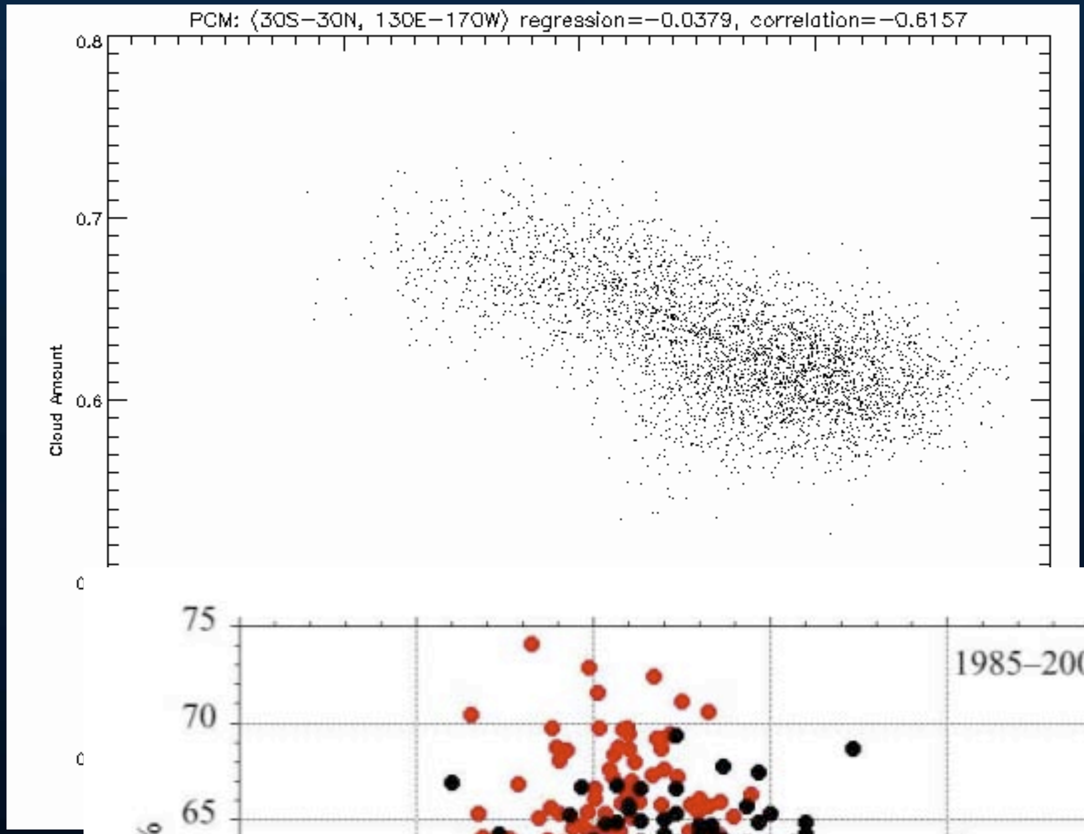
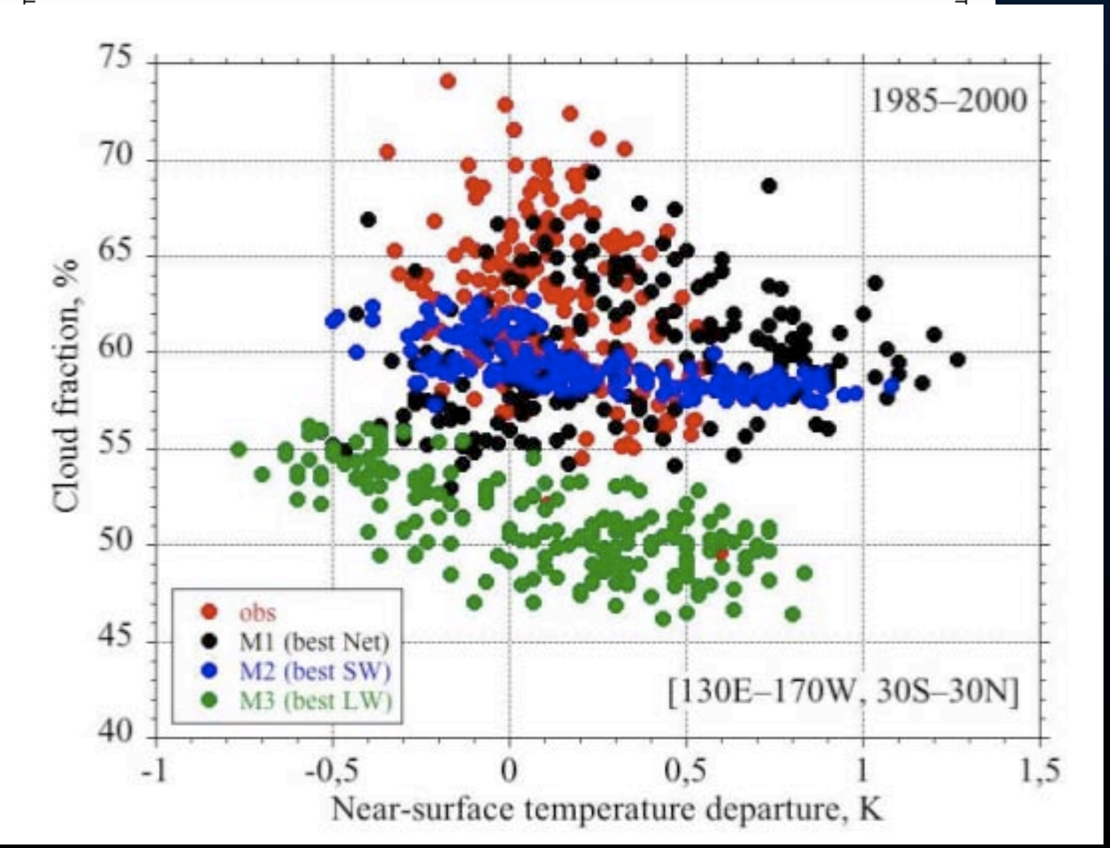


Lindzen et al., 2001





Sherwood et al 2009

Conclusions

- Convection and atmospheric humidity engage in two-way interaction. This may help stabilize relative humidity.
- Tropical waves/organization appear sensitive to this interaction and in principle provide a test of whether it is modeled correctly.
- Moisture-related feedbacks cannot easily be deduced from observations. Deductions should be properly tested on a GCM (and if surface T is involved it better be an AOGCM).
- Daily behavior of convection in GCMs is poor, and the problems are evident even in model climatologies.
- Convective control on *T* up to 100 hPa in the Tropics is too weak in GCMs. This may have implications for stratospheric climate feedbacks and convective parameterizations.