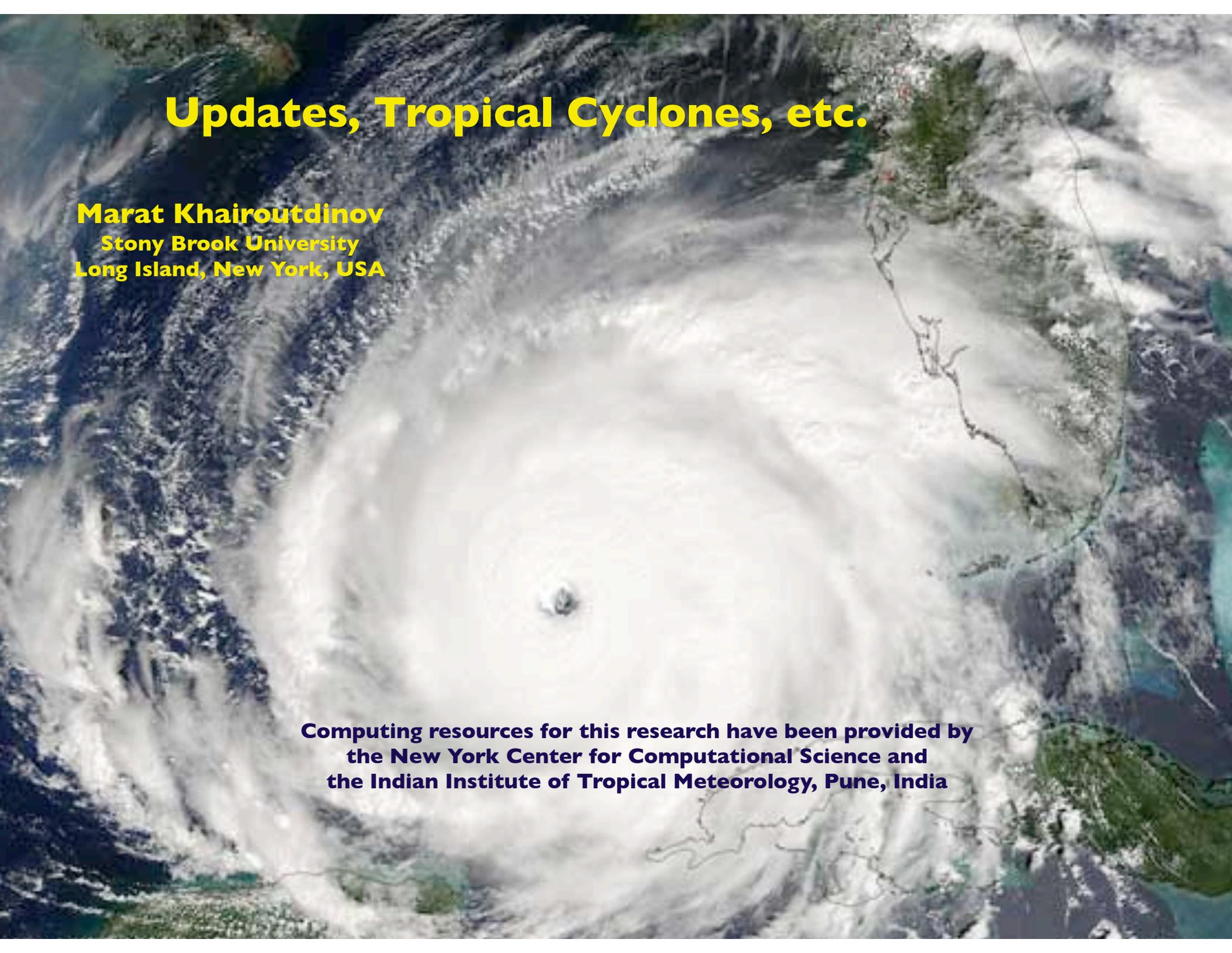


Updates, Tropical Cyclones, etc.

A satellite image of a tropical cyclone, showing a well-defined eye and spiral cloud bands over the Indian Ocean. The cyclone is centered in the lower-left quadrant of the image. The surrounding ocean is dark blue, and the landmasses of Africa and the Indian subcontinent are visible in the background.

Marat Khairoutdinov
Stony Brook University
Long Island, New York, USA

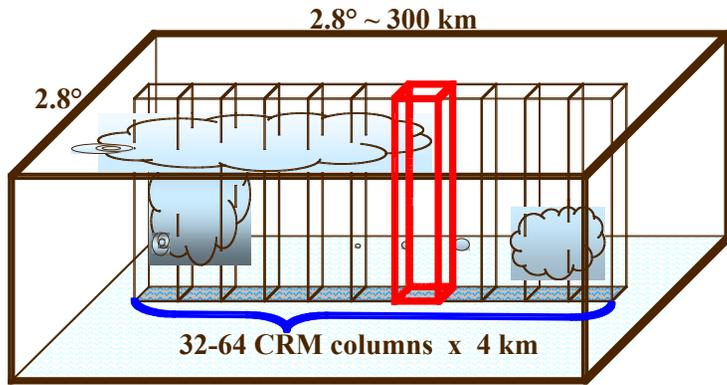
**Computing resources for this research have been provided by
the New York Center for Computational Science and
the Indian Institute of Tropical Meteorology, Pune, India**

Talk Topics:

- **Tests of MMF with MiniLES**
- **Tropical cyclones and stability of tropical climate**



Prototype MMF Approach:



$$\frac{\partial \bar{s}}{\partial t} = -\overline{\nabla_s V} - \frac{\partial \bar{s} \bar{\omega}}{\partial p} + Q_1$$

\swarrow LS Resolved Tendency \nwarrow Column-Physics Tendency (parameterizations)

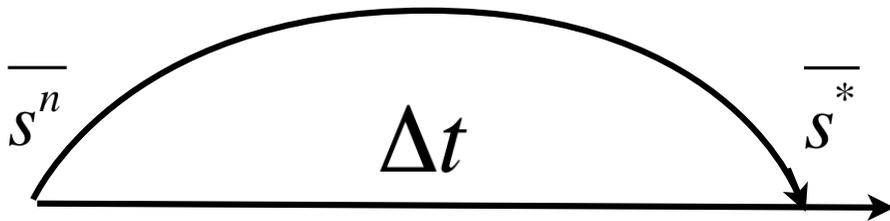
CRM Forcing:

$$-\overline{\nabla_s V} - \frac{\partial \bar{s} \bar{\omega}}{\partial p} = \frac{\bar{s}^* - \bar{s}^n}{\Delta t}$$

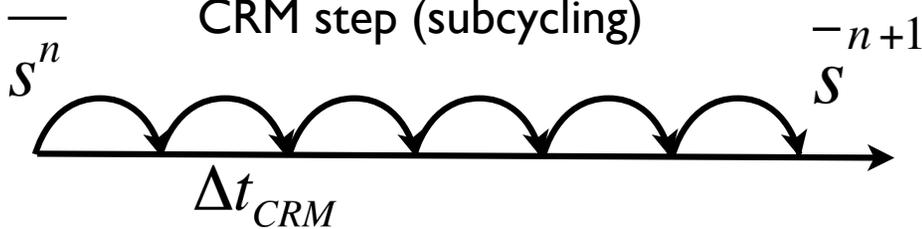
Column-physics Tendency:

$$Q_1 = \frac{\bar{s}^{-n+1} - \bar{s}^*}{\Delta t}$$

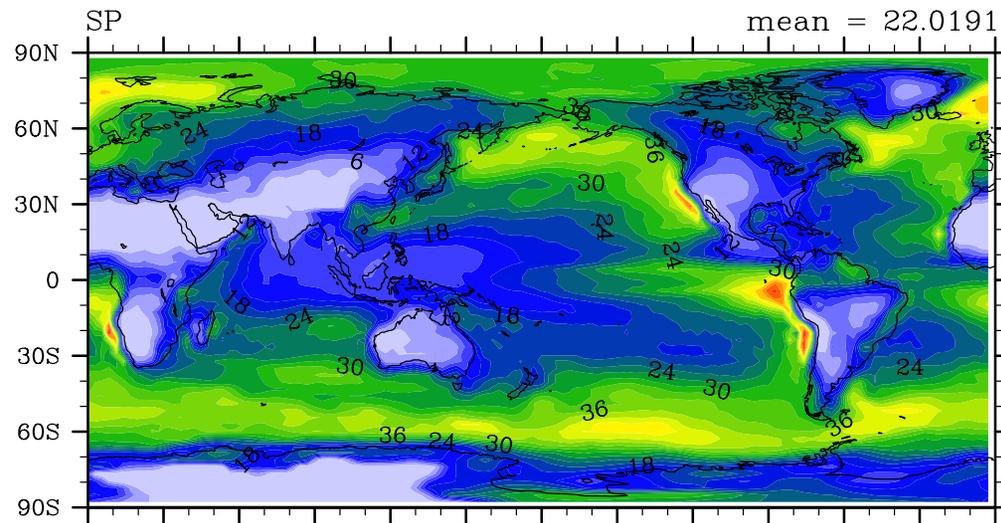
Dynamics Step:



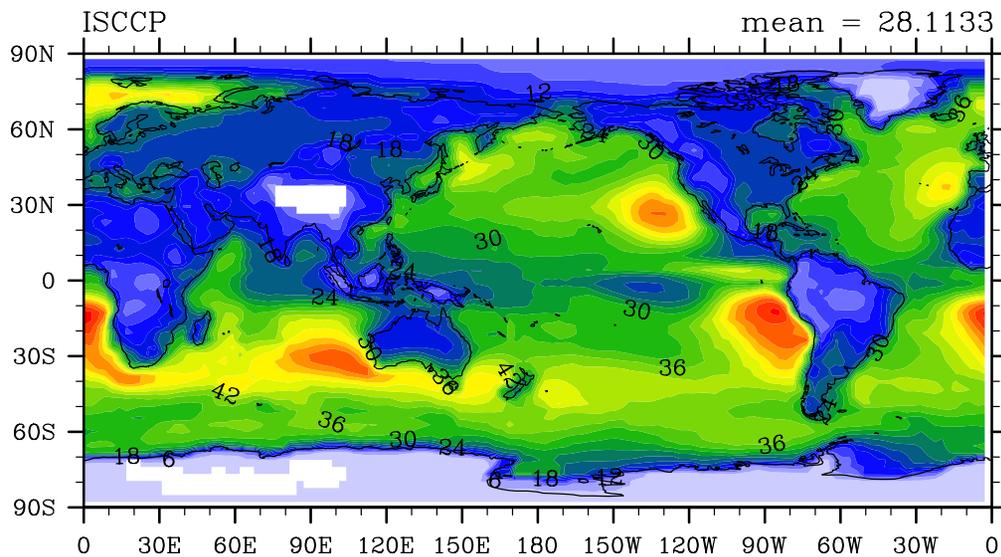
CRM step (subcycling)



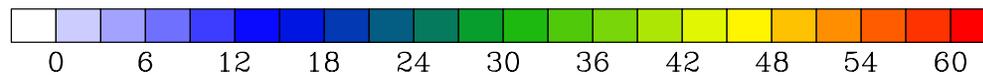
Annual low-cloud cover from ISCCP cloud simulator



SP-CAM

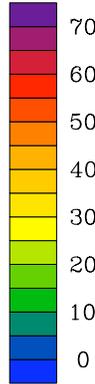
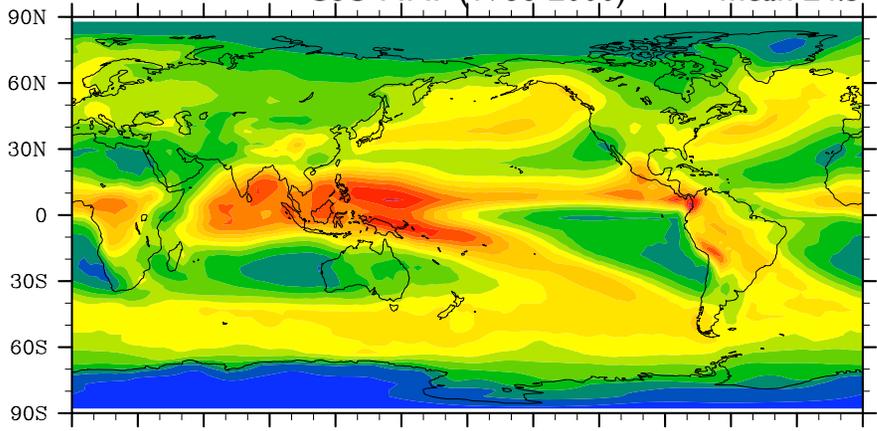


ISCCP (Satellites)



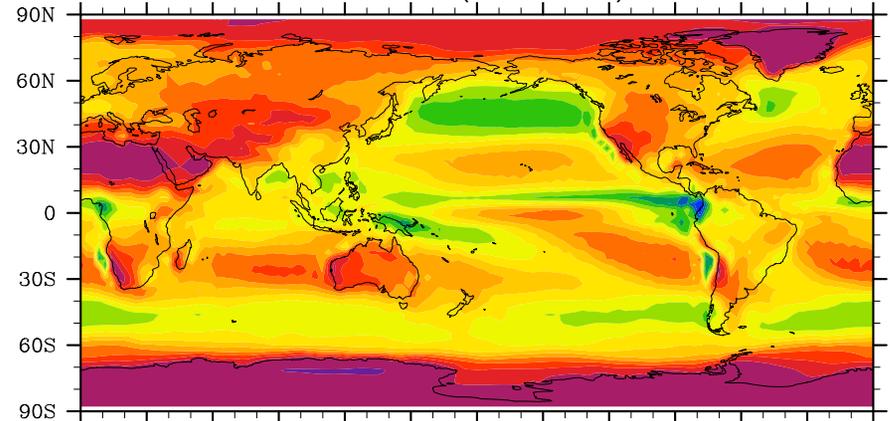
Annual Longwave Cloud Effect (W/m^2)

CSU MMF (1986-2000) mean 24.5

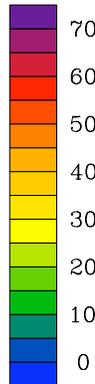
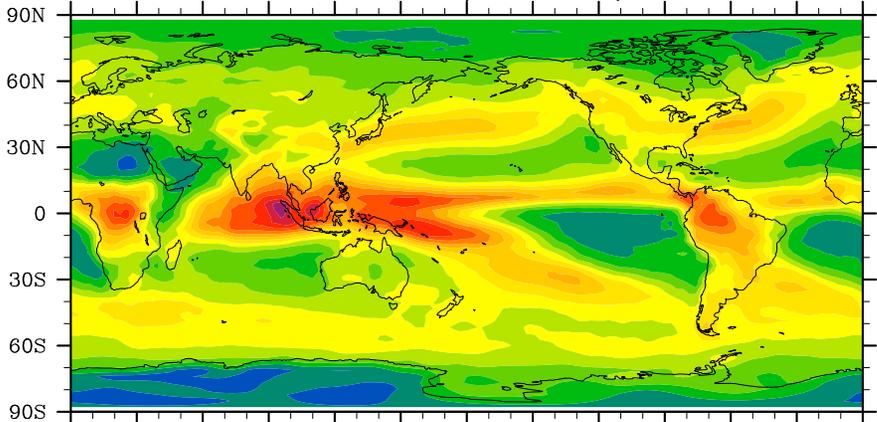


Annual Shortwave Cloud Effect (W/m^2)

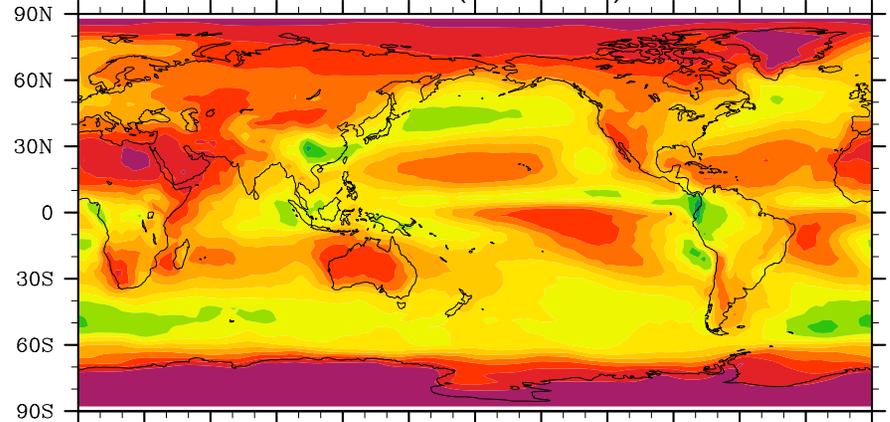
CSU MMF (1986-2000) mean -52.5



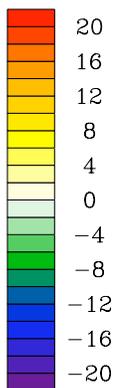
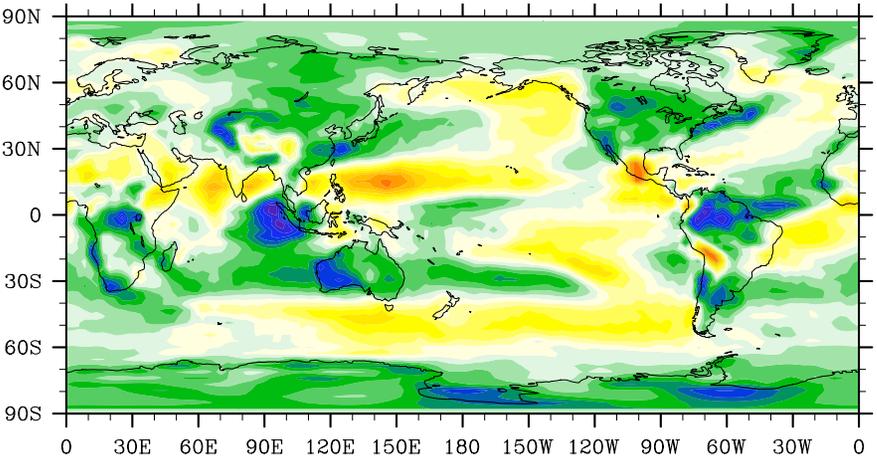
ISCCP-FD (1986-2000) mean 25.6



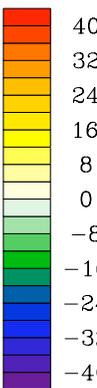
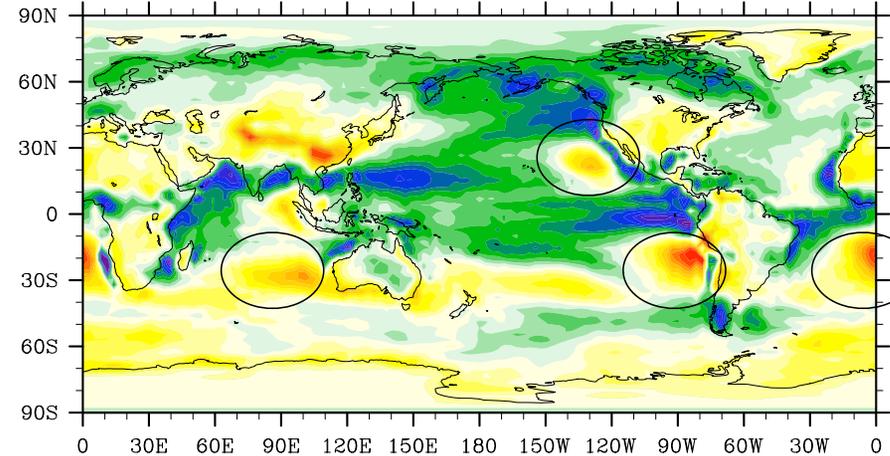
ISCCP-FD (1986-2000) mean -50.0



MMF minus ISCCP-FD mean -1.1



MMF minus ISCCP-FD mean -2.5



0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0

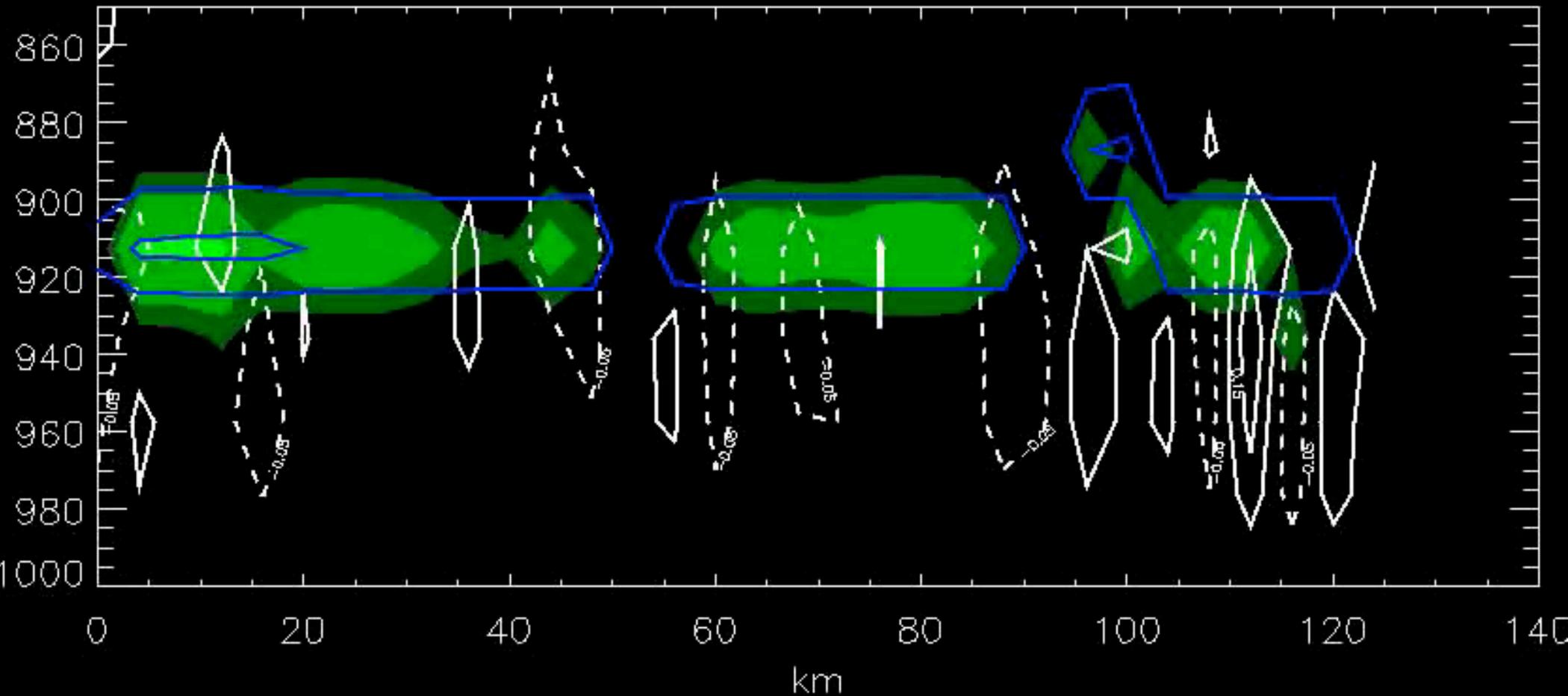
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0

There are shallow marine BL clouds too!

SP clouds animation by Charlotte Demott

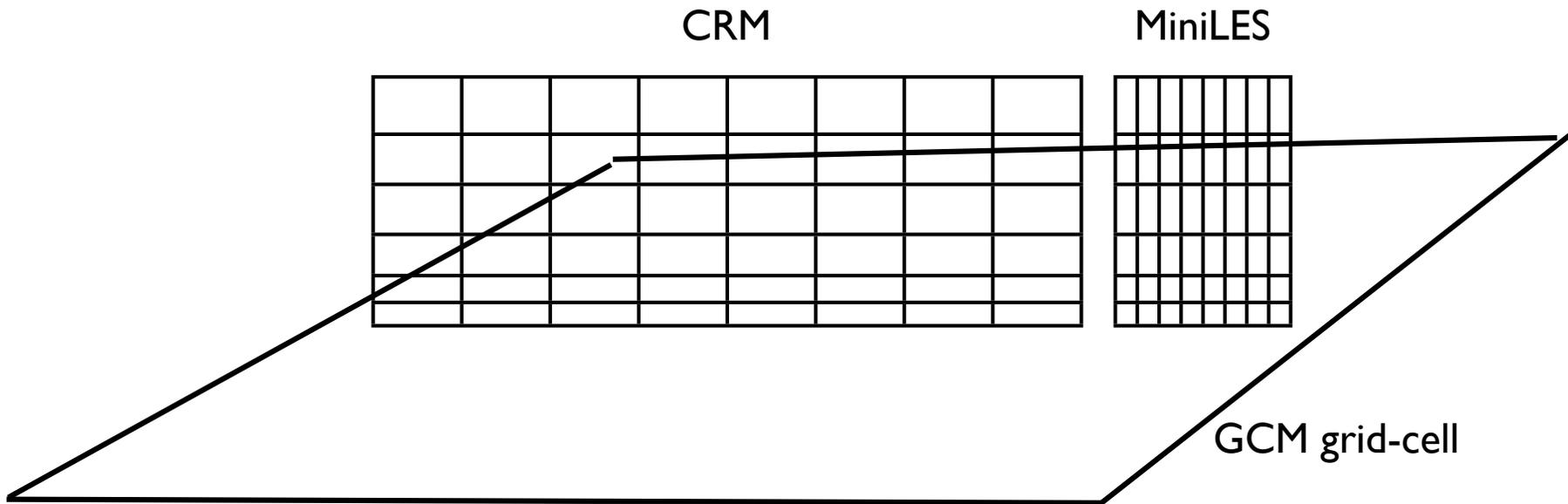
32N, 231E (off coast of CA)

July 1 UTC 1



CRM-MiniLES Prototype Model

MiniLES: SP with an LES-like horizontal grid spacing;
LES - Large-Eddy Simulation, which is a technique to model turbulence and small and thin low-level clouds.

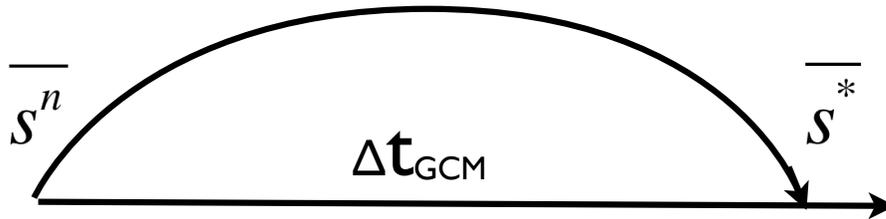


MiniLES allows no condensation above 5000m to suppress deep convection

The SP-MiniLES model is 70% more expensive than SP-CAM

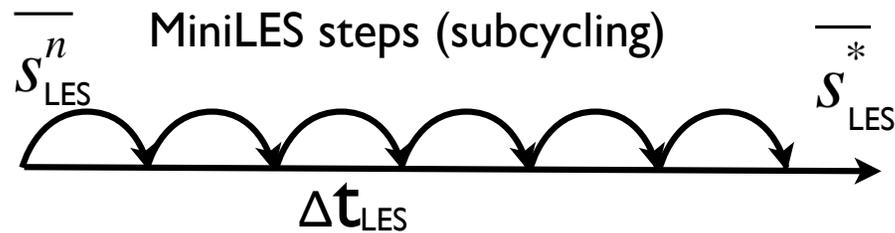
MiniLES-CRM-GCM Coupling

Dynamics Step:



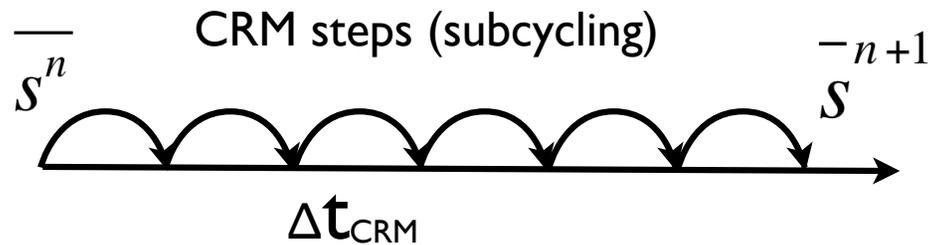
MiniLES Forcing:

$$-\overline{\nabla_s V} - \frac{\partial \bar{s} \bar{\omega}}{\partial p} = \frac{\bar{s}^* - \bar{s}_{LES}^n}{\Delta t_{GCM}}$$



CRM Forcing:

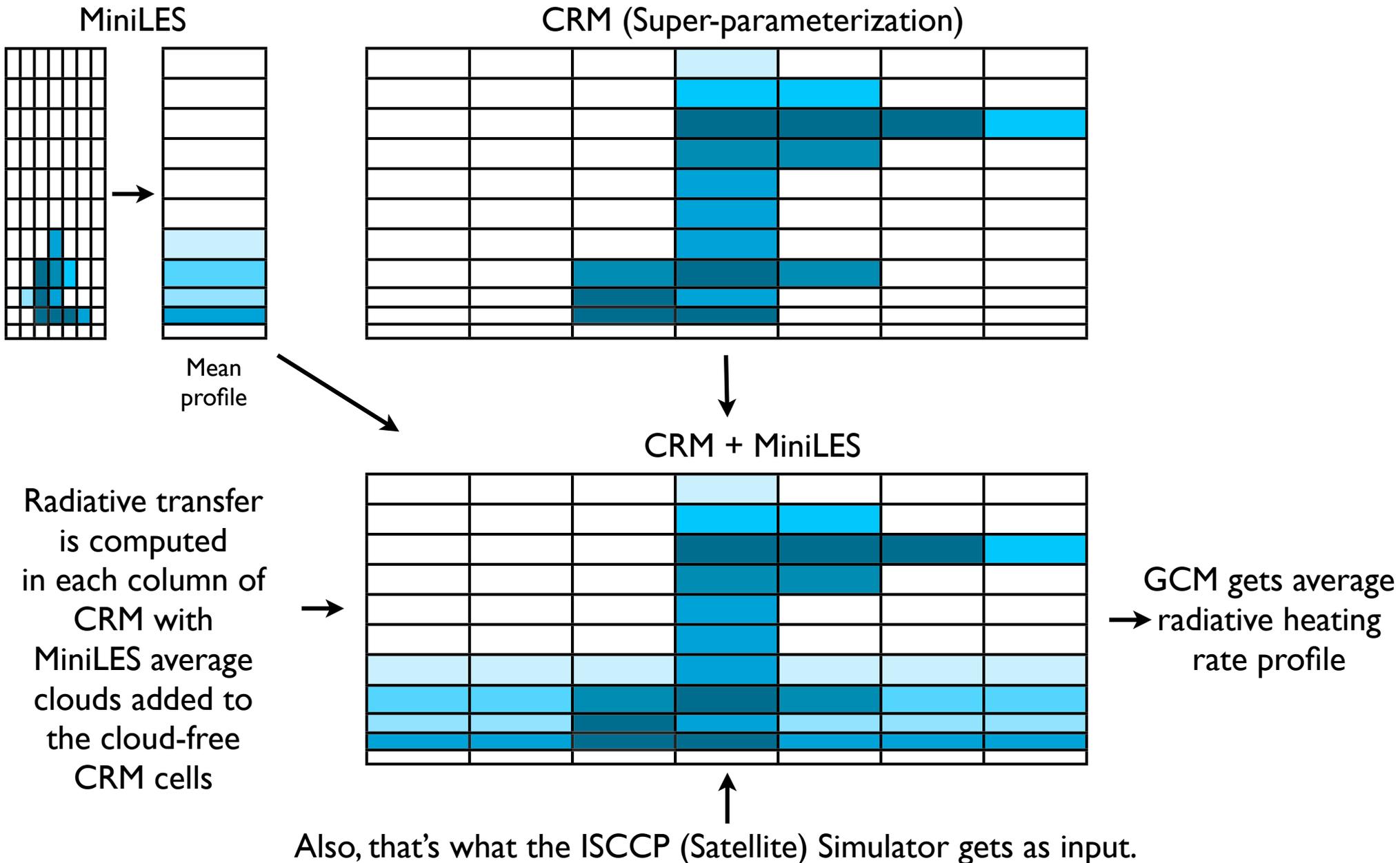
$$-\overline{\nabla_s V} - \frac{\partial \bar{s} \bar{\omega}}{\partial p} = \frac{\bar{s}_{LES}^* - \bar{s}^n}{\Delta t_{GCM}}$$



Column-physics Tendency:

$$Q_1 = \frac{\bar{s}^{-n+1} - \bar{s}^*}{\Delta t}$$

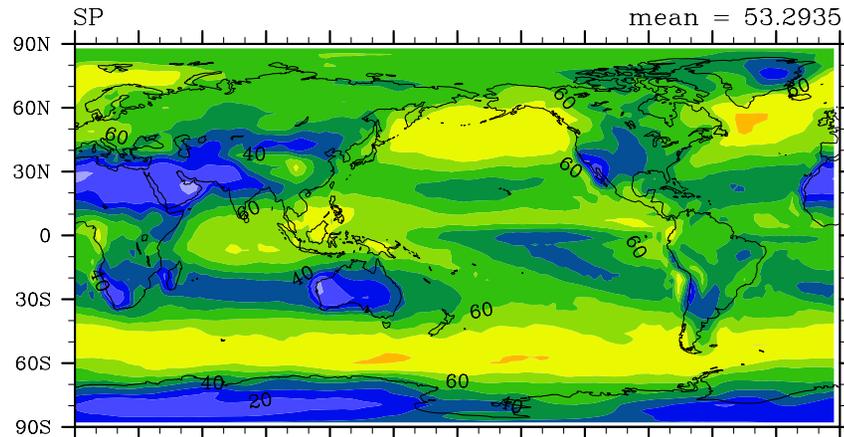
Schematic for the radiative transfer in the SP+MiniLES framework



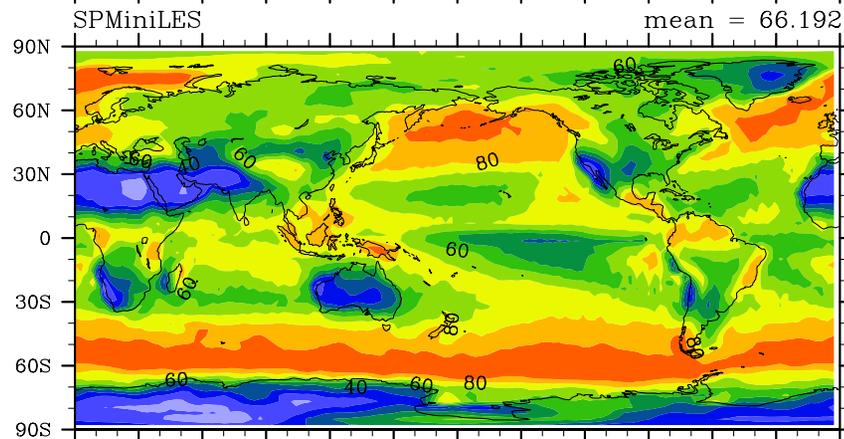
Preliminary Test

- **GCM Dycore: Semi-Lagrangian, T42 (128x64), L30; $\Delta t=900s$**
- **SP: 32x28, $\Delta x=4000m$, $\Delta t=20s$**
- **MiniLES: 32x28, $\Delta x=250m$, $\Delta t=20s$**
- **Microphysics: SAM's 1-Moment**
- **Duration: 2 years + 4-month spinup**

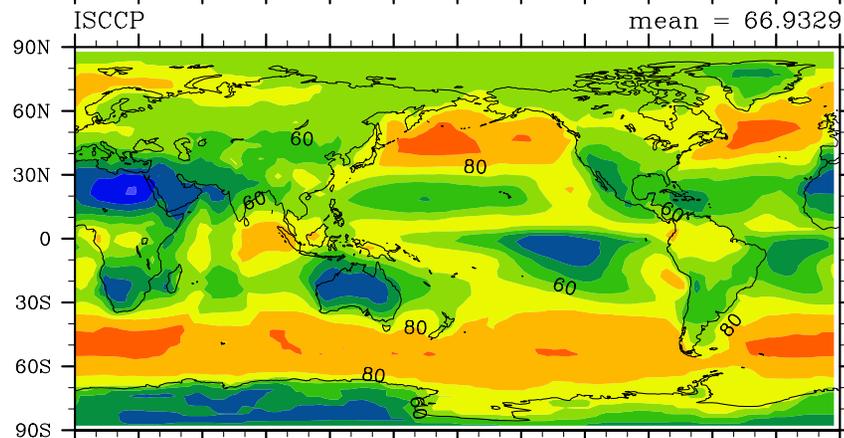
Annual total cloud cover from ISCCP cloud simulator



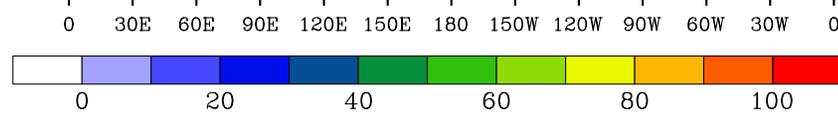
SP-CAM



SP+MiniLES-CAM

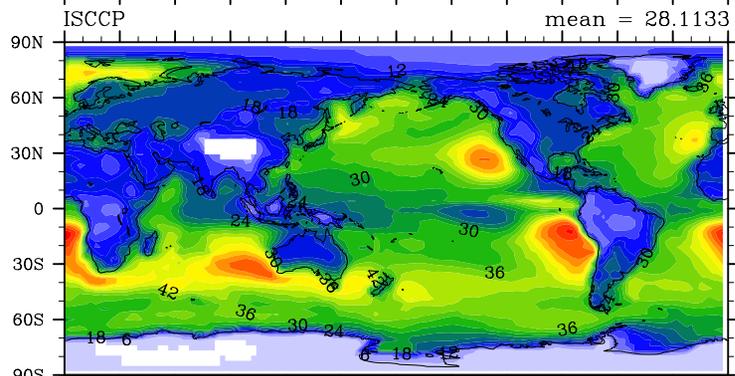
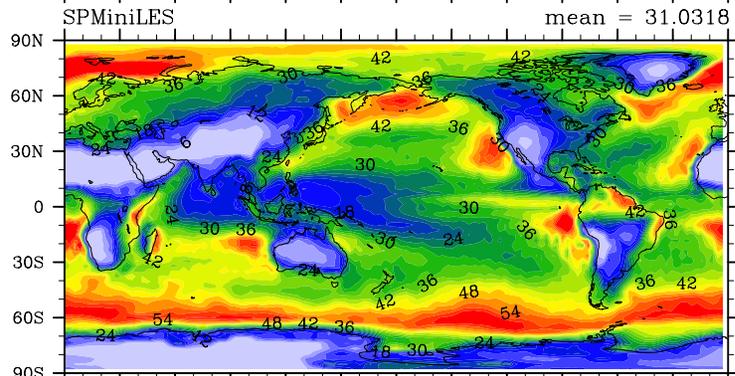
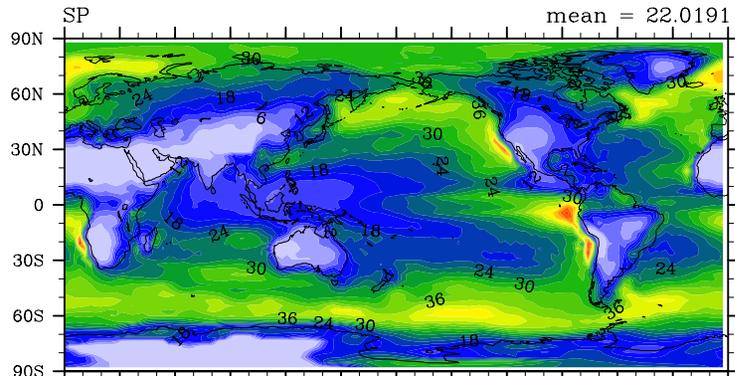


ISCCP (Satellites)

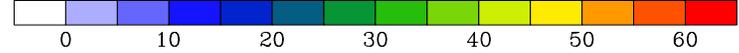
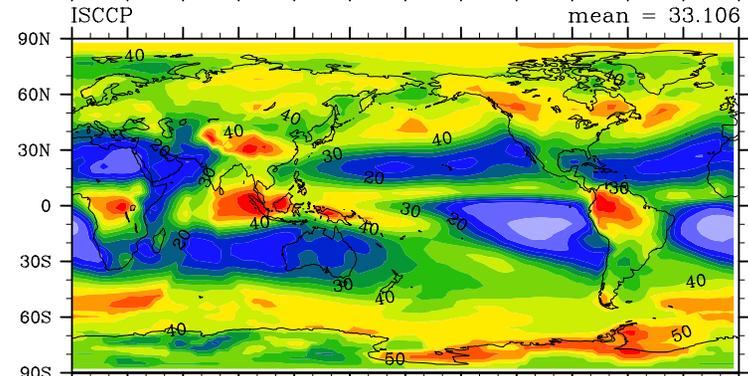
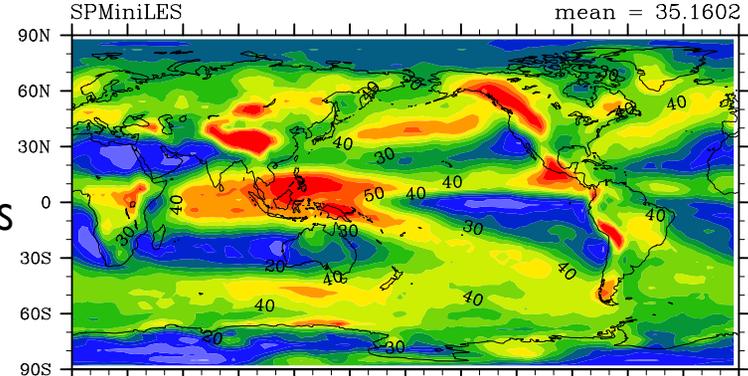
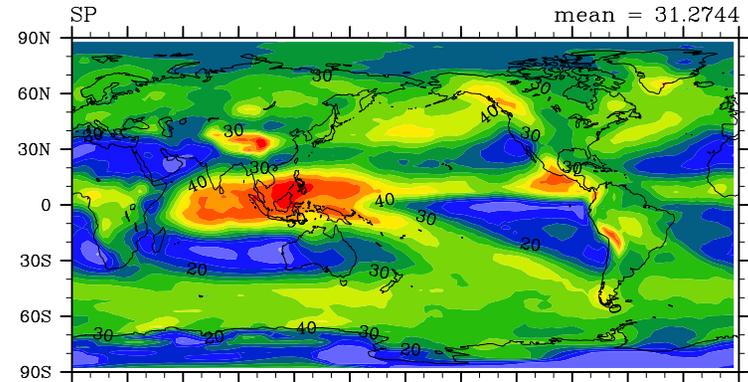


Annual mean output from the ISCCP cloud simulator

Low Clouds (below 700 mb)



Mid and High Clouds (above 700 mb)



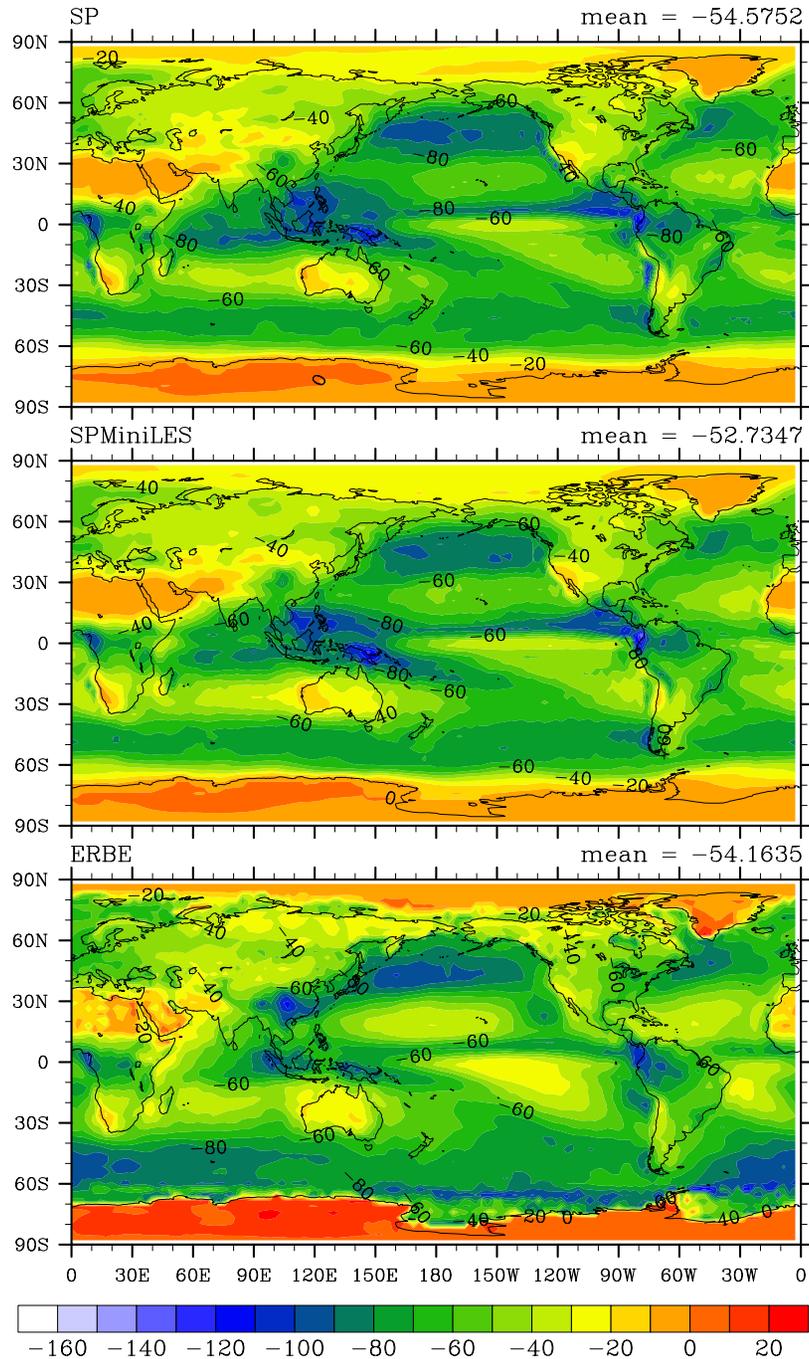
SP

SP+MiniLES

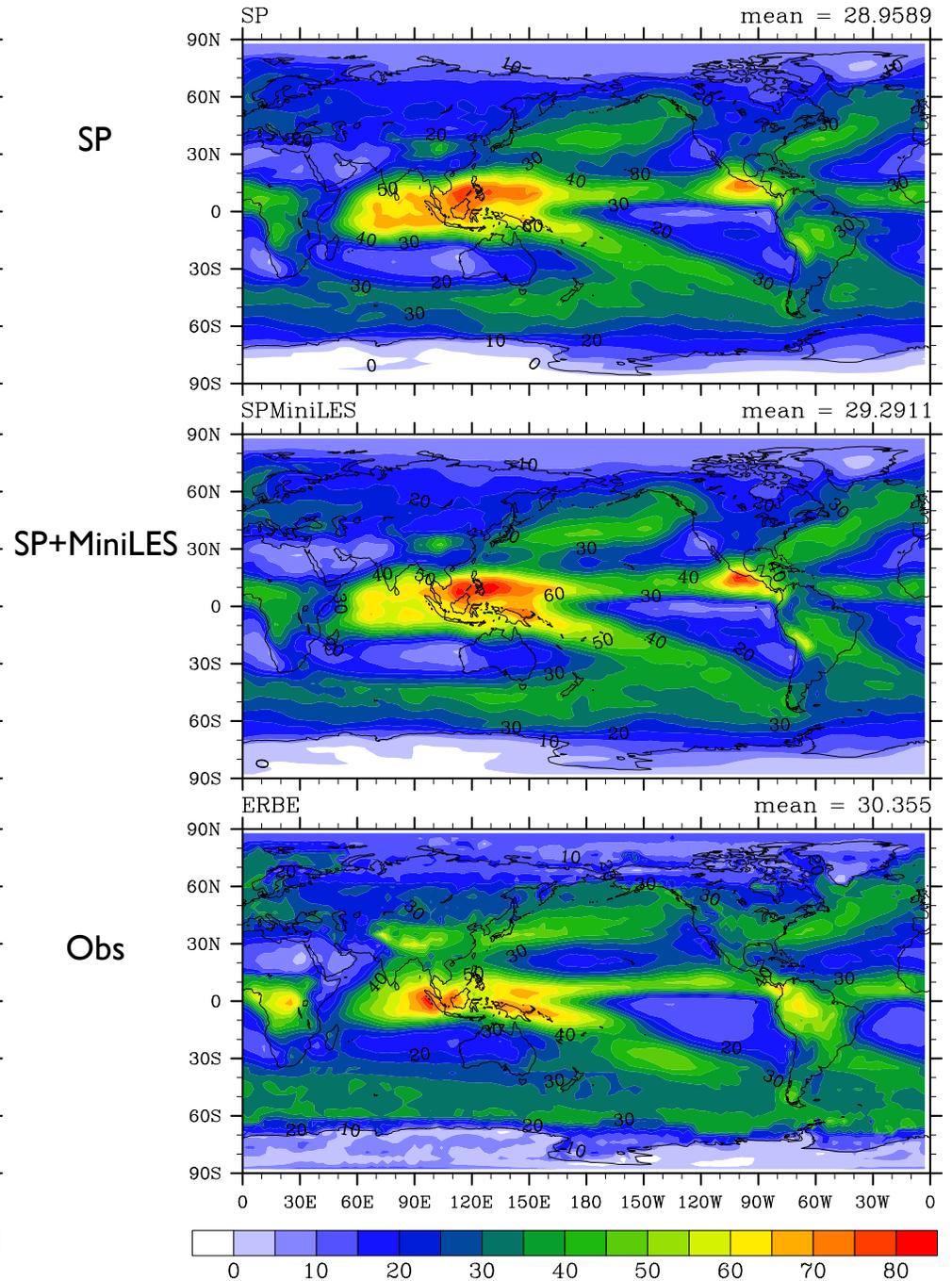
Obs

Annual mean output from the ISCCP cloud simulator

Shortwave Cloud Forcing

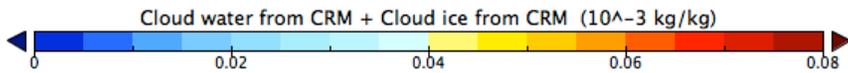
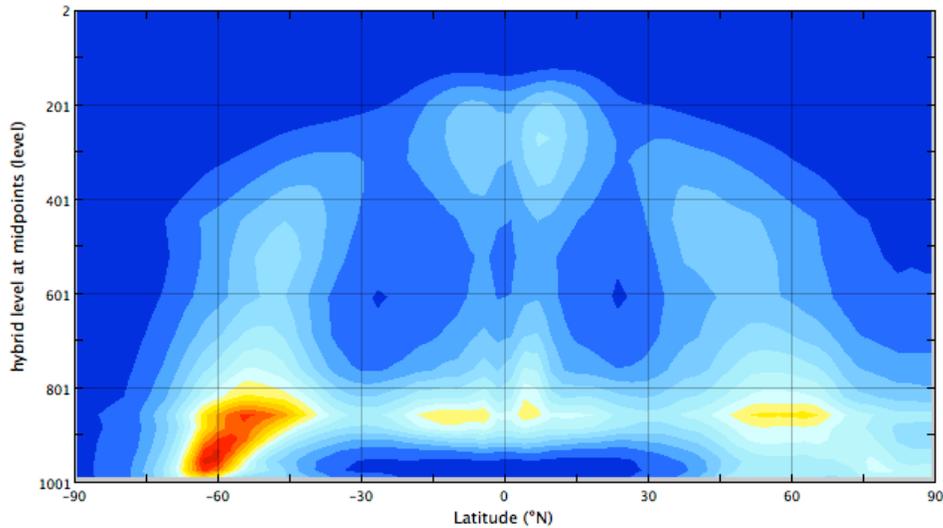


Longwave Cloud Forcing

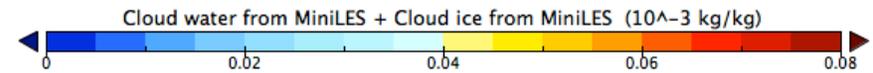
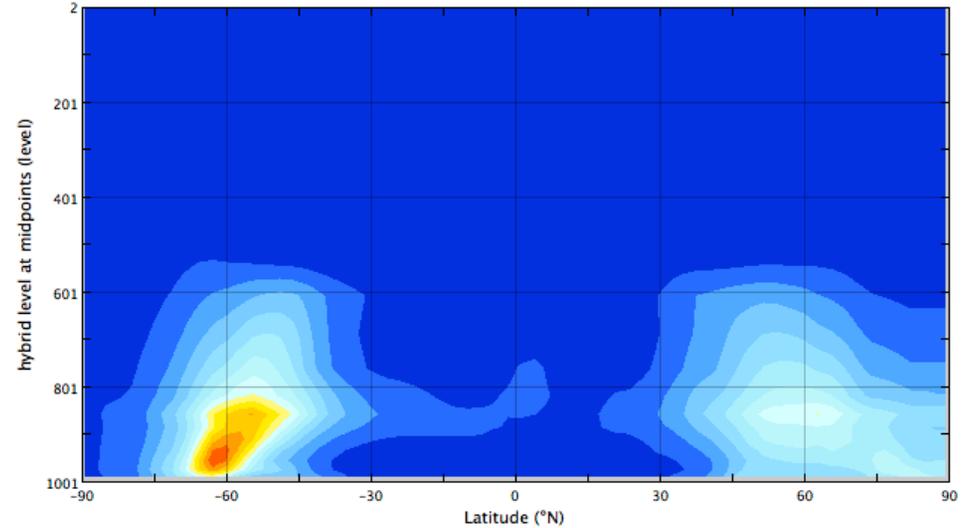


Annual zonal-mean distribution of cloud liquid/ice water

Cloud water from CRM



Cloud water from MiniLES

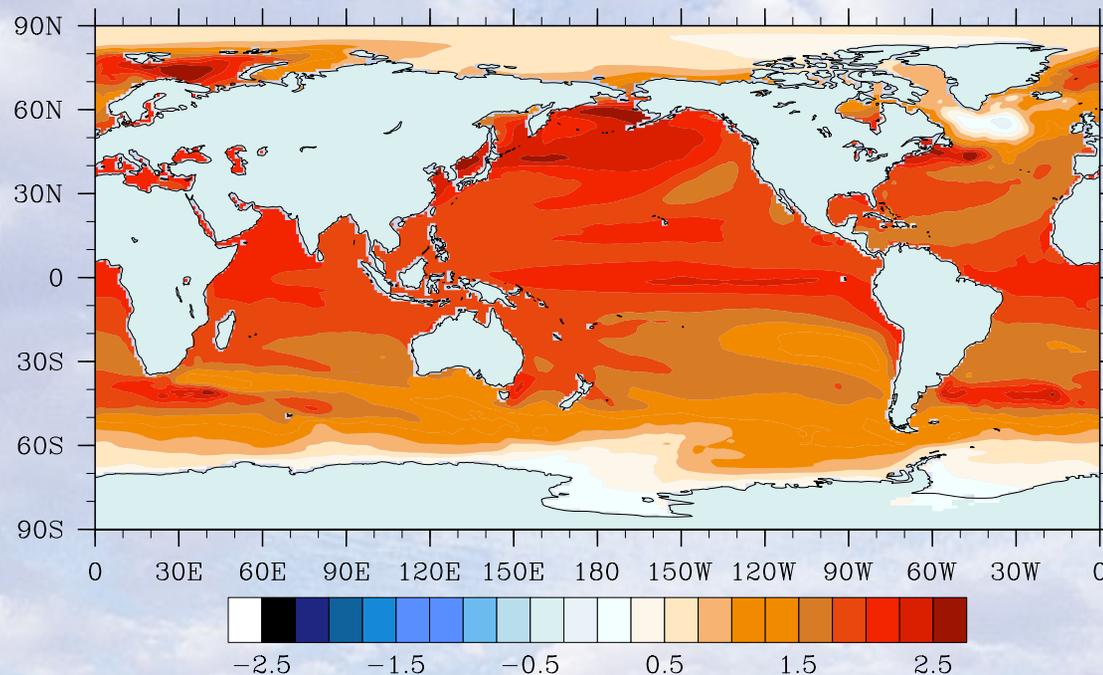


Low-cloud water represented on CRM grid is higher than represented on MiniLES grid.
That explains the relatively small effect on solar cloud forcing in MiniLES simulations.

Climate-change Time-Slice Test

- **Control (Present):** Prescribed climatological monthly SSTs
- **Perturbed (Future):** Prescribed IPCC composite SST anomalies
- **Duration:** 2 years + 4-month spinup

AR4 Models' Composite 2000s-2090s SST Change



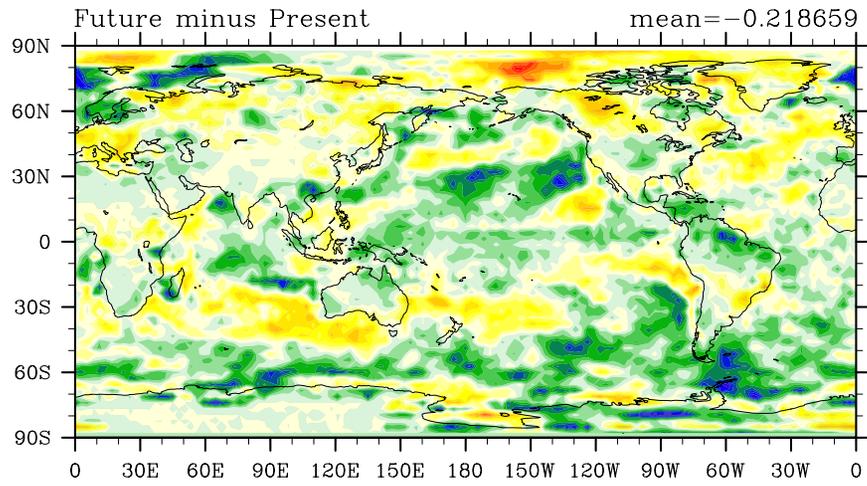
**Change (future - present) of various globally and annually averaged variables
in MMF with SP only and with SP+MiniLES**

Global change	SP	SP-MiniLES
$\Delta T_s, K$	1.9	1.9
$\Delta PW, mm$	4.3	4.4
$\Delta OLR, W/m^2$	3.7	3.8
$\Delta ASR, W/m^2$	0.0	0.0
$\Delta LWCF, W/m^2$	0.10	0.13
$\Delta SWCF, W/m^2$	-0.5	-0.4
$\Delta C_{Low}, \%$	0.2	-0.2
$\Delta C_{Mid}, \%$	-0.4	-0.9
$\Delta C_{High}, \%$	0.5	0.7
$\Delta C_{Tot}, \%$	0.4	-0.4
$\Delta LWP, g/m^2$	6.2	6.7
$\Delta Prec, mm/d$	0.2	0.2

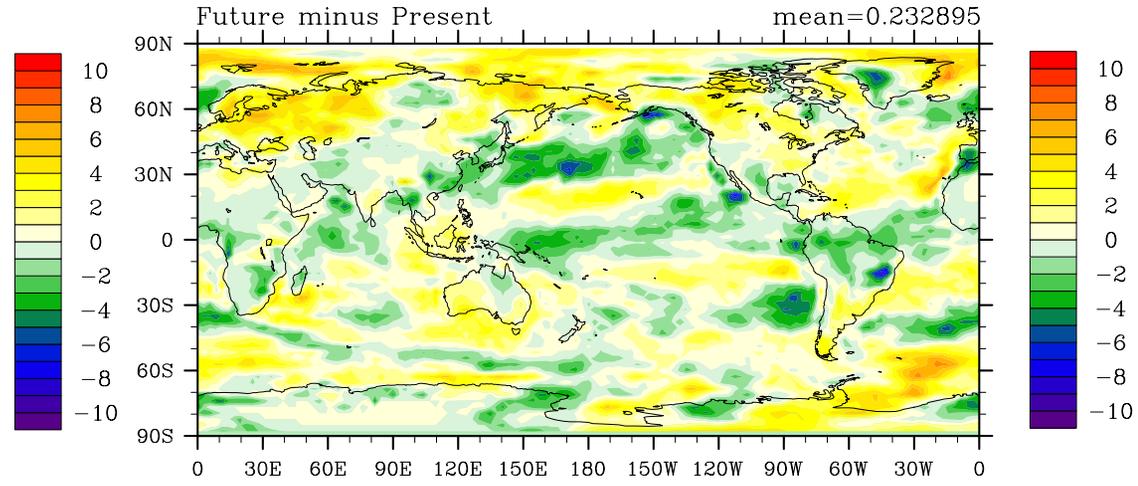
Change of the low-level cloud fraction changes sign in MiniLES simulations. However, as most liquid water is represented on the CRM grid, the effect on SWCF is small.

Change (future - present) of low cloud cover

SP-MiniLES



SP



Near-Future Plans on MiniLES

- ◆ **Improve coupling of MiniLES (suggestions/ideas are welcome)**
- ◆ **Most low-level liquid water and cloudiness should be represented on MiniLES grid, not CRM grid**
- ◆ **Study the SP+MiniLES framework offline in RCE setting**

Radiative-Convective Equilibrium (RCE) Idealization of Tropics

No explicit lateral transport
in/out the domain
(which is doubly periodical)

Radiation

Microphysics

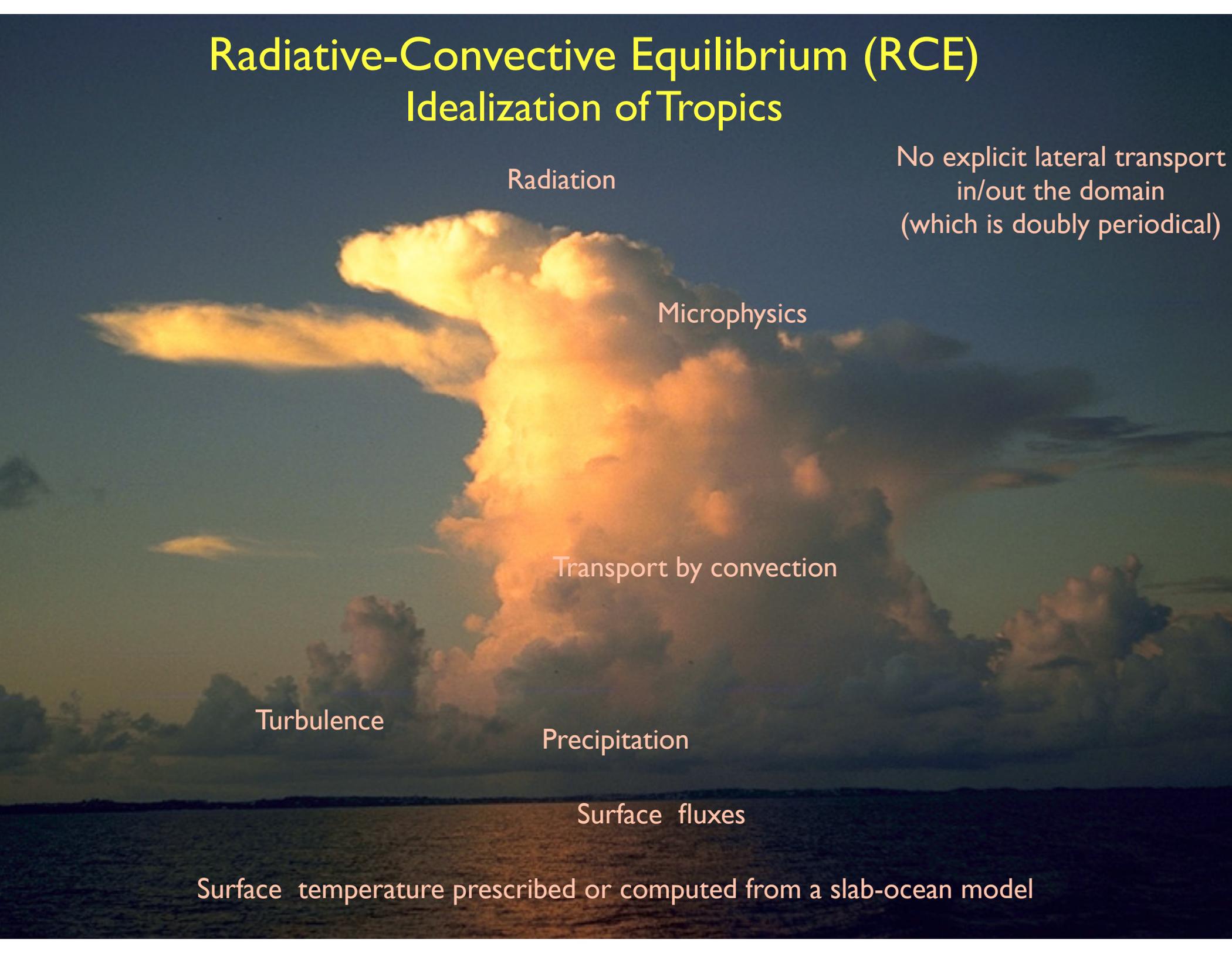
Transport by convection

Turbulence

Precipitation

Surface fluxes

Surface temperature prescribed or computed from a slab-ocean model



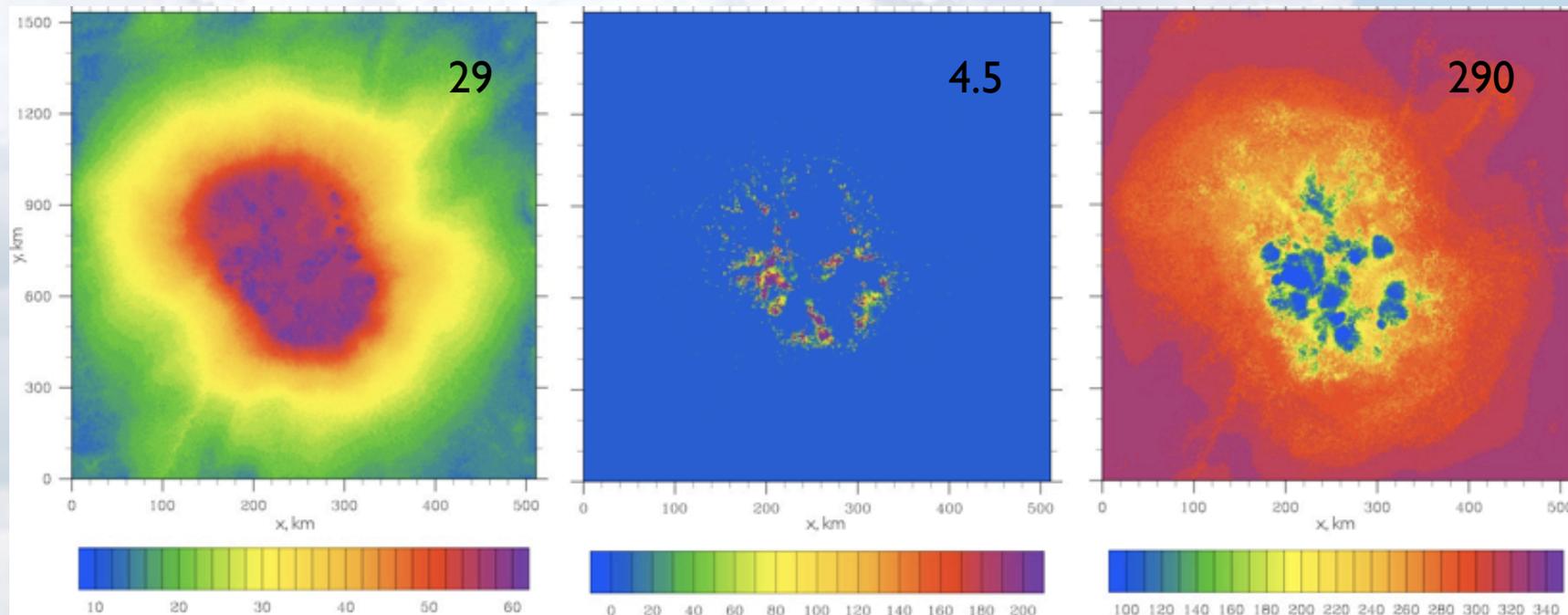
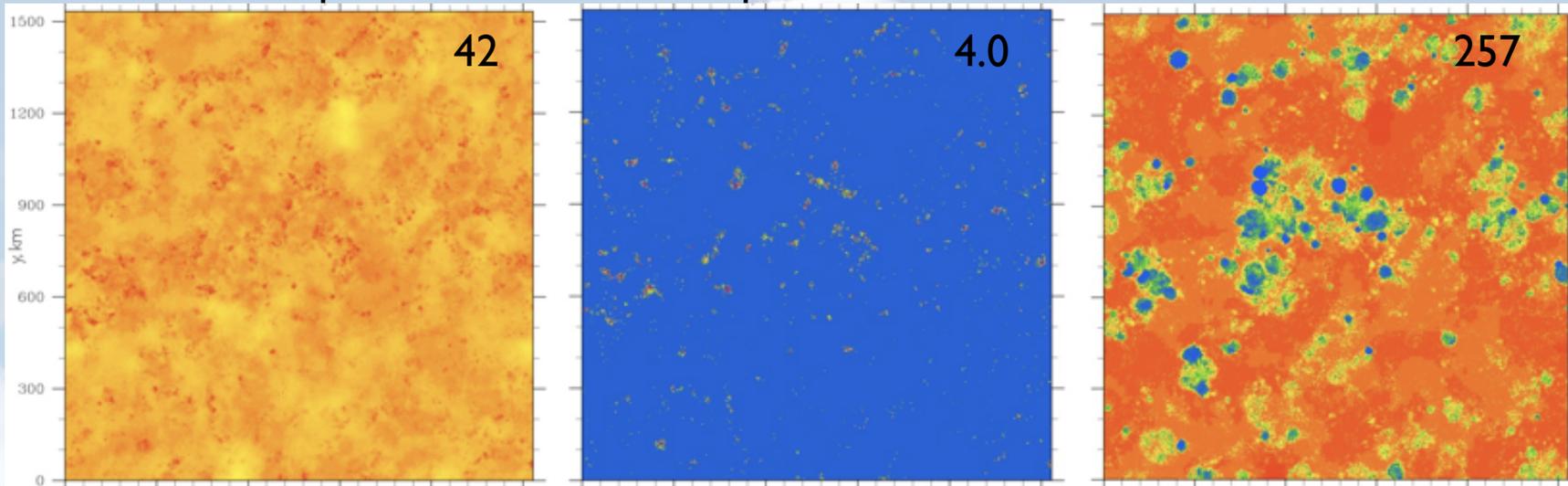
Self-aggregation of convection in RCE over large domain with no rotation (Bretherton and Khairoutdinov, 2004; Bretherton et al. 2005)

Column Vapor, mm

Precipitation, mm/d

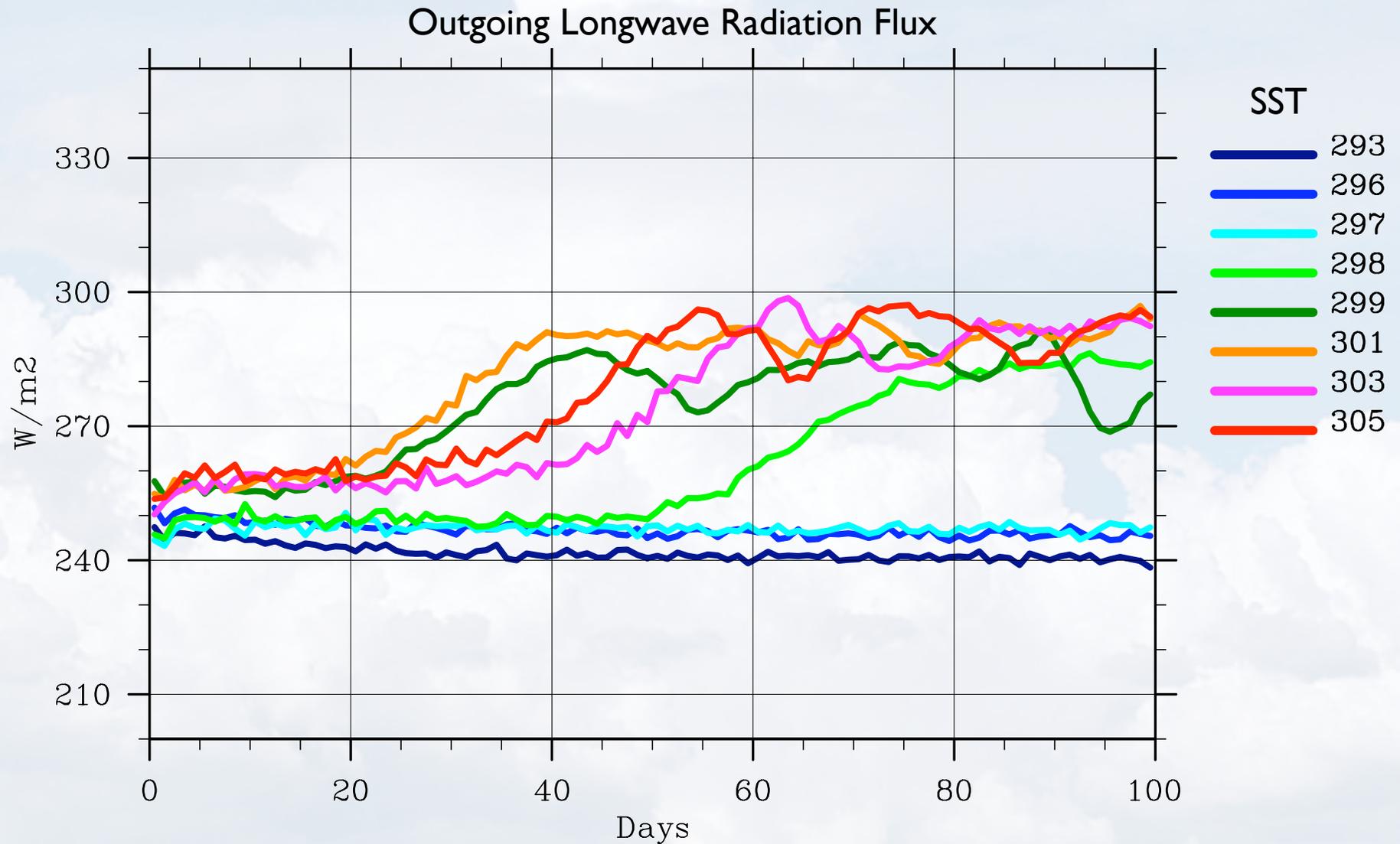
OLR W/m^2

1500 km

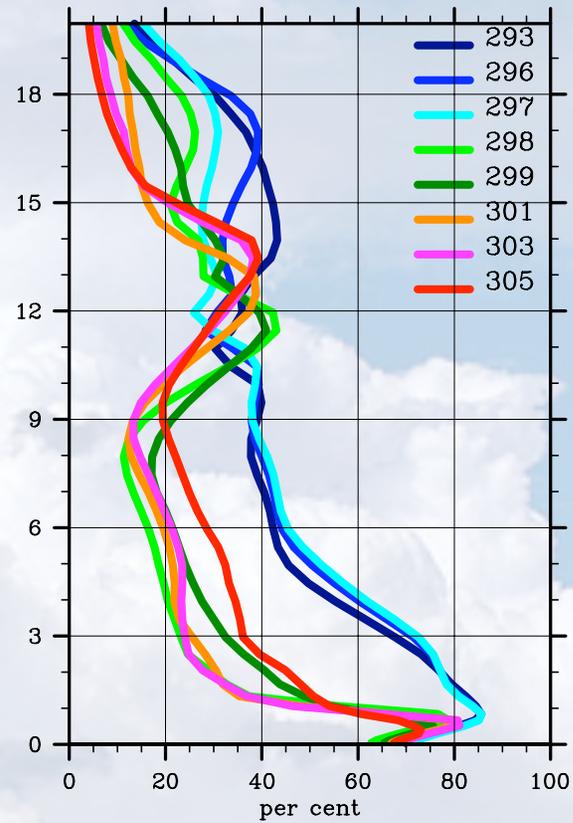
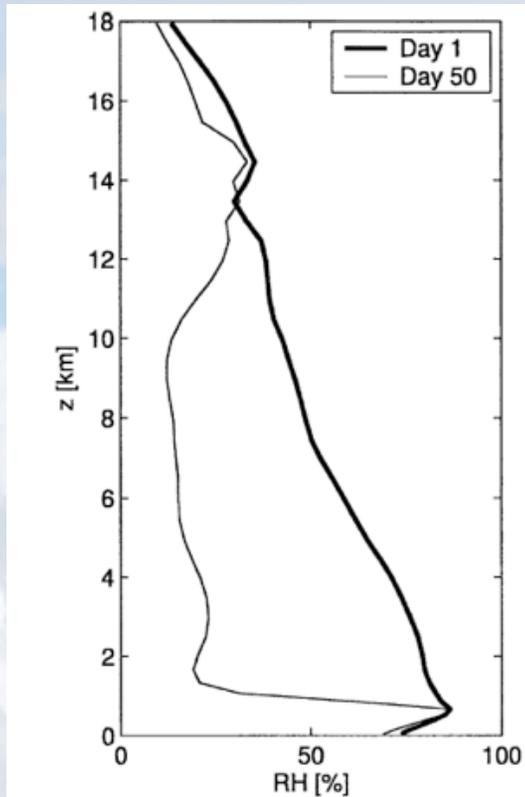


Self-aggregation of convection in RCE over large domain with no rotation

Dependence on SST: “On/off switch”



**Aggregated-convection state has, on average,
much drier troposphere
than random-convection state**



Bretherton et al. (2005)

- **Hypothesis (Emanuel 2009):** Tropical convection is attracted to the transition critical state between aggregated and disaggregated regimes.
- **Consequence:** If tropical convection is indeed in near-SOC state, the climate sensitivity of Tropics may be low (strong negative feedback).

Warming SSTs

Self-aggregation of convection

Drying of the Troposphere

Reduction in Greenhouse Effect

Cooling SSTs

Disaggregation

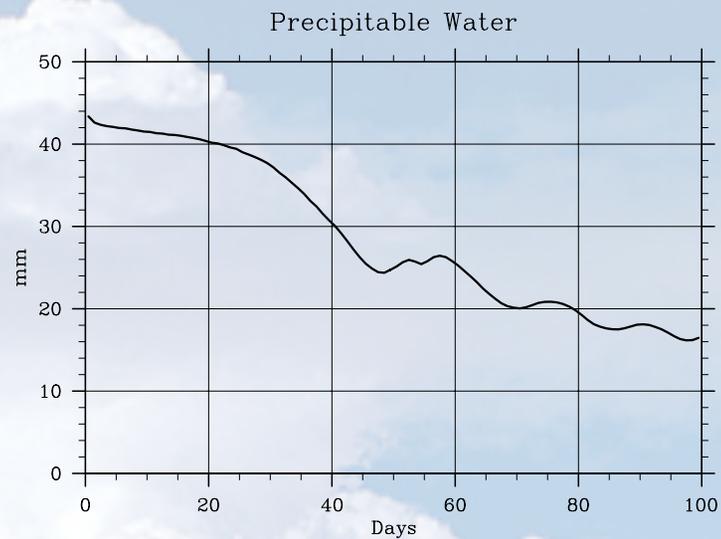
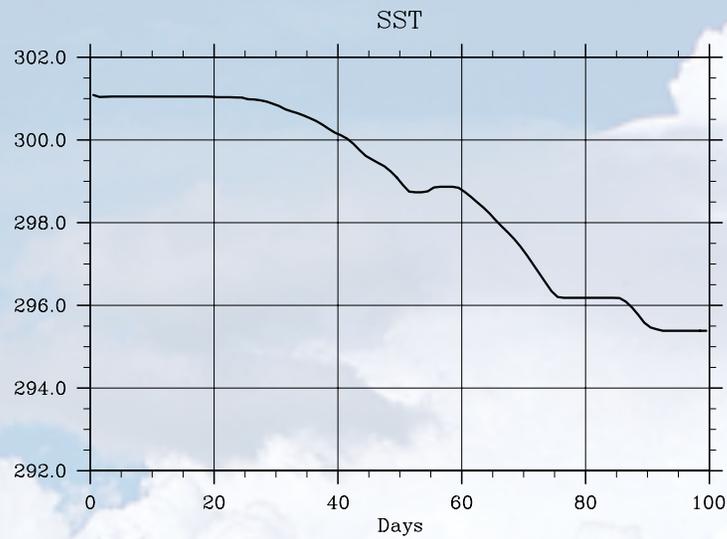
Re-moistening of the Troposphere

Restoration of Greenhouse Effect

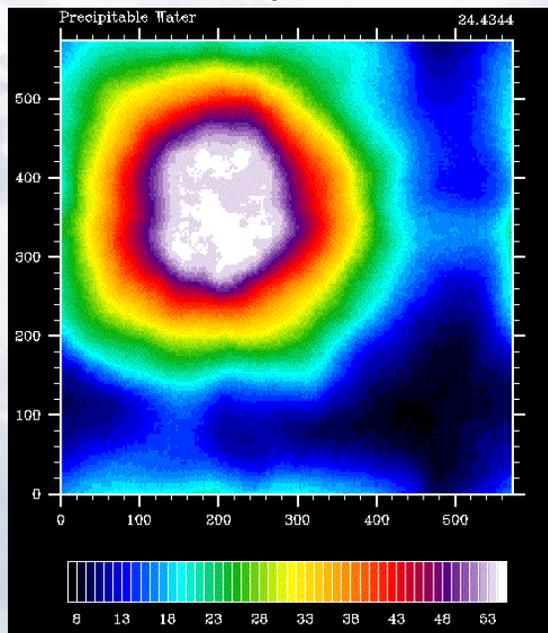
Restoration of SSTs

RCE with Interactive SST (slab-ocean model)

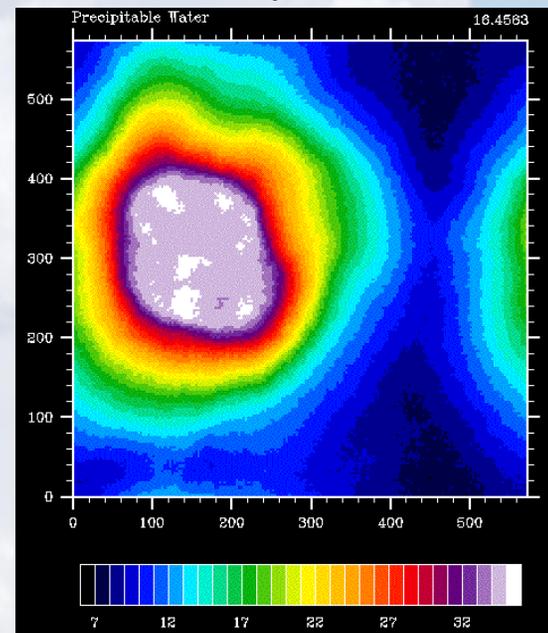
Hysteresis! convection does not disaggregate as SST drops.



day50



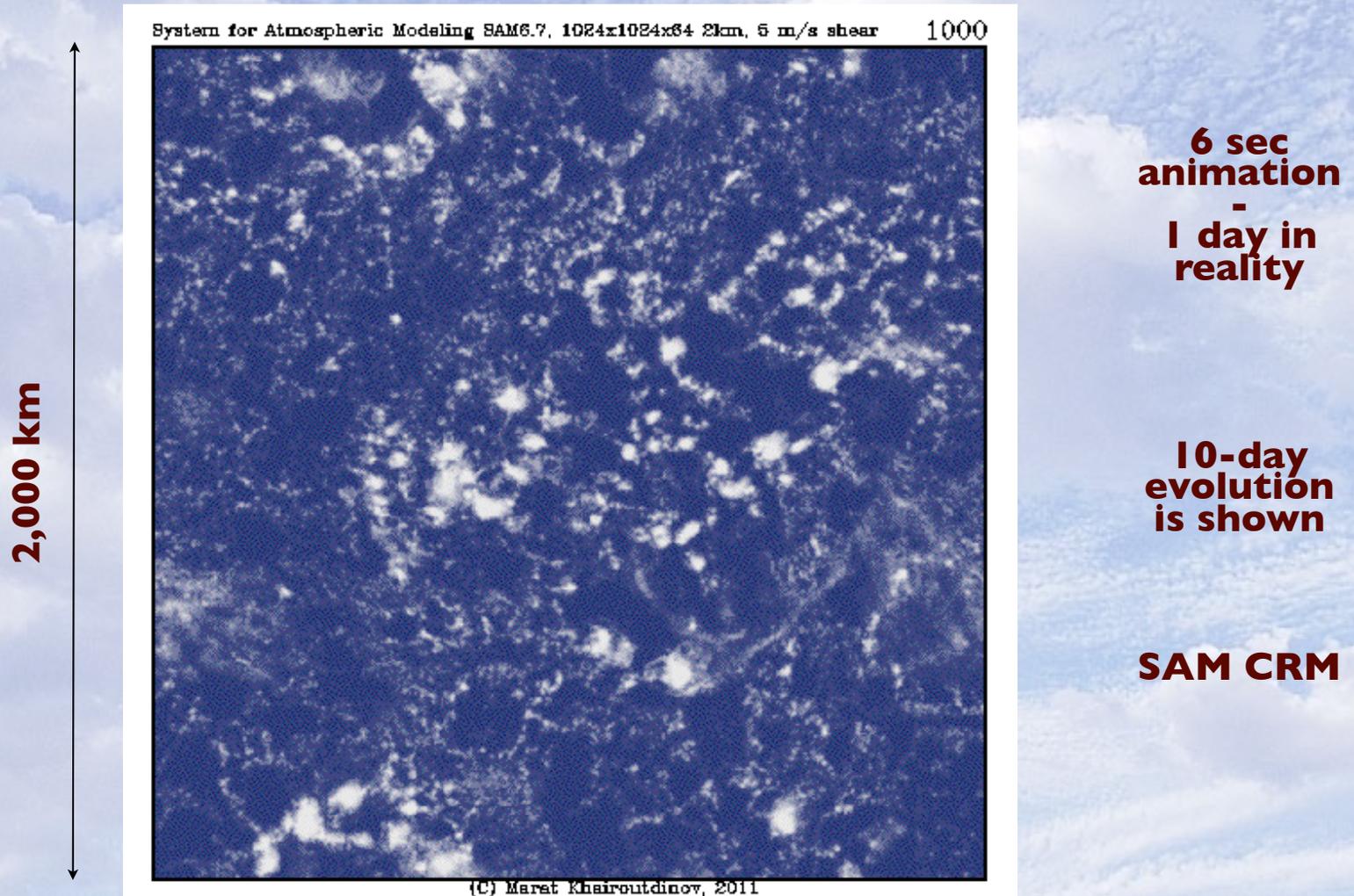
day100



Try tropical cyclones instead?!



Simulations of hurricane formation from random convection in RCE with wind shear



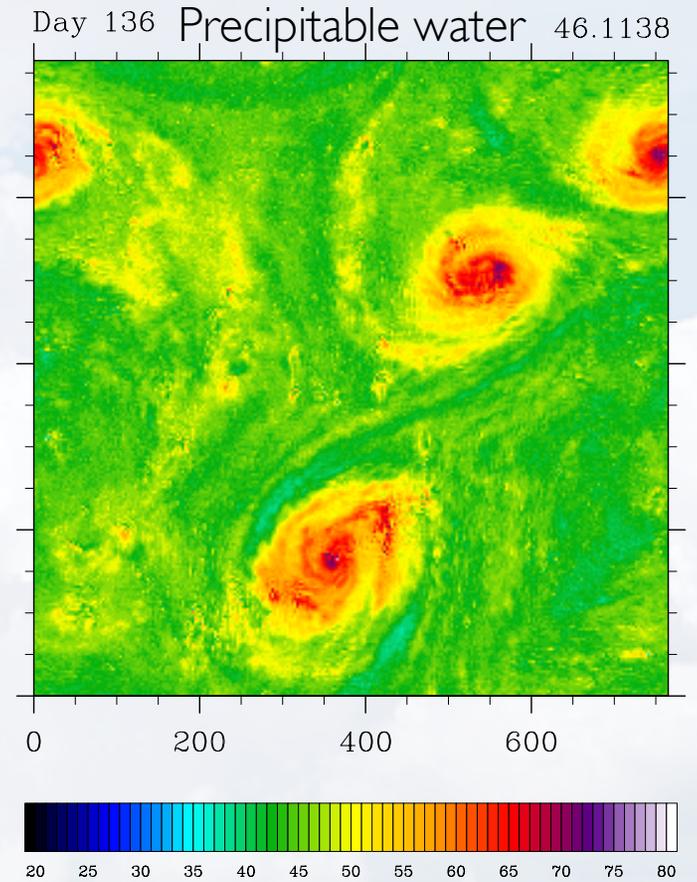
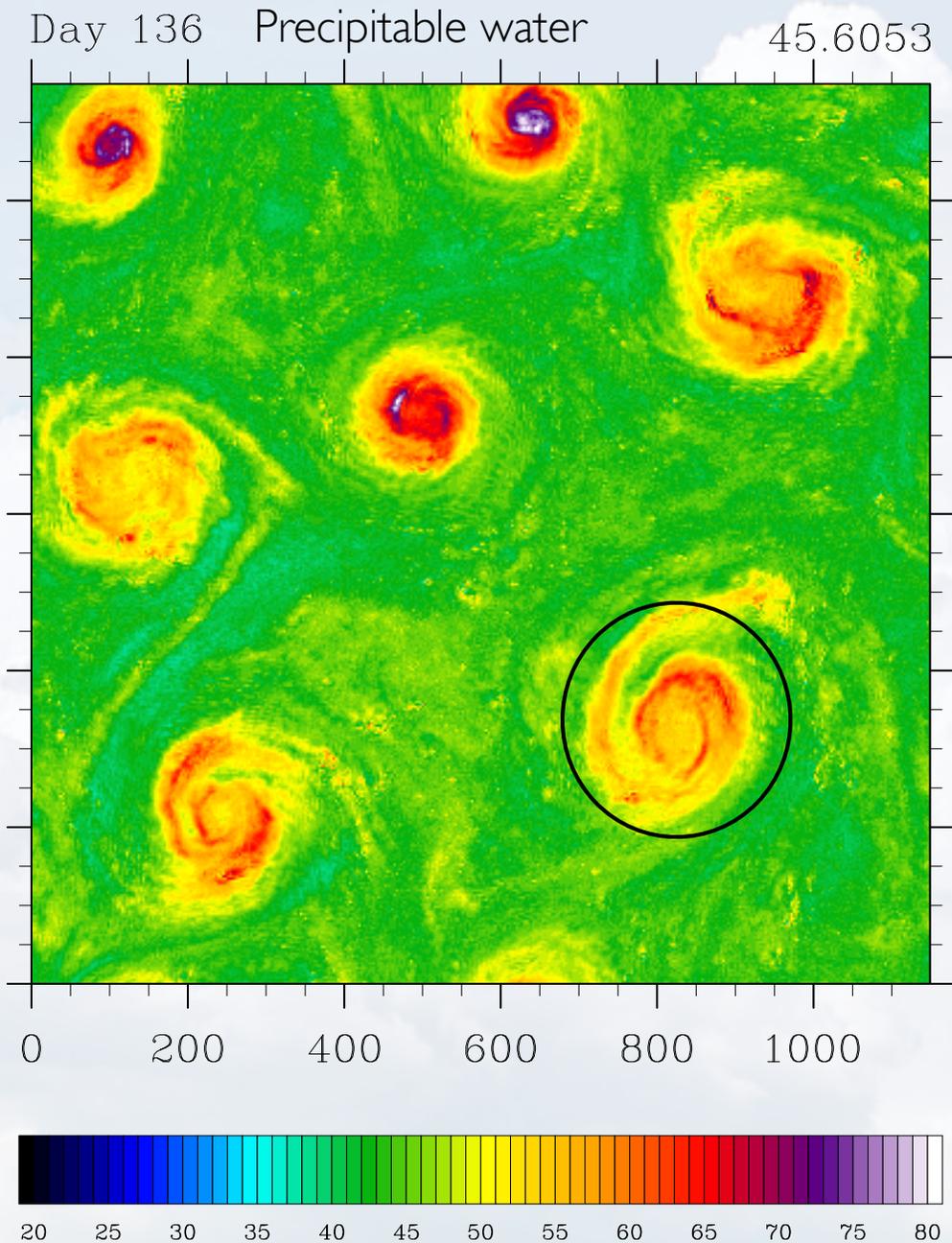
Random convection tends to aggregate into clusters

Increase f to $5 \times 10^{-4} \text{ s}^{-1}$
SST=300K

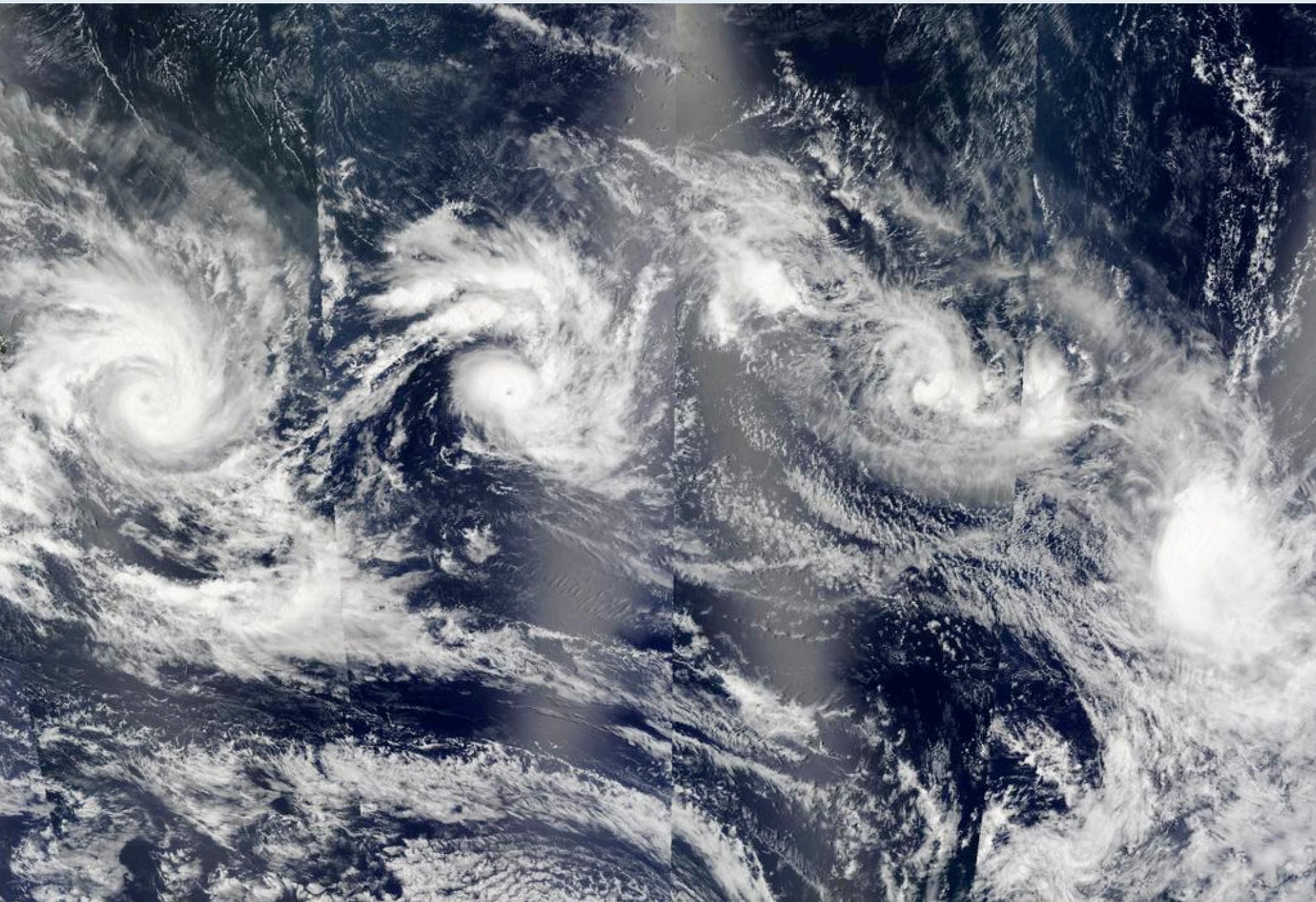
$$\text{TC size: } R = \frac{V_{PI}}{f}$$

$$\text{Number of cyclones: } N \propto \frac{f^2}{V_{PI}^2} \propto \frac{f^2}{T_S^2}$$

$$\text{Maximum Intensity: } V_{PI} \propto T_S$$



It does happen on Earth



Simulations

- **Model: SAM 6.9 with CAM radiation and a single-moment microphysics;**
- **Prescribed fixed SSTs: 294K, 297K, 300K, 303K;**
- **No rotation cases: 384 x 384 x 27 km³, dx=3 km; duration 100 days;**
- **Rotation cases: 768x 768 x 27 km³, dx=3 km; duration 400 days;**
- **Additional larger-domain runs: 1152x 1152 x 27 km³; duration 100 days;**
- **Large Coriolis parameter: $f = 5 \times 10^{-4} \text{ s}^{-1}$**

Omega 500mb

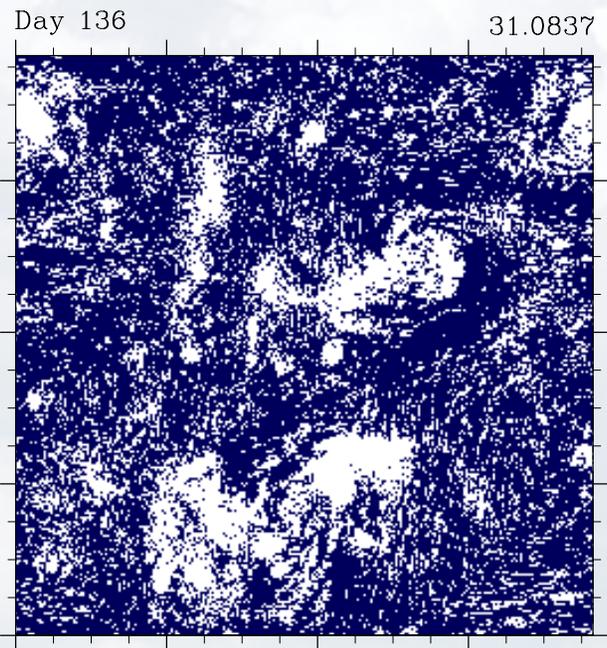
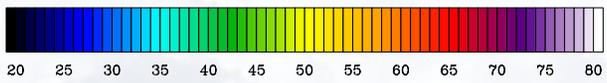
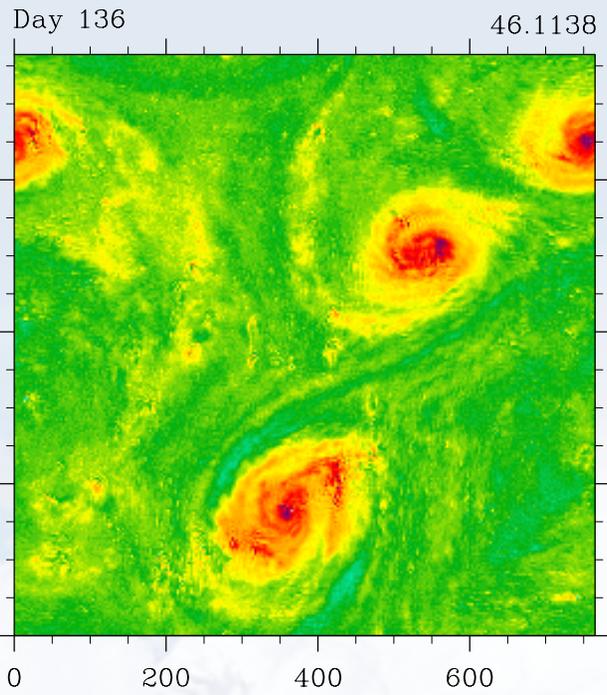
Omega 500mb

Omega 500mb

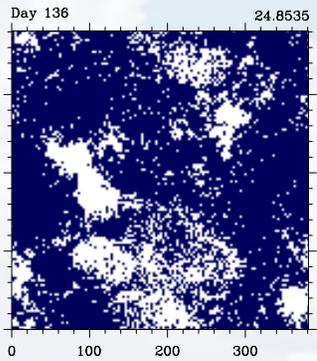
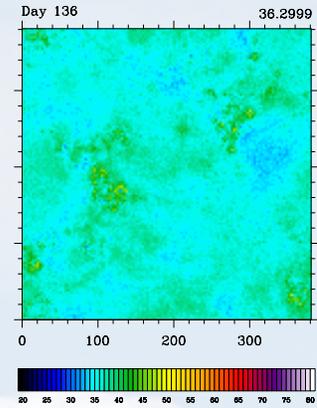
Rotation

SST=300K

No Rotation



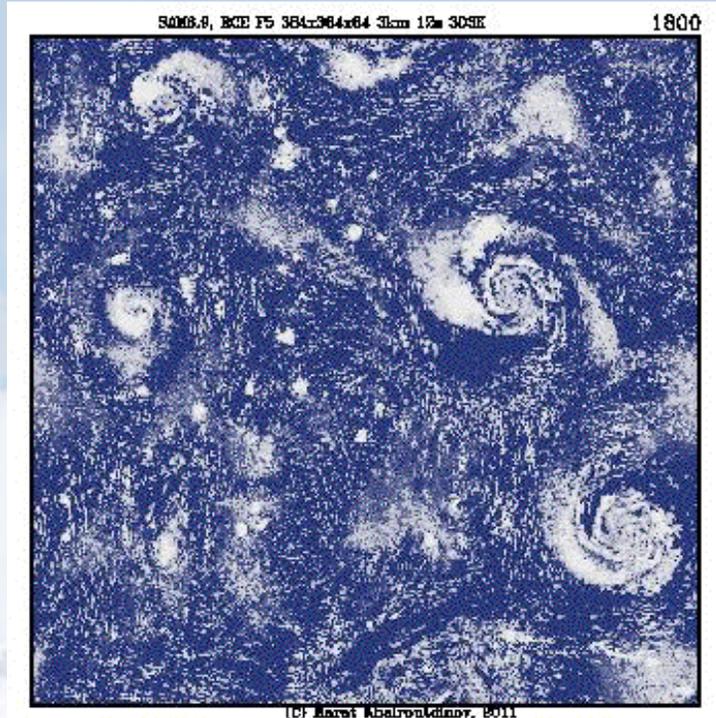
Precipitable water



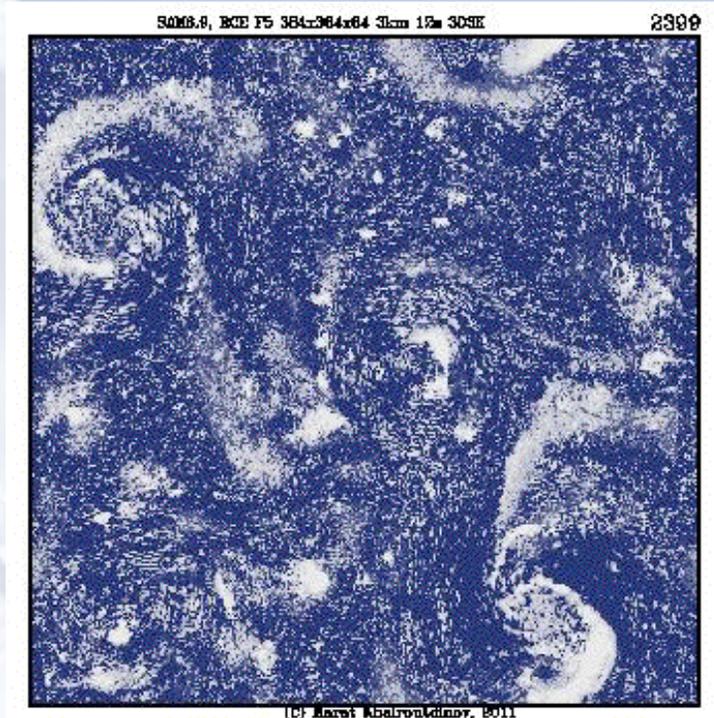
Cloud Mask

RCE with $f = 5 \times 10^{-5} \text{ s}^{-1}$
Domain 1150x1150 km; $dx=3\text{km}$

SST = 303K

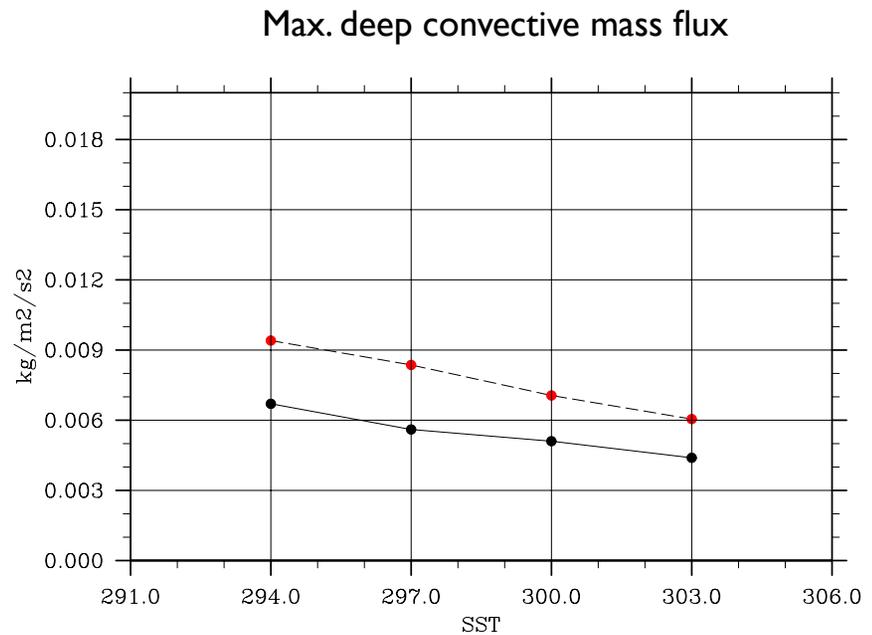
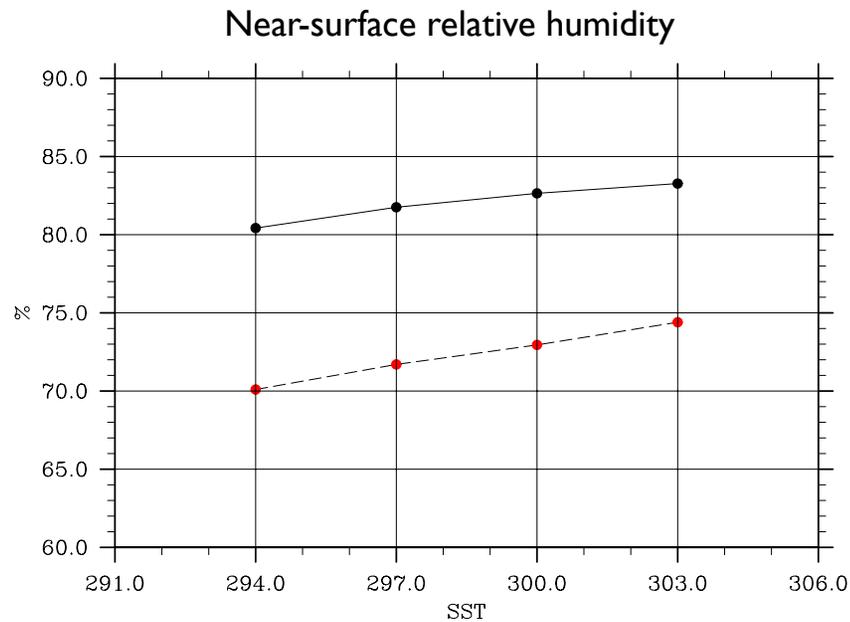
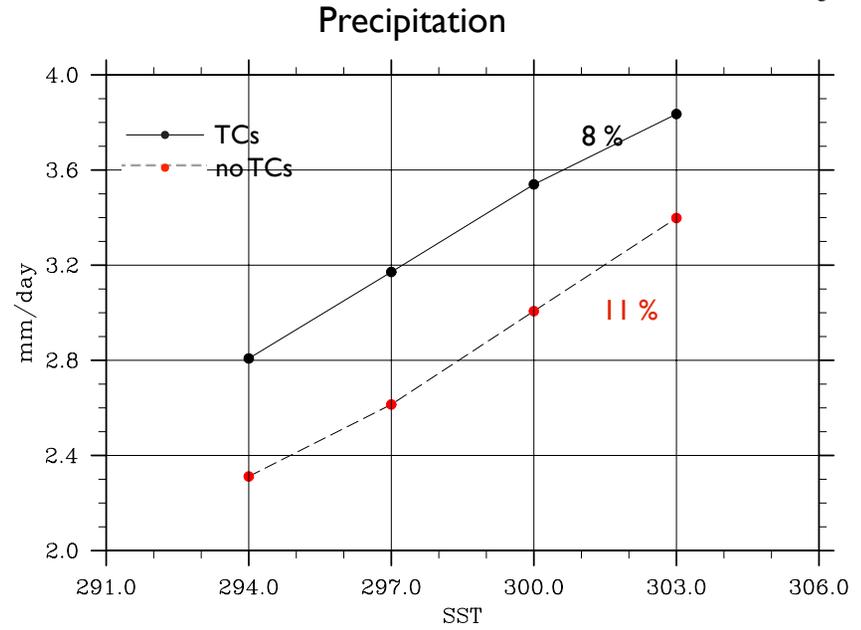
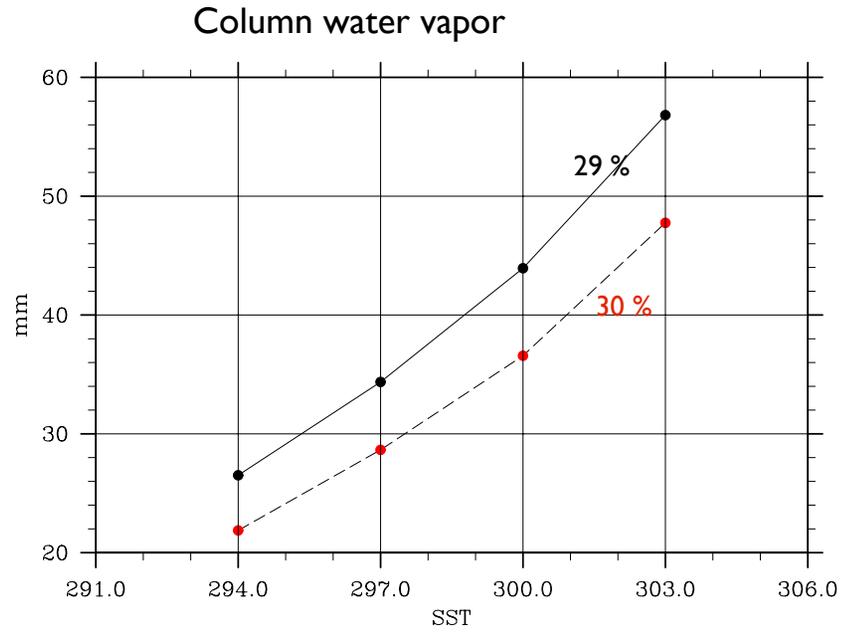


SST = 300K



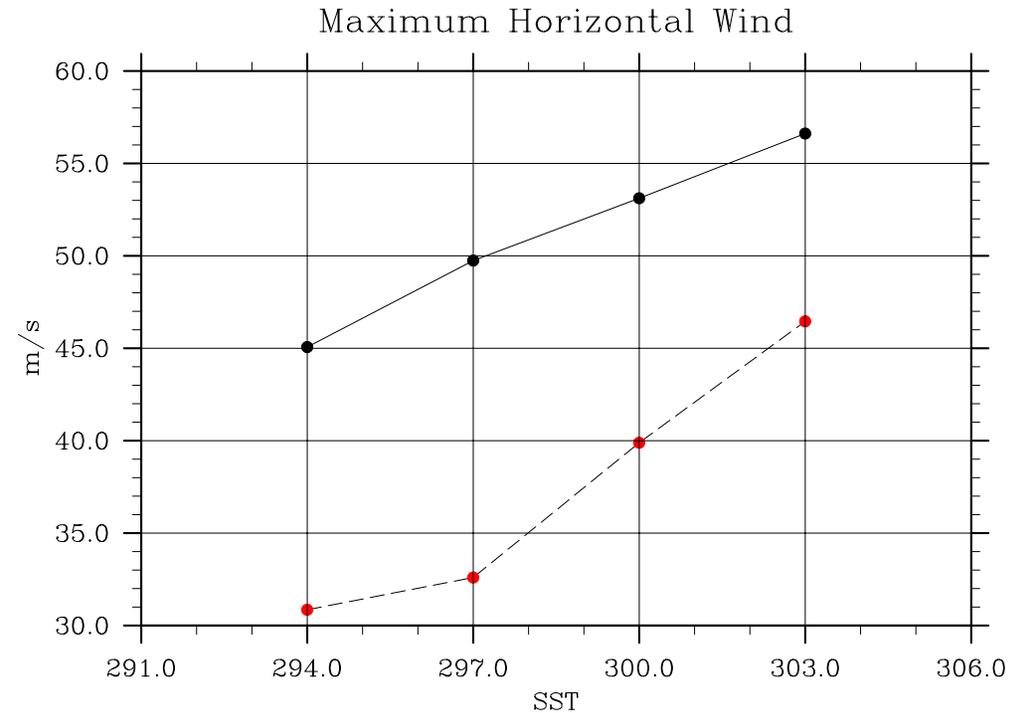
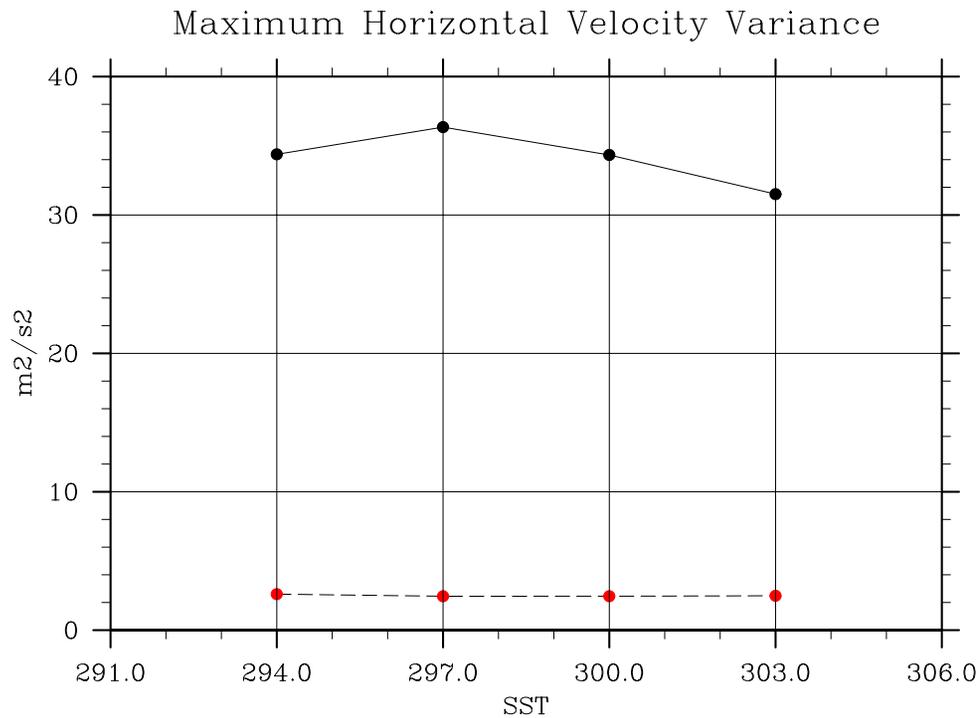
Unexpectedly, precipitating water in RCE with TCs is higher than without them.

$$P \approx M_c q_{pbl}$$



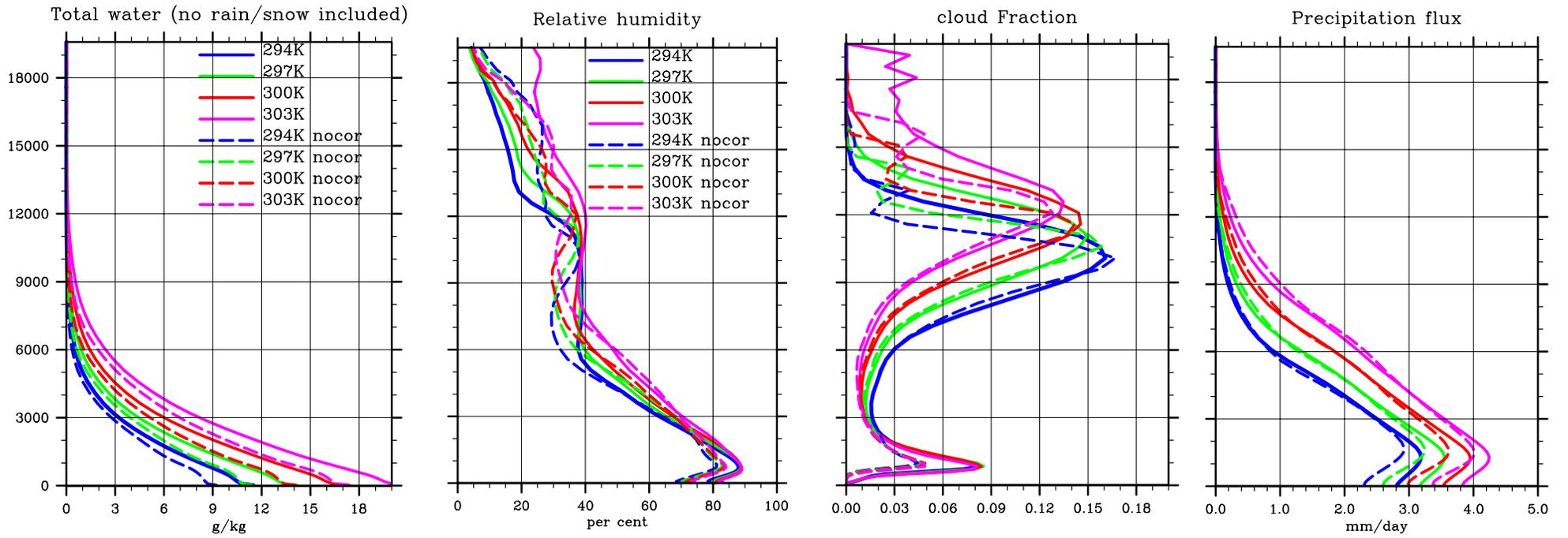
Relative humidity is higher too.

A lot more 'windy' in PBL with abundant TCs spinning around...



$$E = C_E U_h (q_*(T_S) - q_h)$$

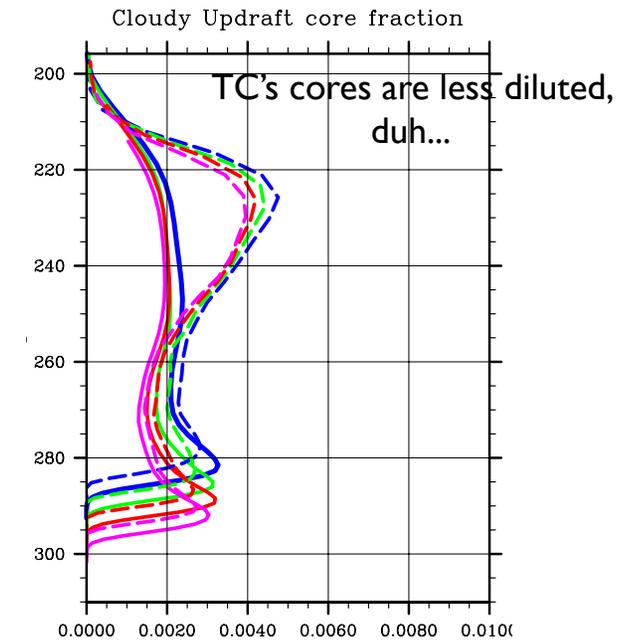
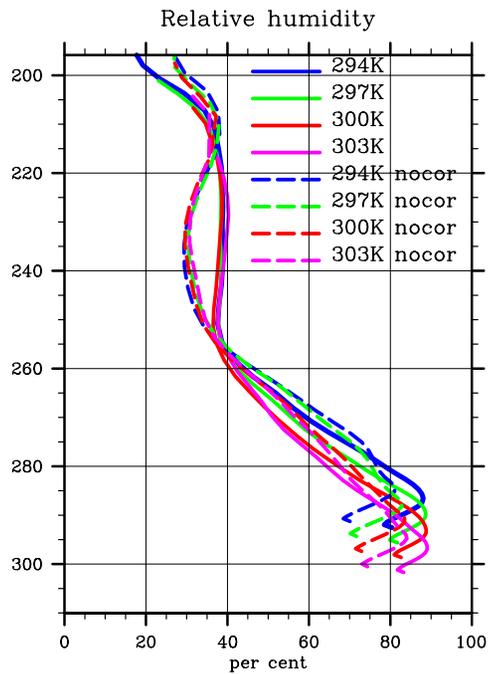
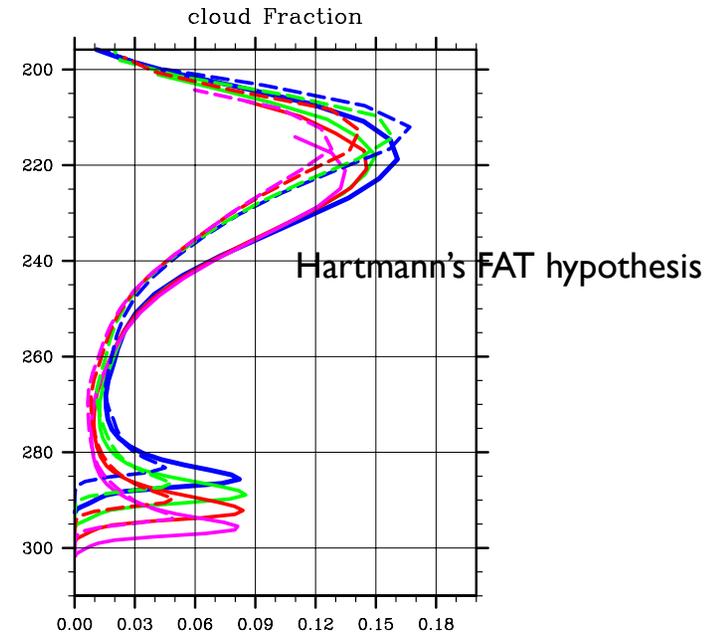
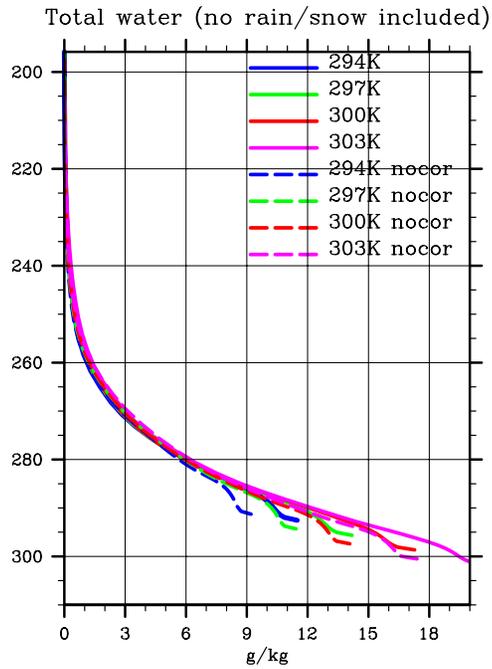
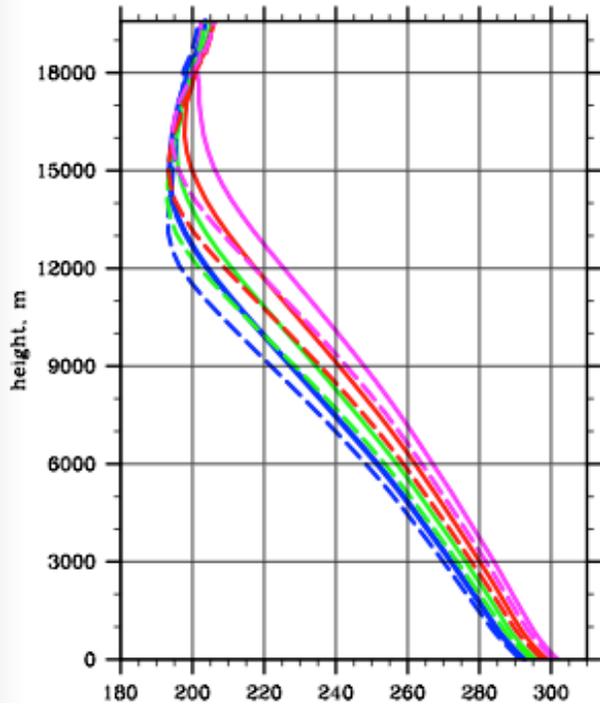
Evaporation from the ocean is largely constrained by the energy budget, but with the near-surface wind being much stronger, the only way to accomplish that is to moisten the PBL



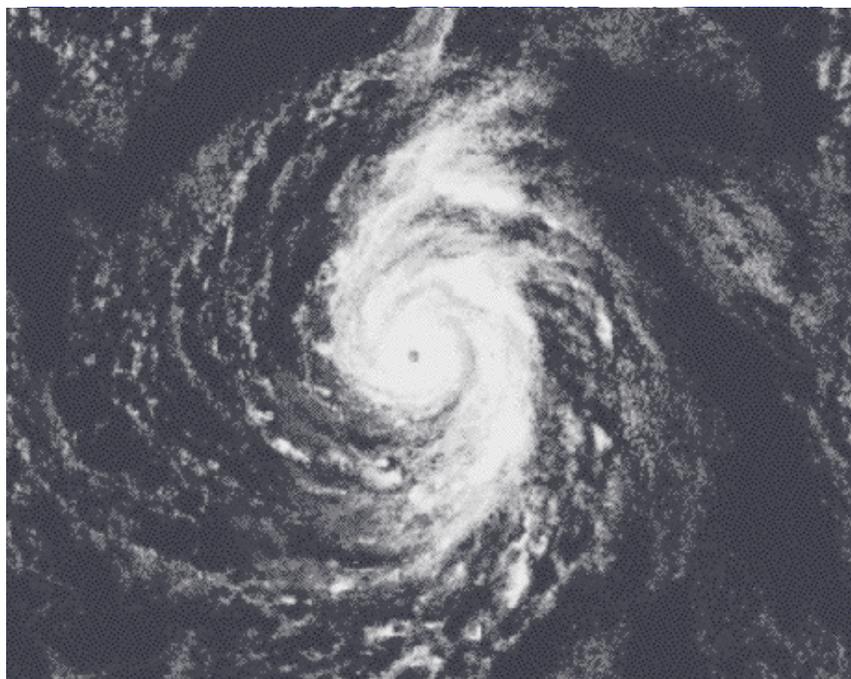
All the profiles are time averages over the last 2/3 of each run.

Using temperature as the vertical coordinate:

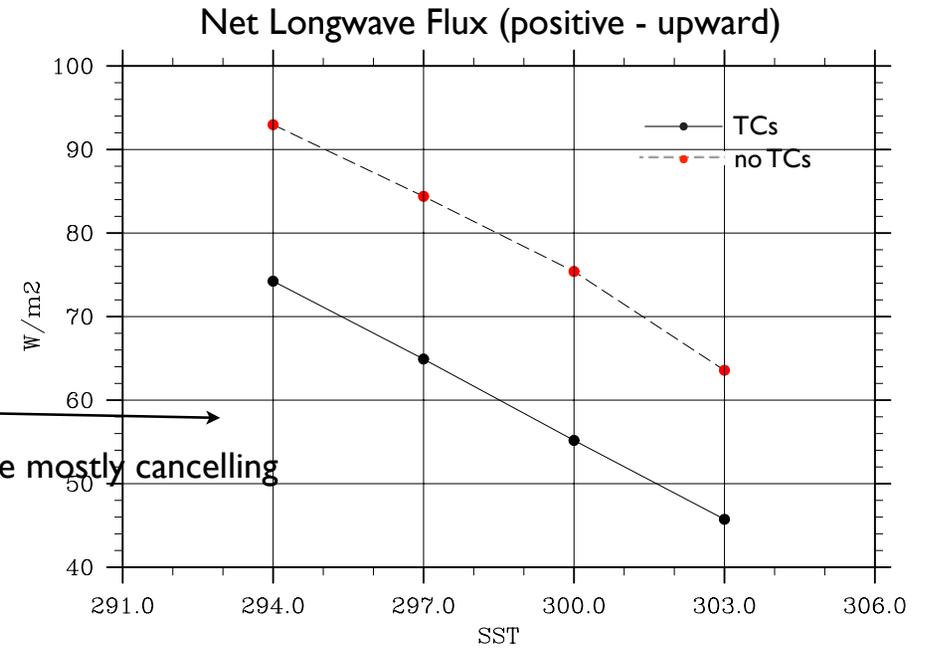
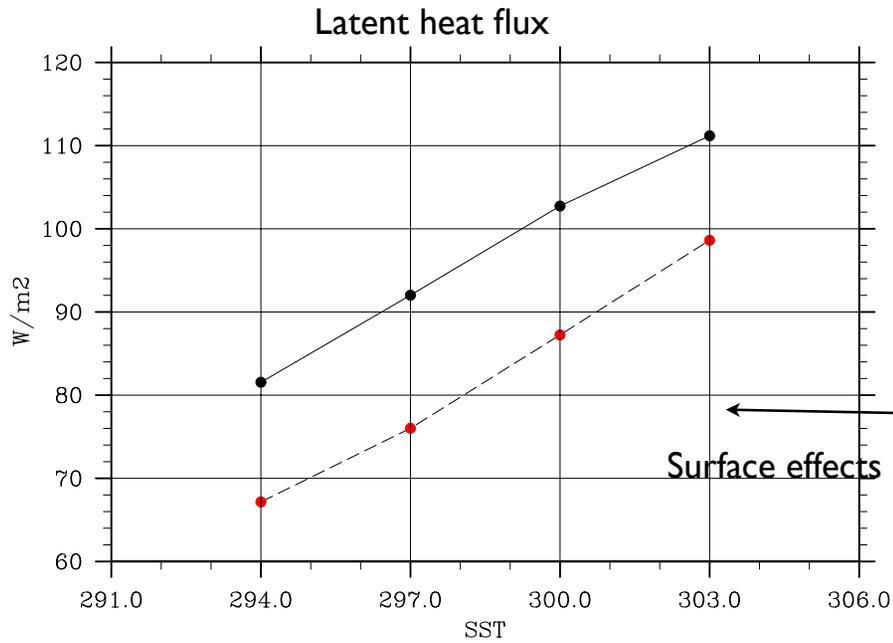
Troposphere with TC's
is also warmer



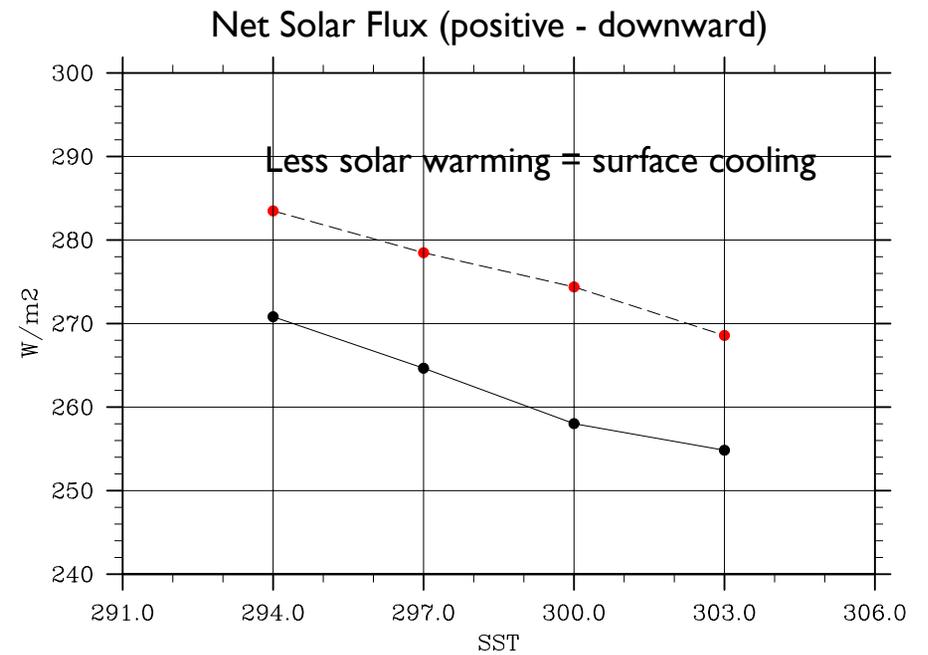
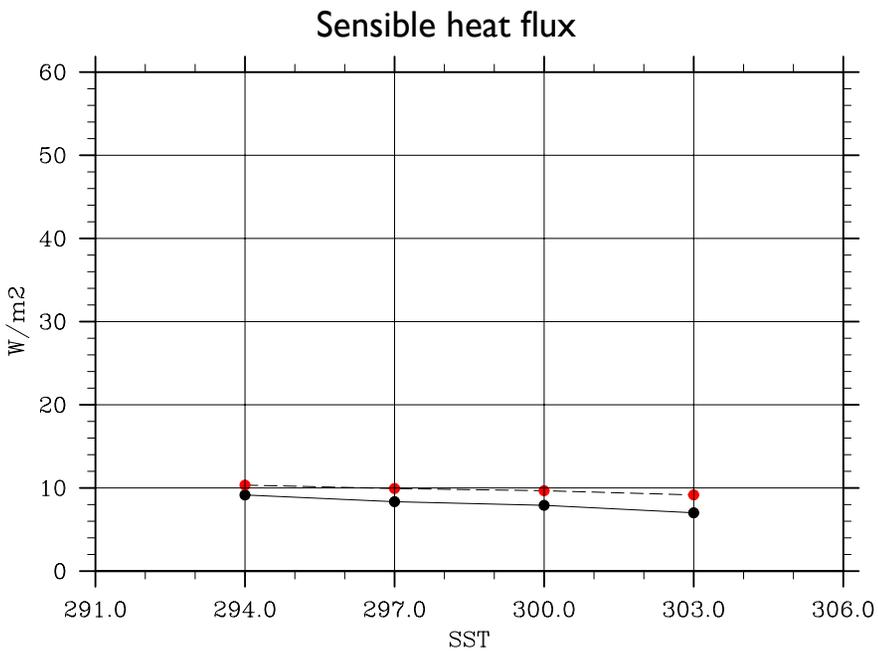
Observed TCs are surrounded by shallow/congestus clouds



Components of the surface energy balance

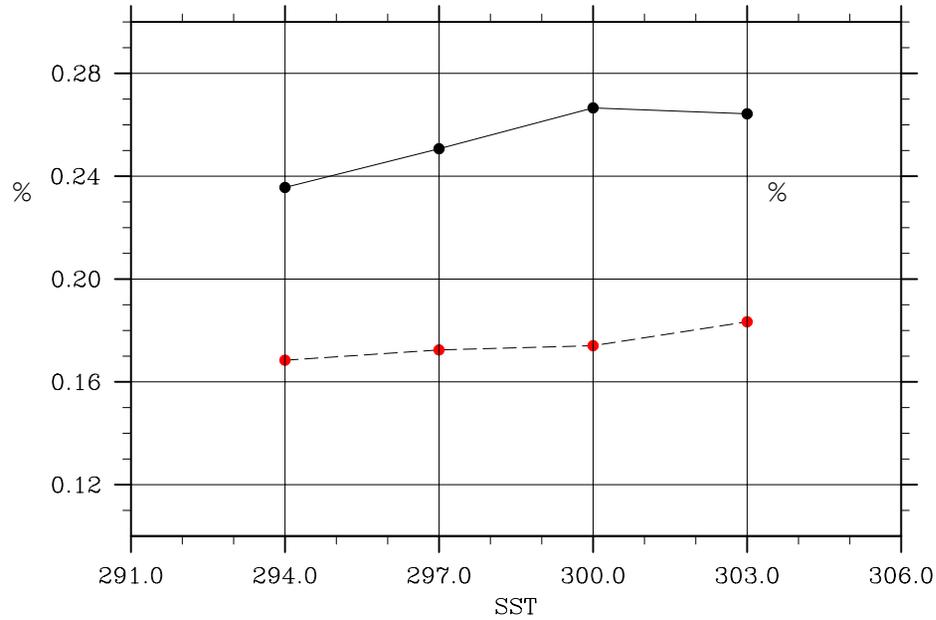


Surface effects are mostly cancelling

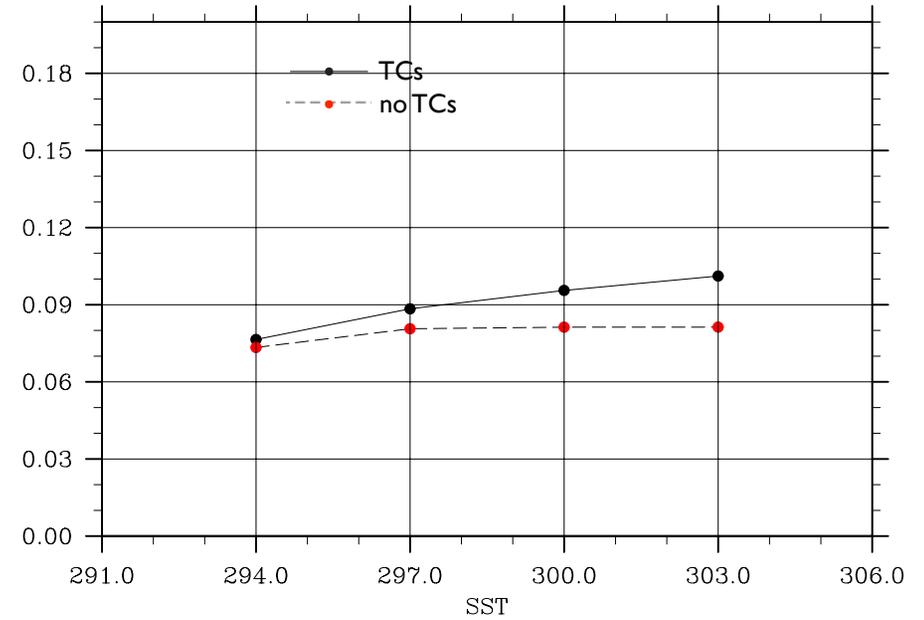


It is the shallow clouds that are different... Environment with lots of TCs favors more shallow convection?!

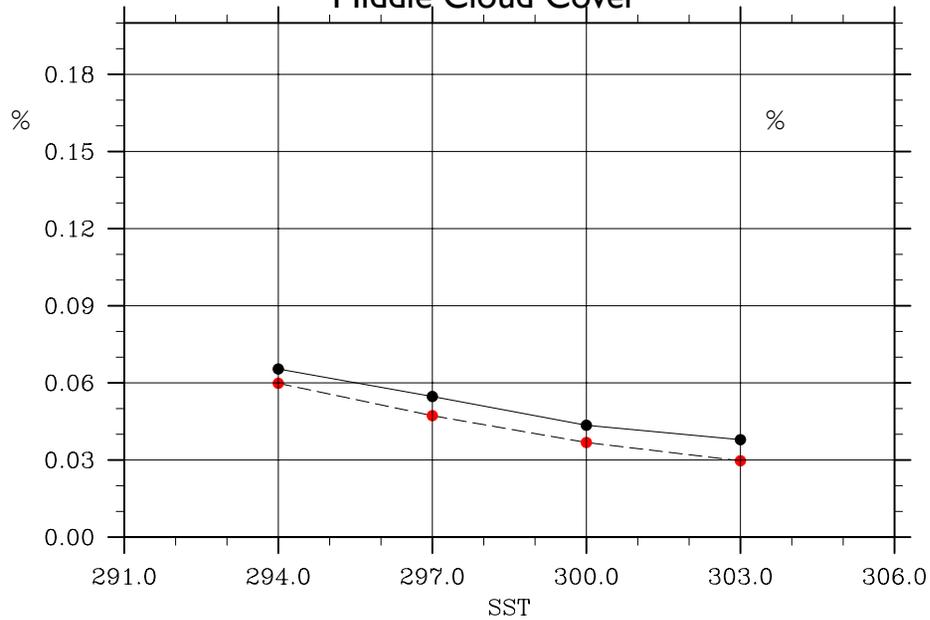
Total Cloud Cover



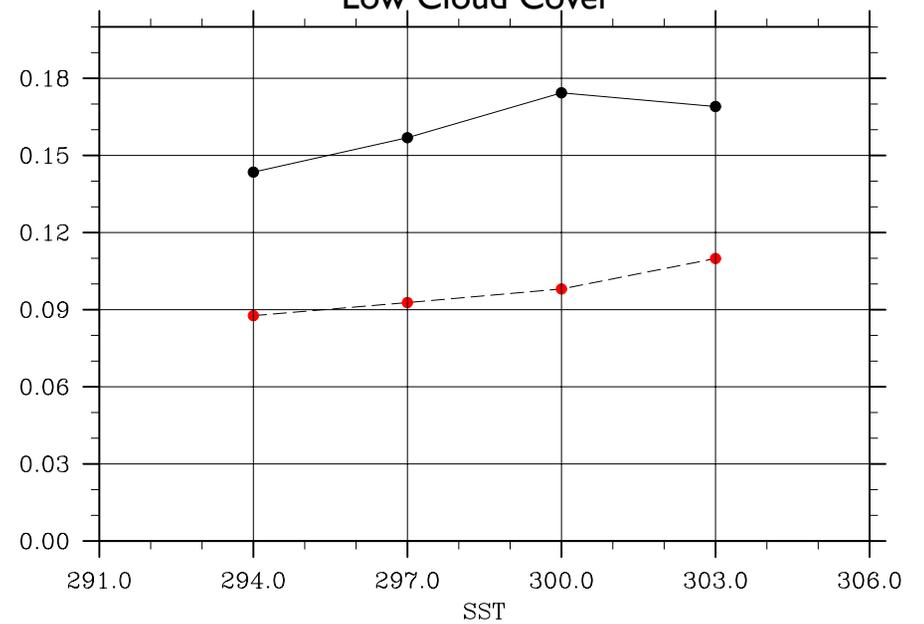
High Cloud Cover



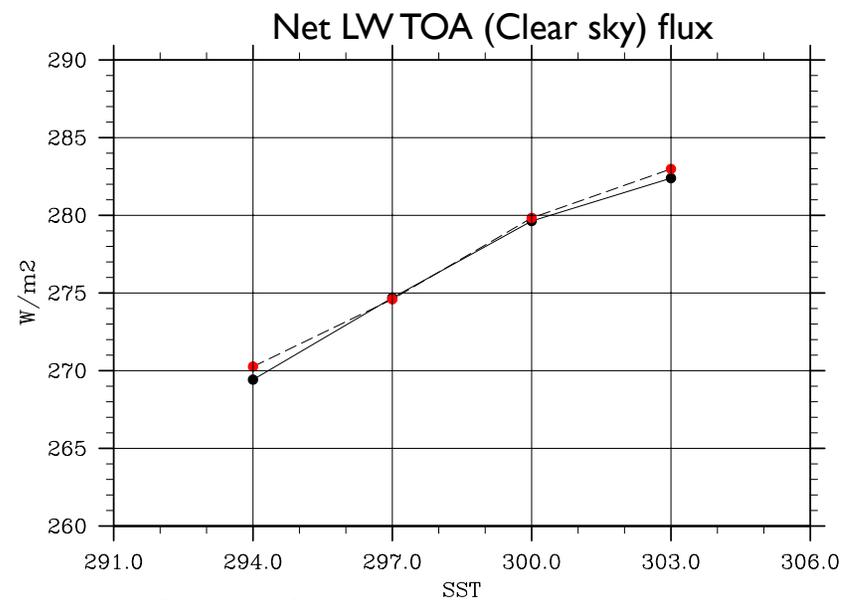
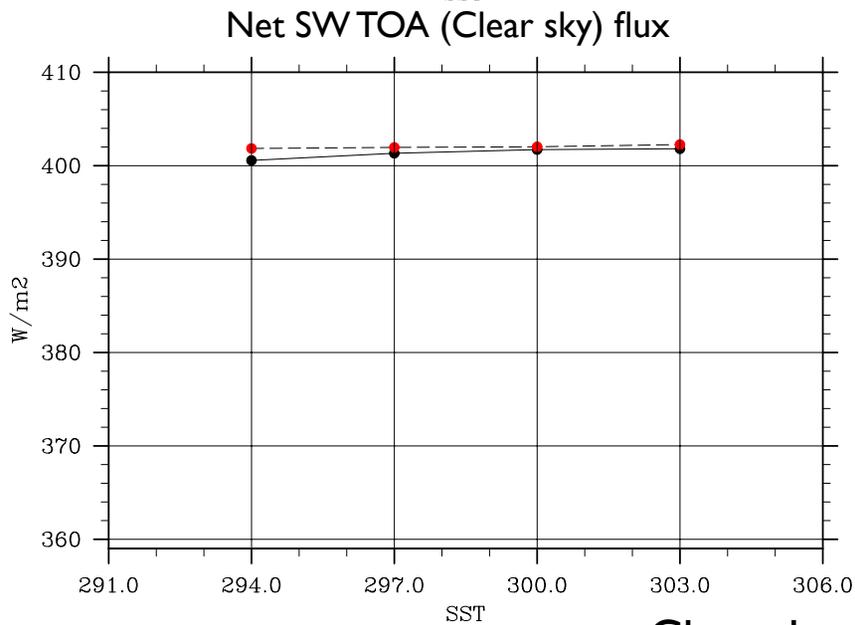
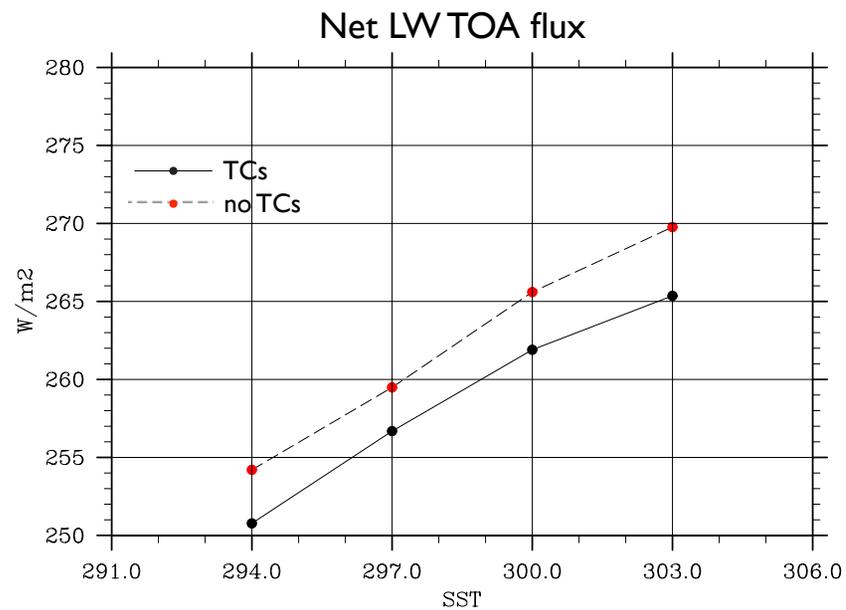
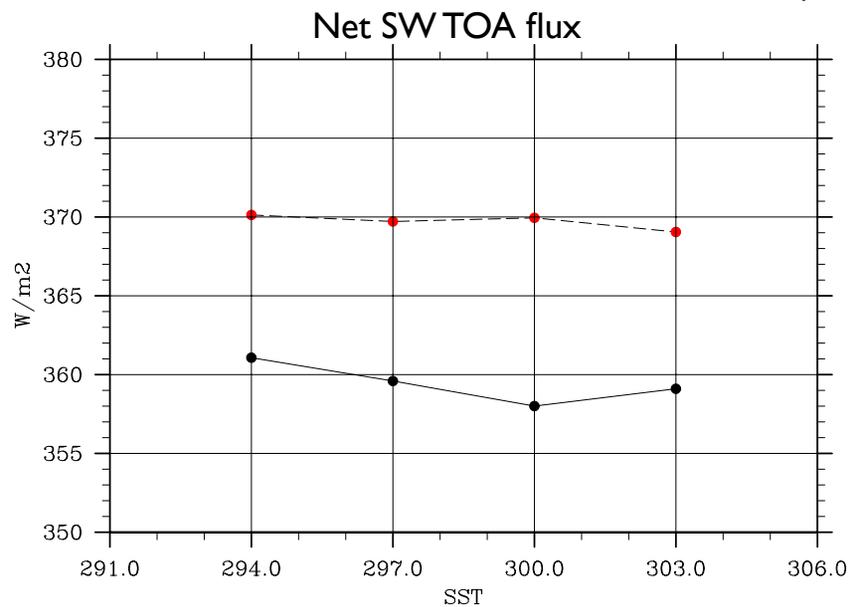
Middle Cloud Cover



Low Cloud Cover



It's all (low) clouds' fault



Clear-sky effect are identical

Hypothesis 1

Warming SSTs
Self-aggregation of convection
Drying of the Troposphere
Reduction in Greenhouse Effect

Cooling SSTs
Disaggregation
Re-moistening of the Troposphere
Restoration of Greenhouse Effect
Restoration of SSTs

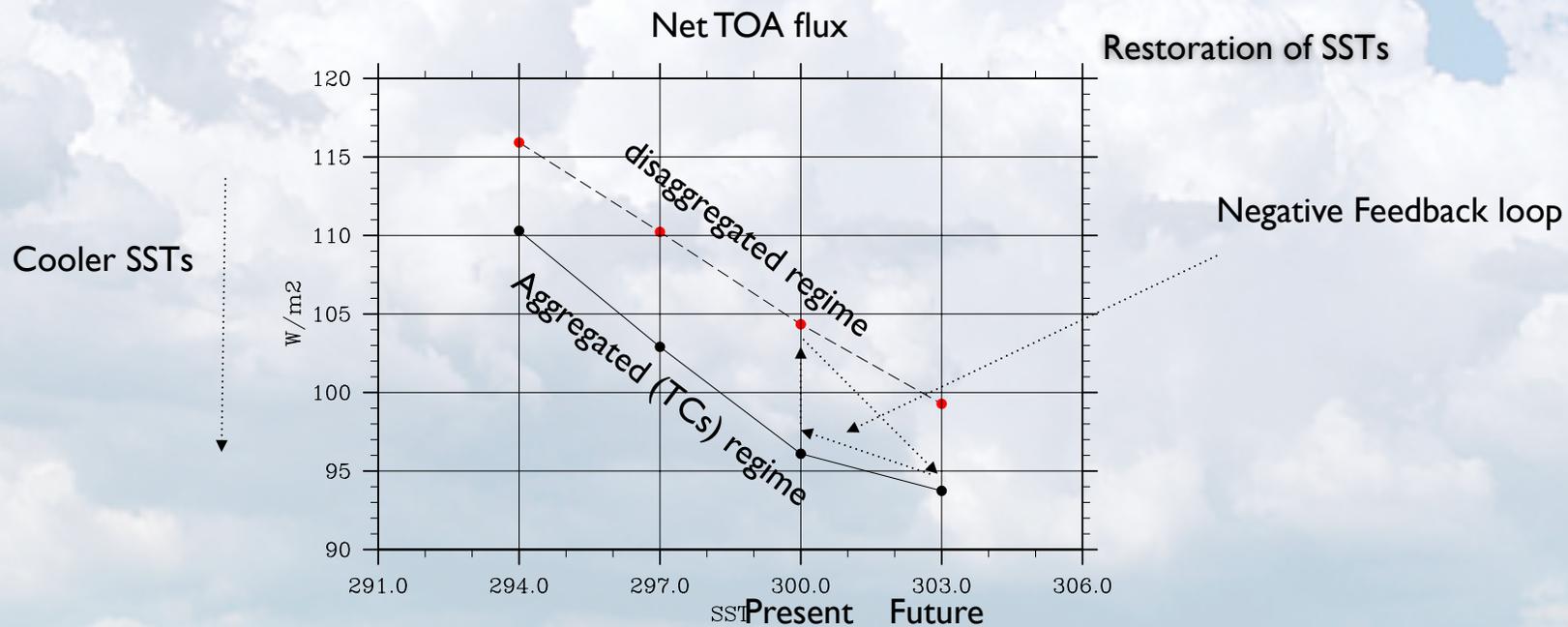
Hypothesis 2

Warming SSTs
Increase in number of TCs
Increase of subsidence over shallow clouds regions

Increase in gustiness in PBL
Moistening of troposphere and PBL

Increase of shallow cloud amount and water content

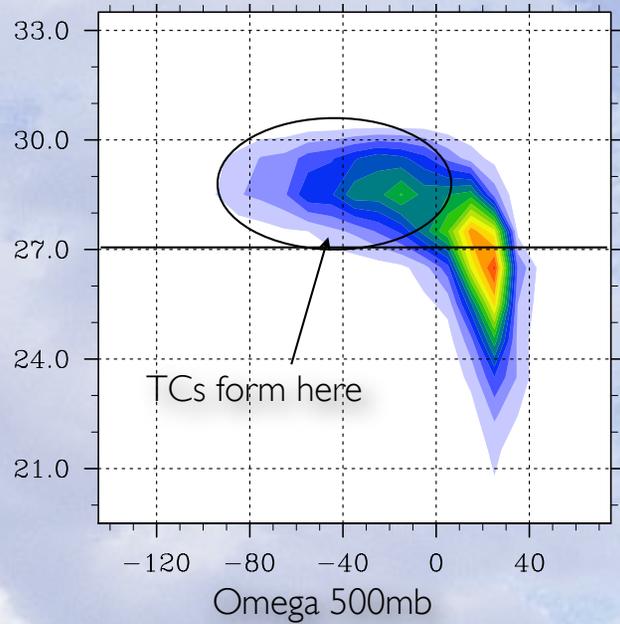
Increase of cloud albedo
Cooling SSTs
Decrease in number of TCs (disaggregation)



Joint PDF of Omega500 and SST (Monthly, ocean-only; 20°S - 20°N) SPCAM time-slice simulations

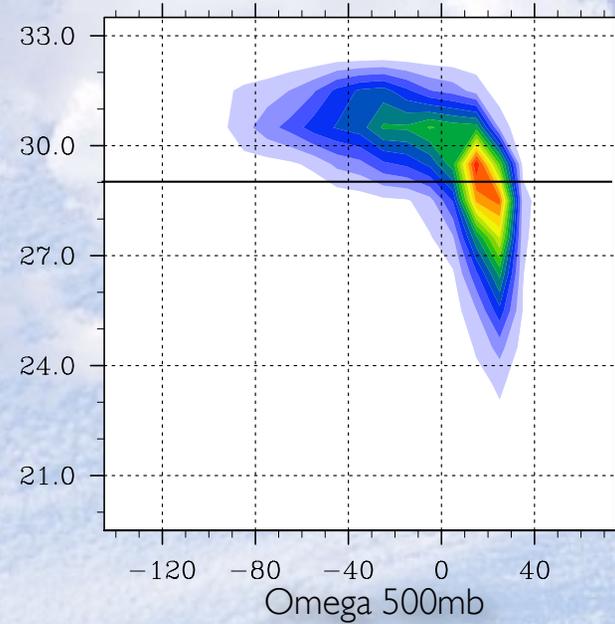
Present SSTs

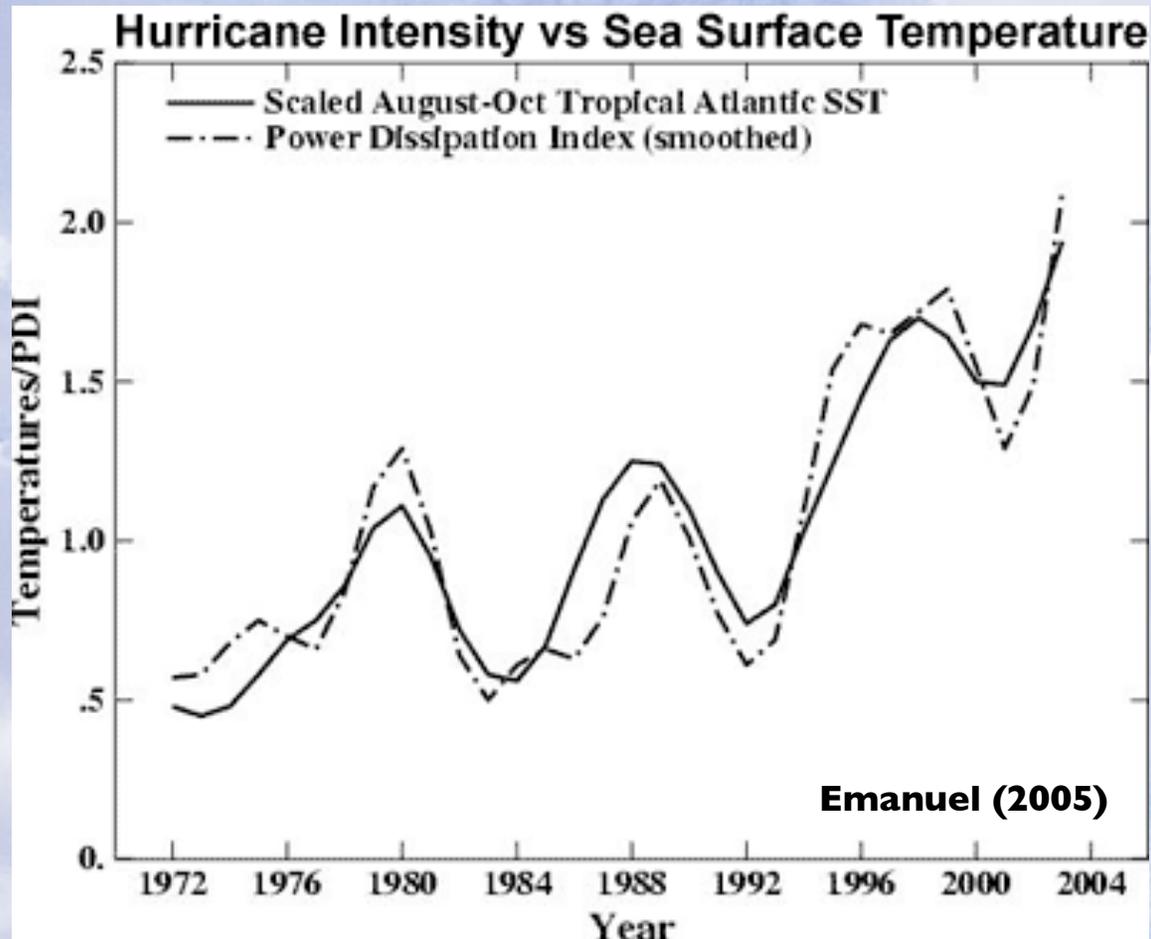
2000-2009 obs SST



AR4 Projected Future SSTs

2090-2099s:AR4 SST;





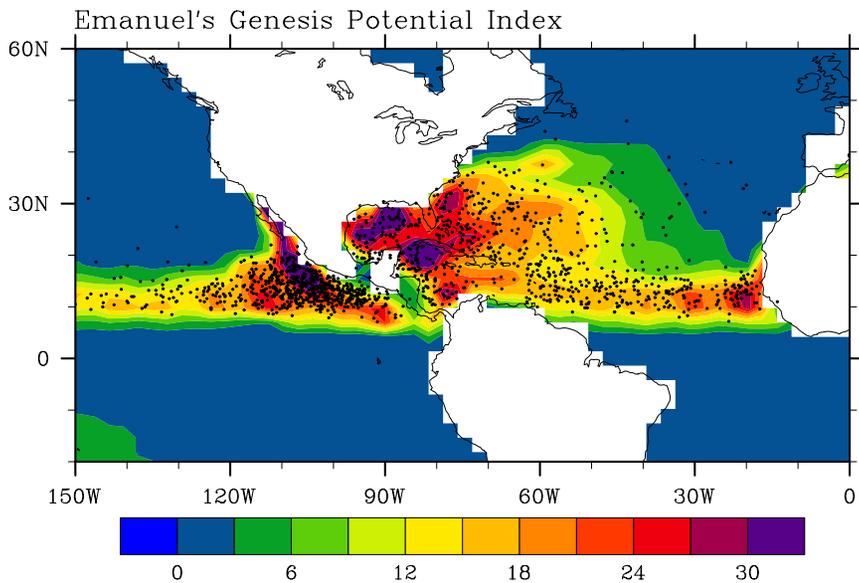
The intensity and, possibly, frequency of TCs in the warming climate is likely to increase.

What is the effect of such a change in the regime of convection on the climate sensitivity of the Tropics?

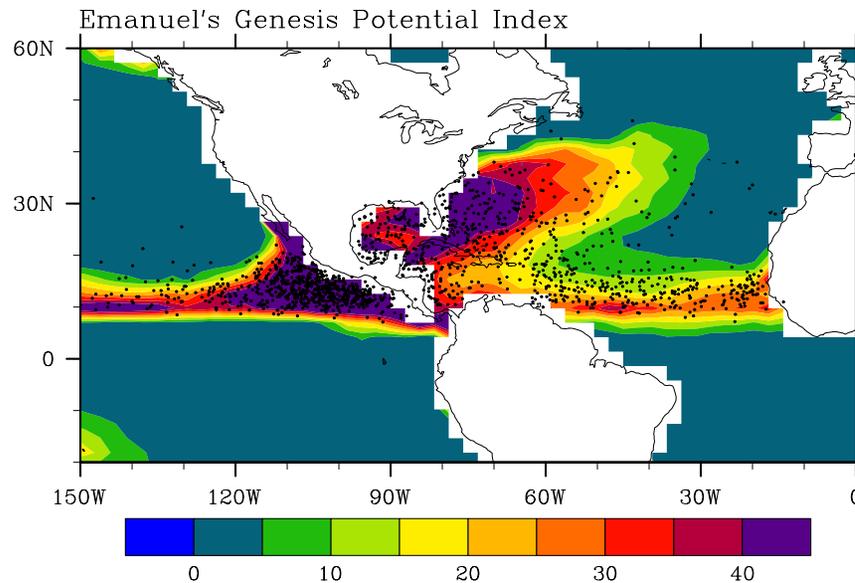
The effect of possible regime change to more TC's is not included in the current generation of the IPCC GCMs.

Genesis Potential Index (GPI) for August-September-October mean conditions

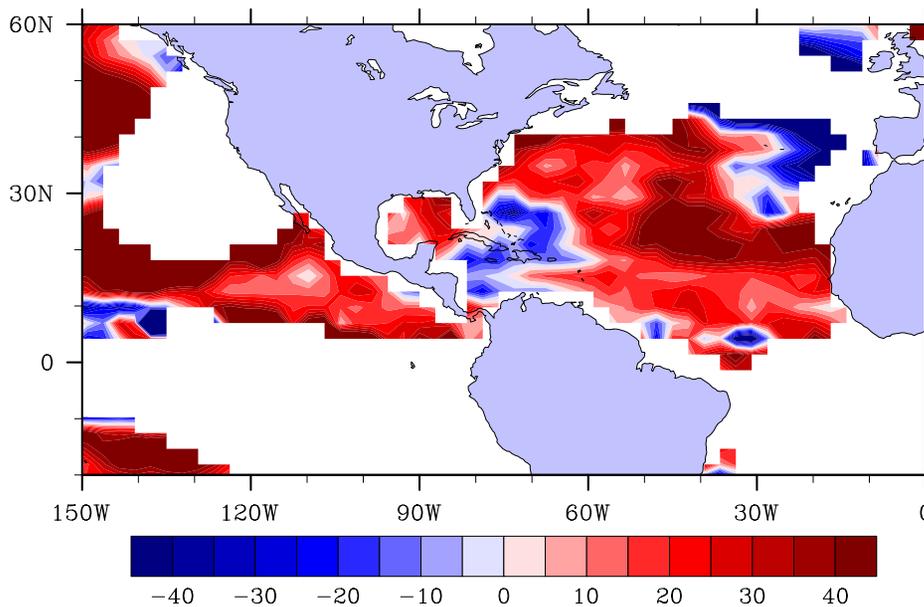
Based on ERA40



SP-CAM



GPI Change in the future (% from present) as simulated by the SP-CAM



Potentially more tropical
cyclones
in the future as the
world keeps warming

Real message here is that ...

- **The physics involving self-organization of tropical convection are currently not represented in IPCC GCMs as their parameterizations currently represent only disaggregated convection;**

