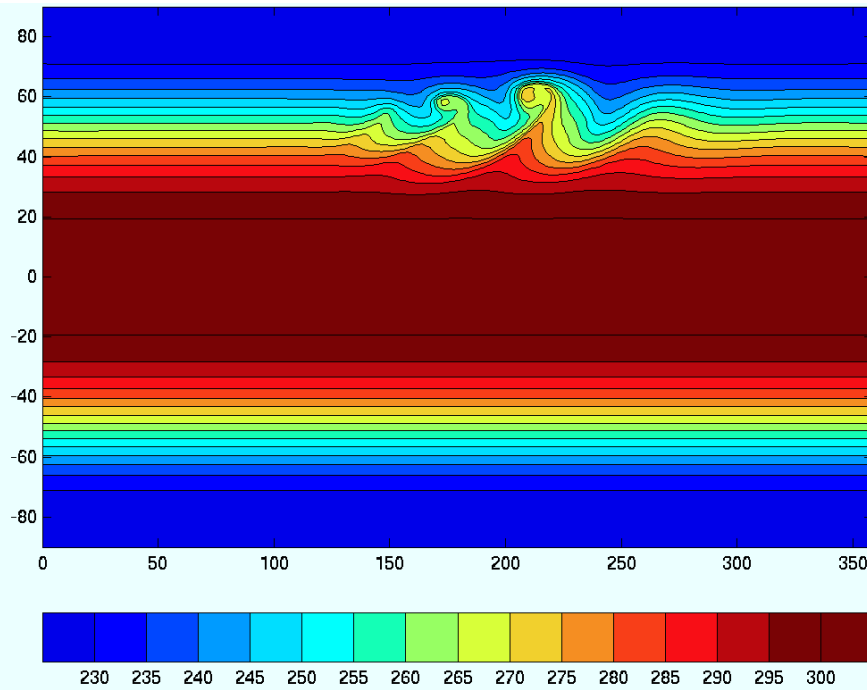
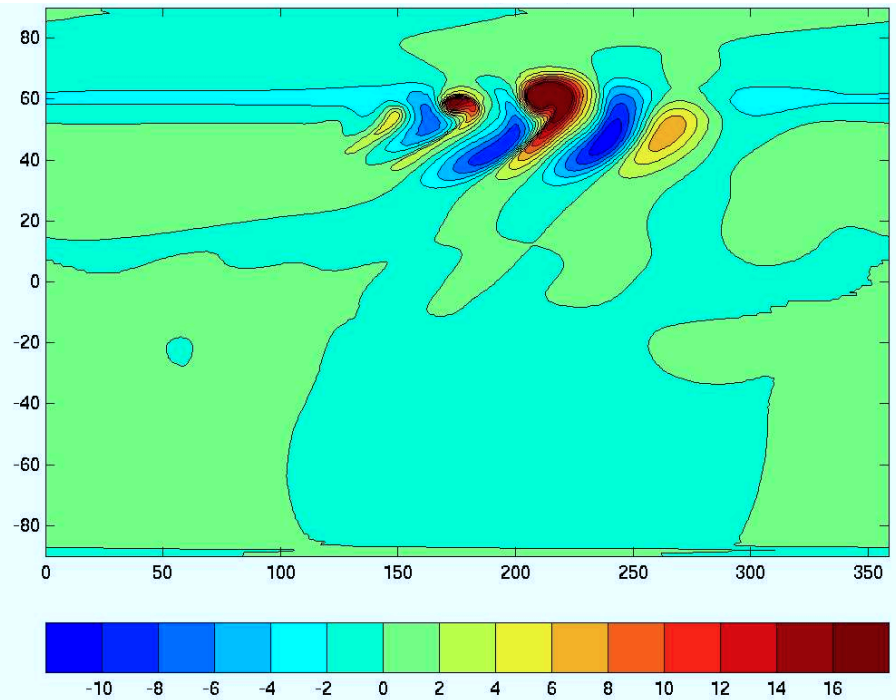


850hPa Temperature

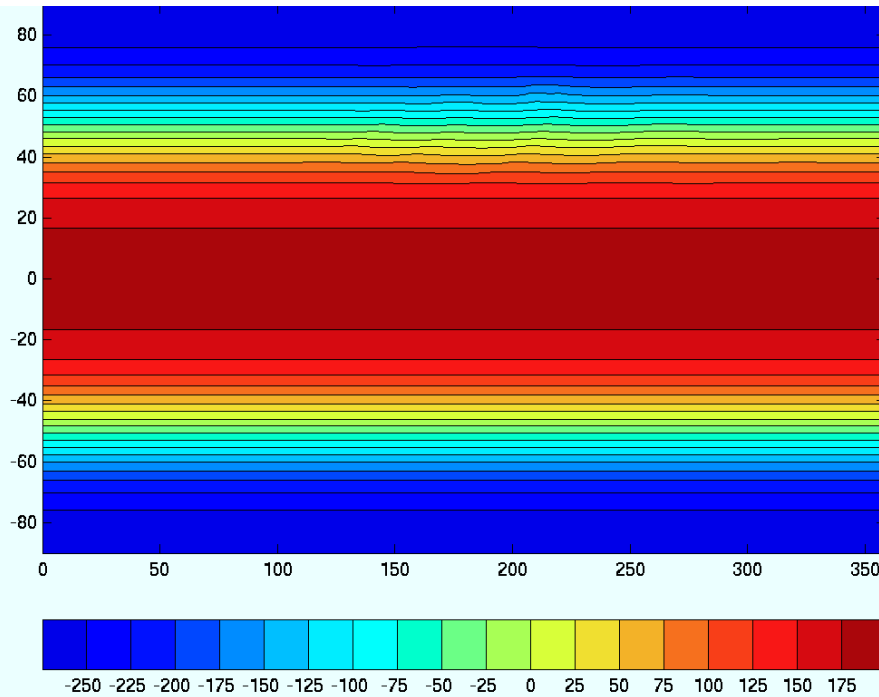


850hPa “Eddy” Temperature
= departure from zonal mean

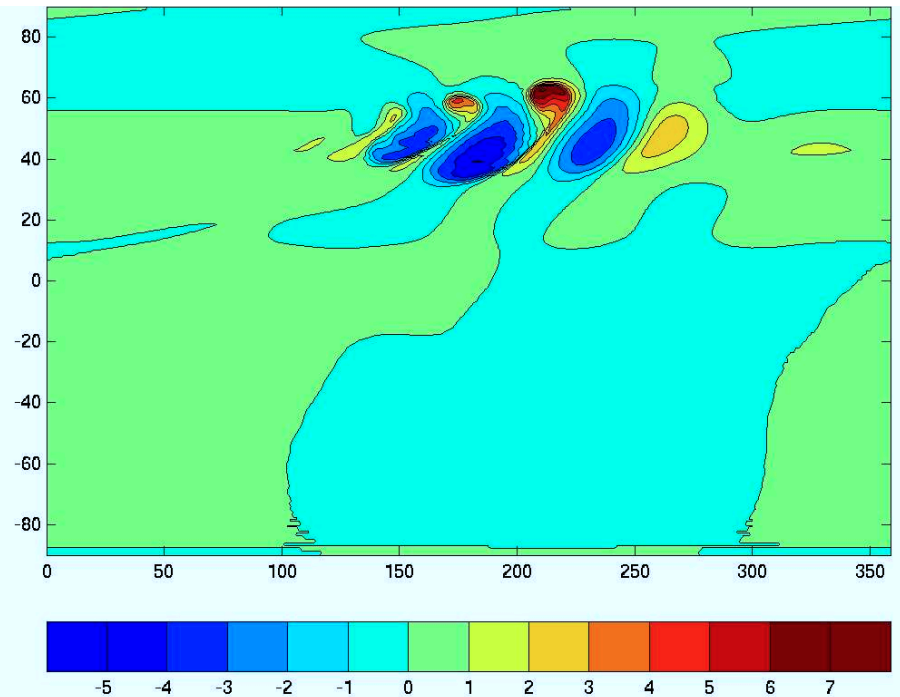


From Baroclinic Wave HW2-3 illustration of eddy temperature

Height of lowest model level

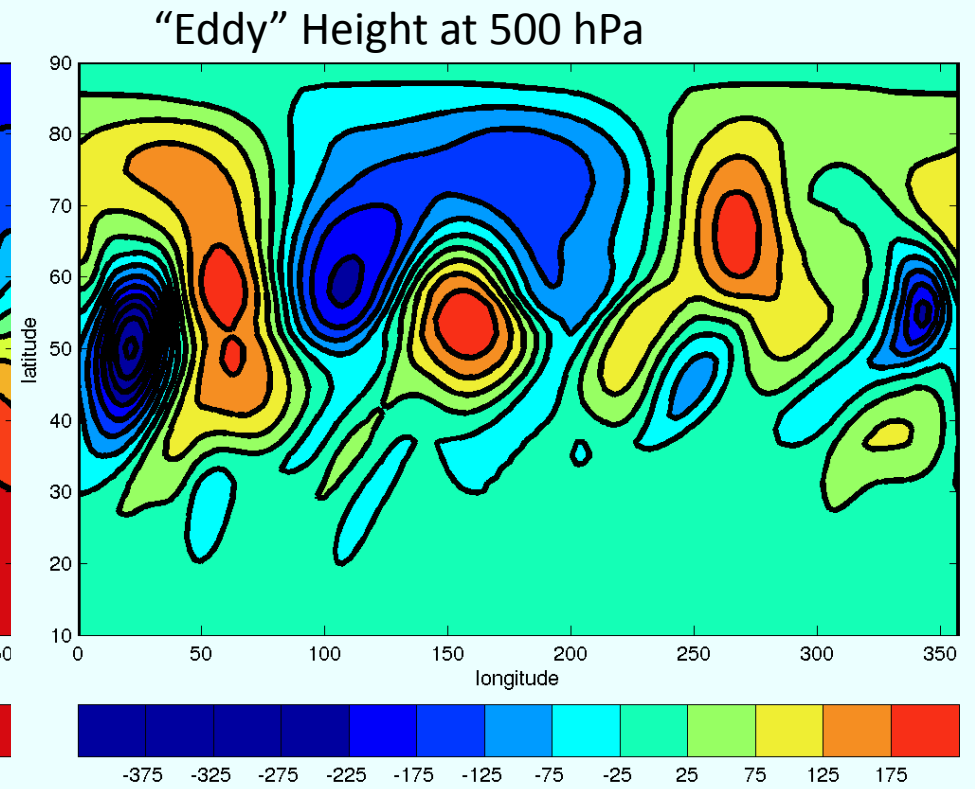
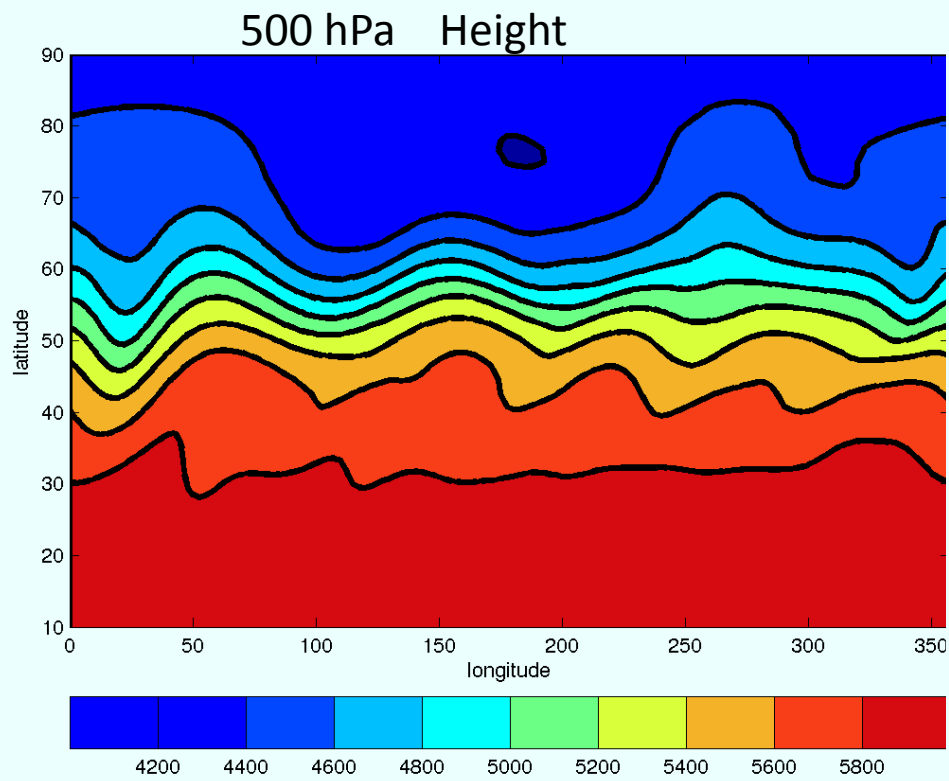


“Eddy” Height of lowest model level



From Baroclinic Wave HW2-3 illustration of eddy height

Also note that the height on left appears to have very little wave, but this is because the pole-to-equator gradient is very large. Removing the zonal mean (as in the eddy height) reveals the wave.



From Baroclinic Wave HW2-3 illustration of eddy height

Hierarchy of atmospheric general circulation models

Adiabatic-only: Dry physics, no radiation, and no surface fluxes of heat/moisture. However this model permitted topography, and we had a zonally symmetric broad ridge around the equator and valleys at the poles. Technically this is not an aqua-planet because of the topography and because there is no evaporation anyway.

Advantage – simpler behaviors and possible to start with balanced initial conditions (the solution is known)

Disadvantage – not realistic.

Aqua-planet: A model with no topography and ocean everywhere. It wouldn't make sense to have dry physics in the atmosphere.

Flat-land (I made this up): **A model with no topography and land everywhere.** Could be adiabatic-only or with moist physics.

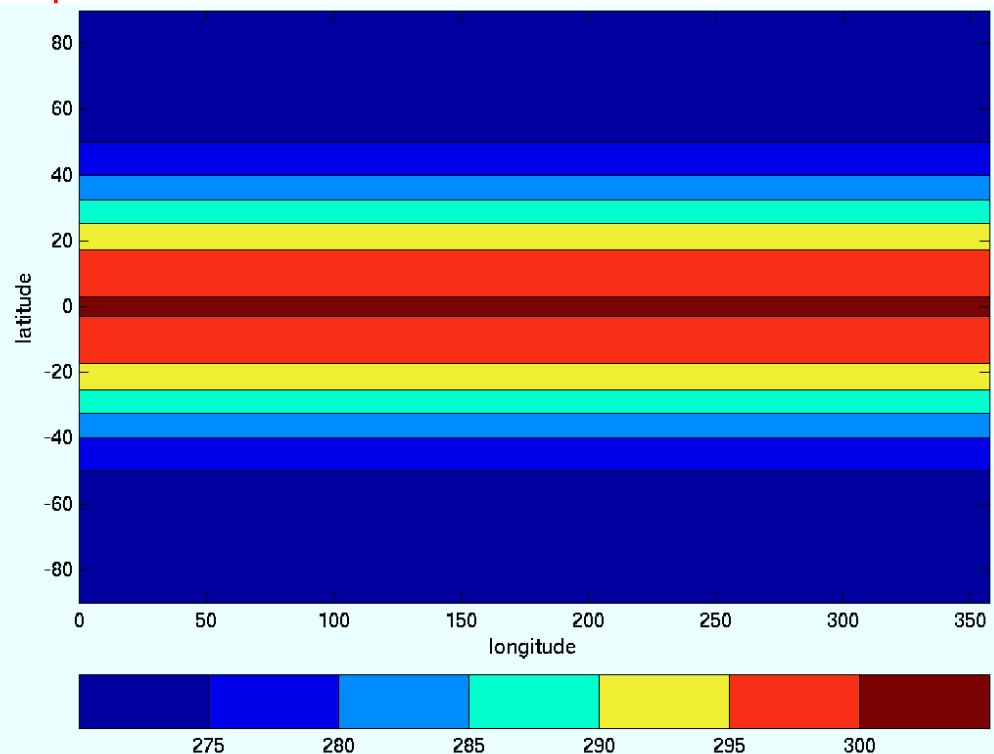


<http://www.met.reading.ac.uk/~mike/APE/>

We prescribed the sea surface temperature from the project. It comes from the following equation where ϕ = latitude

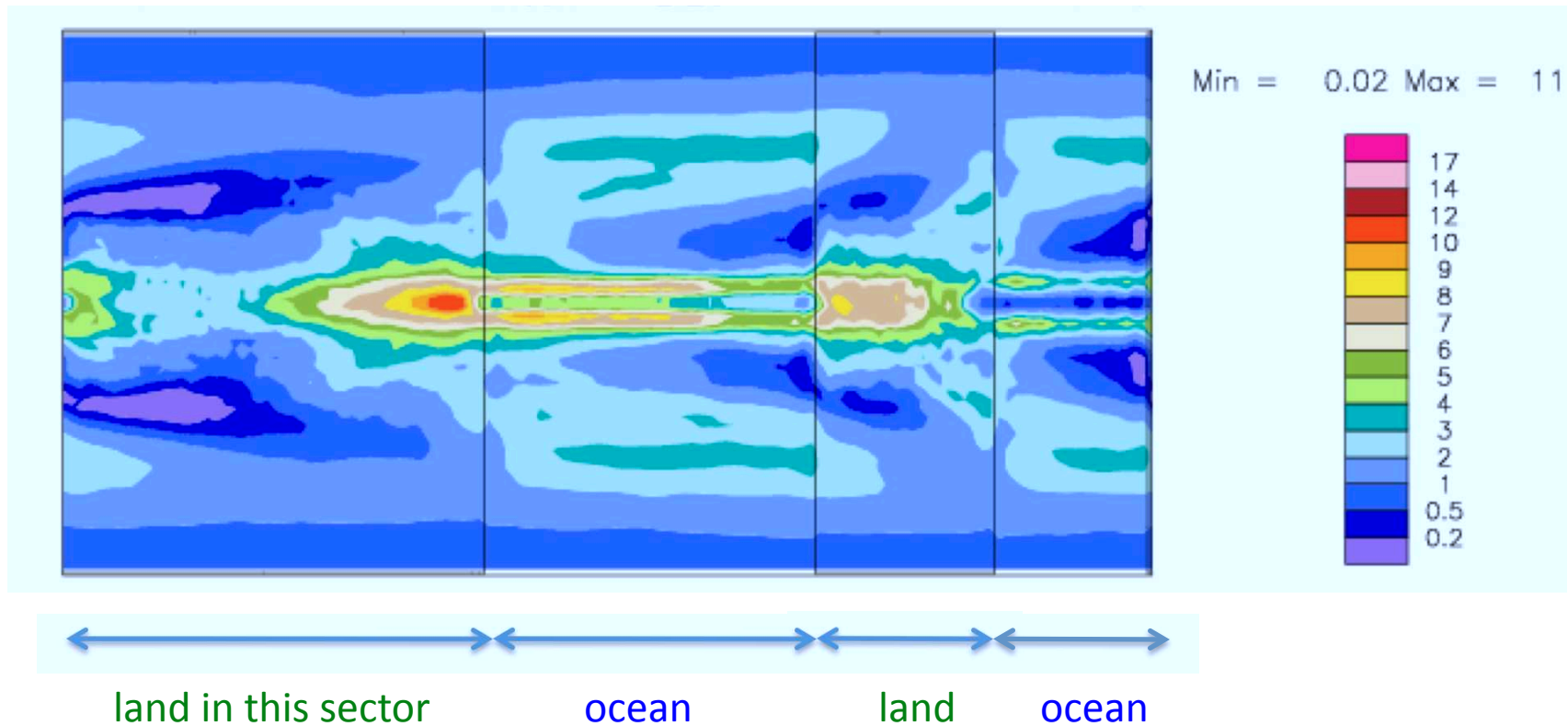
SST =

$$\begin{cases} 27 \left(1 - \sin^2 \left(\frac{3\phi}{2} \right) \right) ^\circ\text{C} & ; \quad 60^\circ\text{S} < \phi < 60^\circ\text{N} \\ 0^\circ\text{C} & ; \quad \text{otherwise} \end{cases}$$



Hybrid of aqua-planet and flat-land (just messing around)

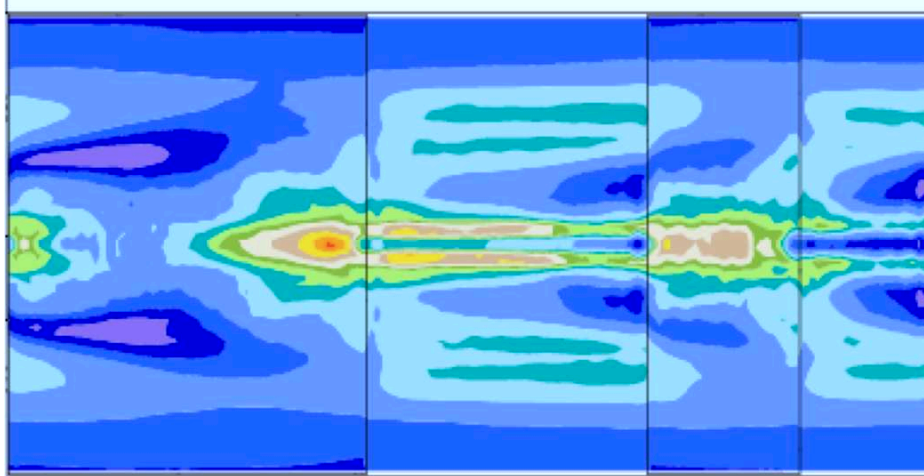
Annual mean precipitation Rate in mm/day



These “oceans” are pools of 50m deep water, rather than prescribed SST as in your runs

Annual mean precipitation Rate in mm/day

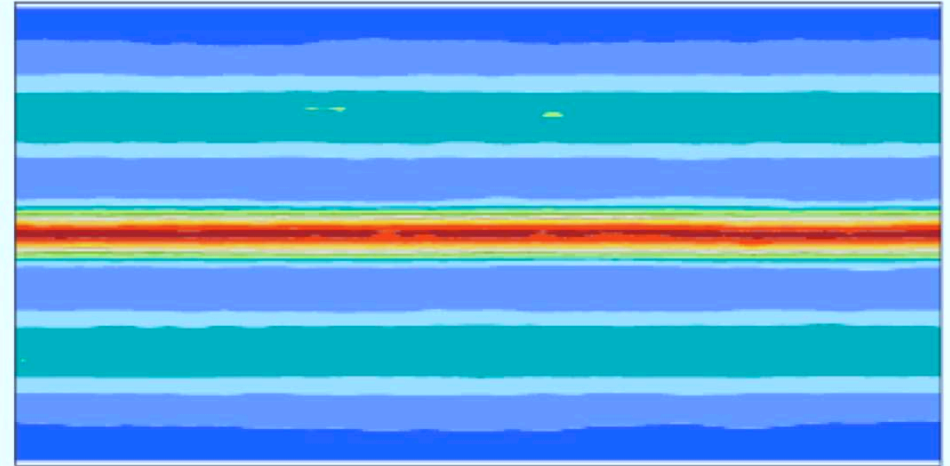
Hybrid



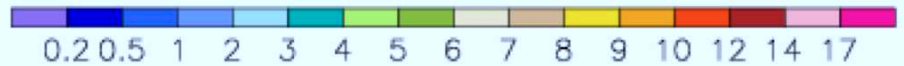
Min = 0.07 Max = 10.09



Aqua-planet



Min = 0.74 Max = 12.63

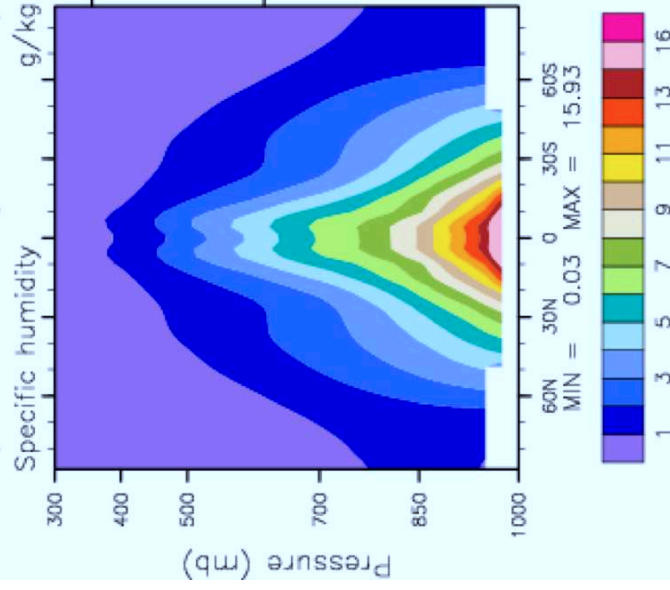


Did you know that a planet would choose to make one intertropical convergence zone in the ANNUAL MEAN if it had no land? I didn't!

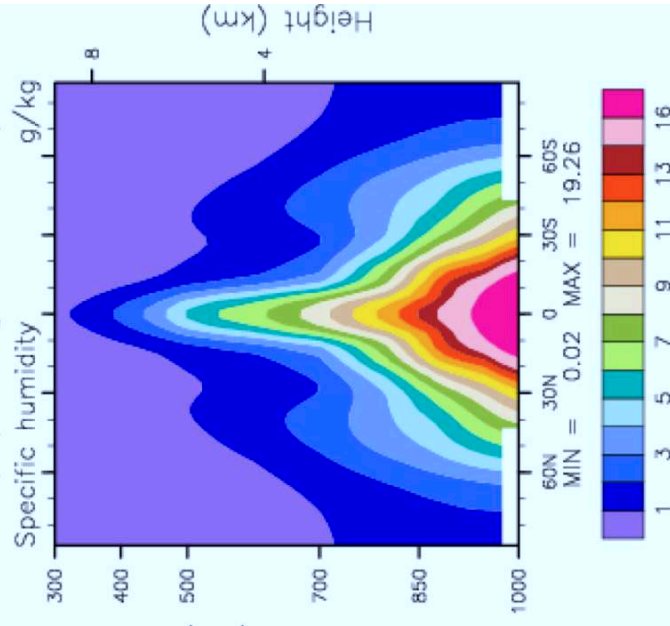
These “oceans” are pools of 50m deep water, rather than prescribed SST as in your runs

ANN

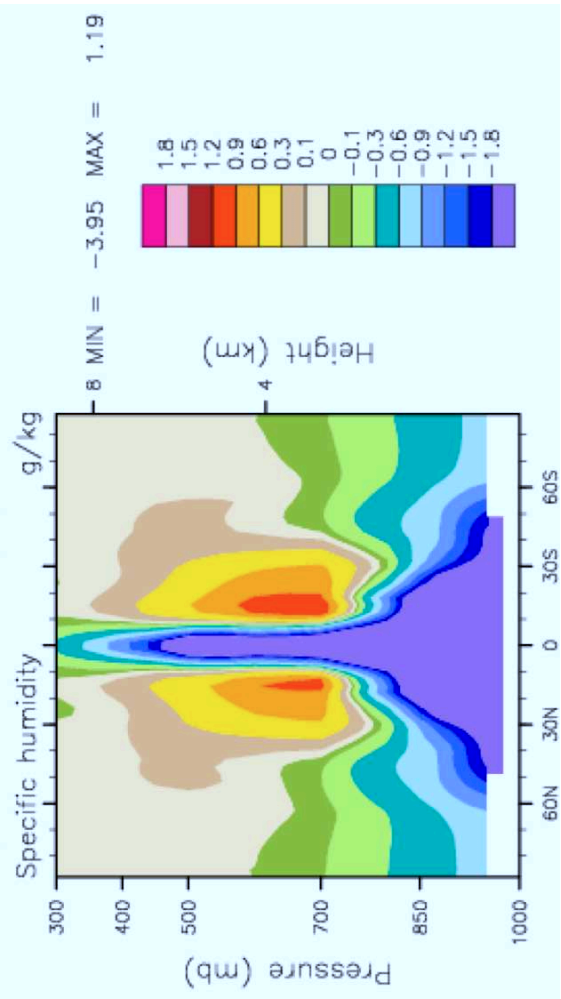
symmetric_land (yrs 174–193)



aquaplanet (yrs 117–136)



symmetric_land – aquaplanet



Definitions

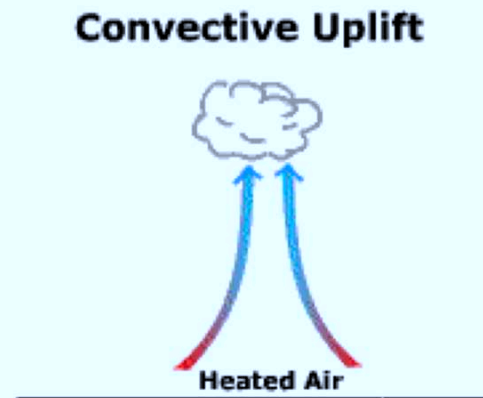
Specific Humidity (Q) is a “mass mixing ratio” or weight of water vapor in a given volume per weight of air. Can have units of g/kg (ppt=parts per thousand) or kg/kg.

Relative Humidity (RH) is $Q/Q\text{-saturated}$, where the denominator is the Q if the air were saturated.

Why introduce water into atmosphere model

1) Condensation transfers heat from surface throughout the atmosphere. Additional fuel for storms. Expect faster moving updrafts and downdrafts. Sharpening of horizontal temperature gradients. Less stable system.

Sunlight warms surface, evaporation cools surface and stores the latent heat in water vapor. The air temperature rises from sensible heating and it becomes buoyant and rises. As it rises, it expands and therefore cools. Cooling can eventually cause air to become saturated and water vapor condenses. Condensation releases latent heat and warms the air above.



Why introduce water into atmosphere model

2) water vapor feedback – well understood positive feedback on climate change



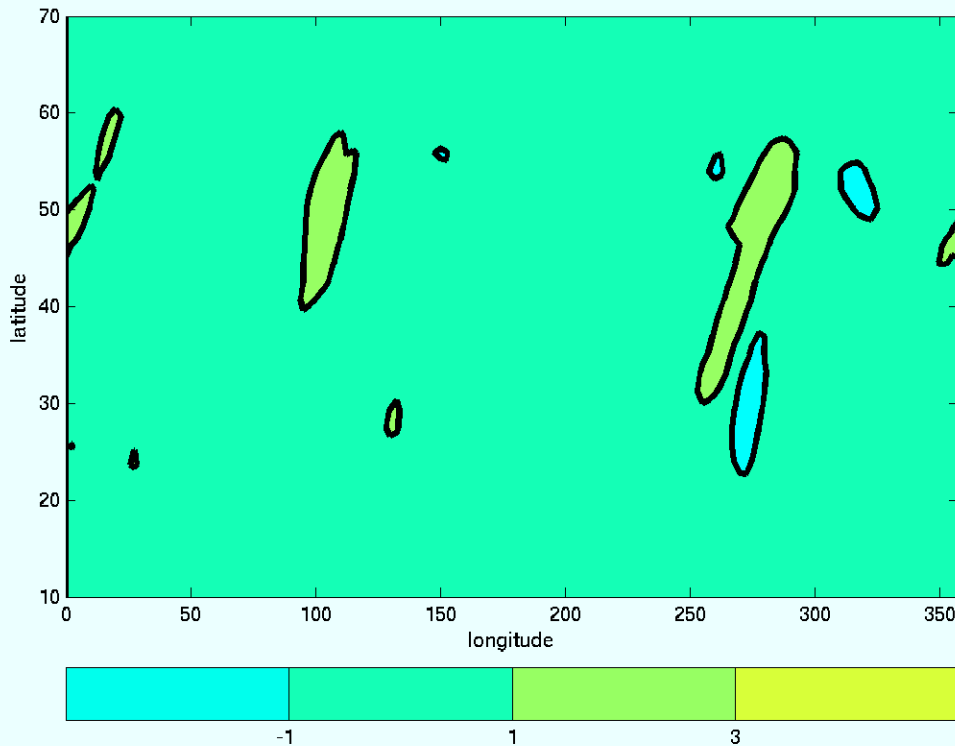
Why introduce water into atmosphere model

3) cloud feedback – poorly understood positive feedback on climate change

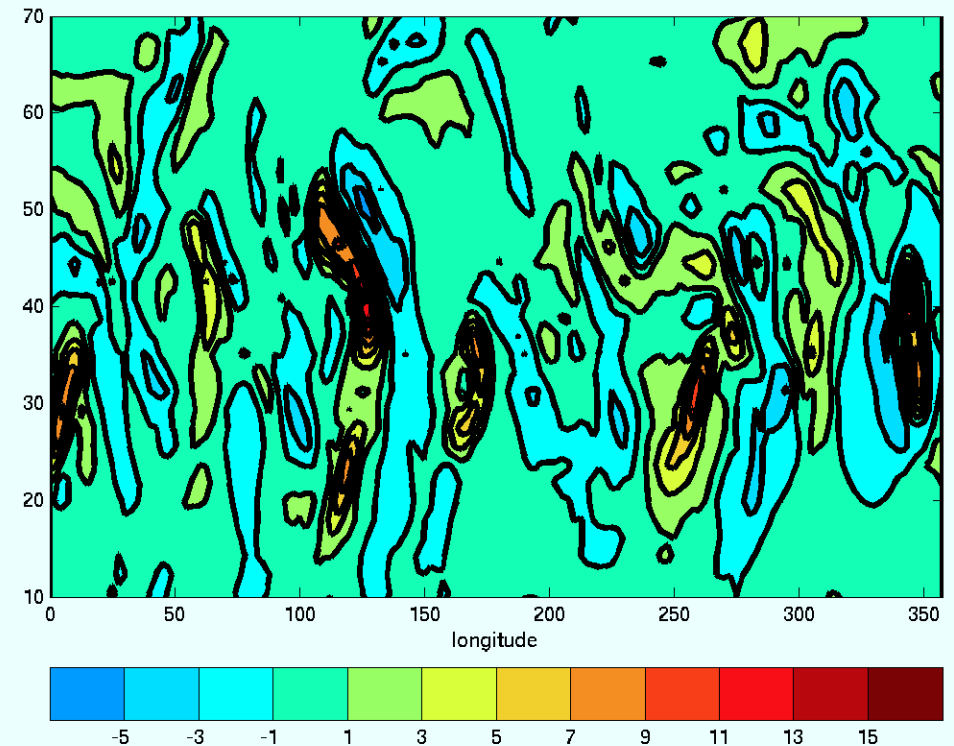


Vertical wind (cm/s) at ~500 hPa in our 2 degree runs

Dry Adiabatic – HW2 & 3



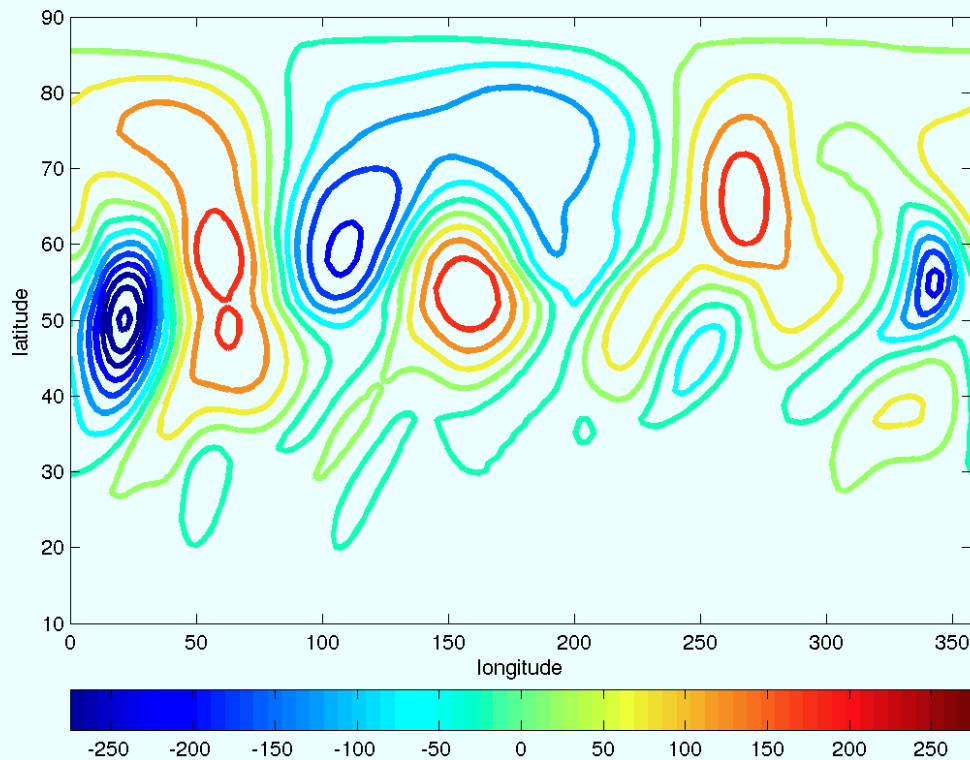
Moist – HW4



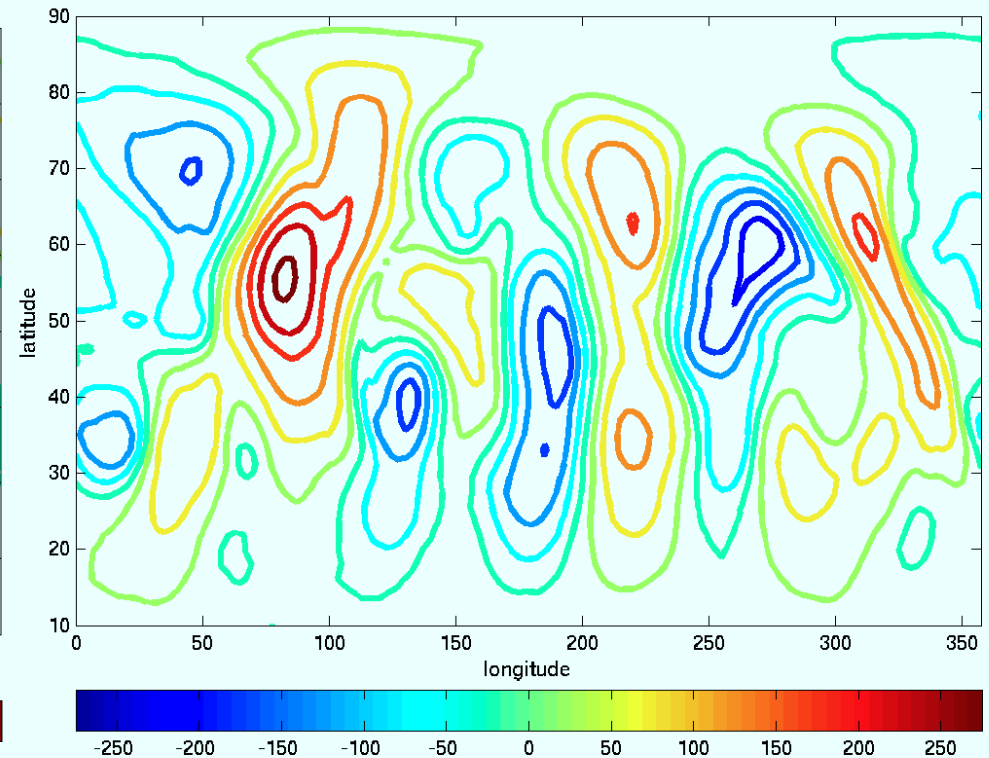
After waves have developed fully in both models, the vertical motion is a factor of ~5 times greater in the moist run BECAUSE OF CONDENSATION!

Eddy Height at ~ 500 hPa in our 2 degree runs

Dry Adiabatic – HW2 & 3

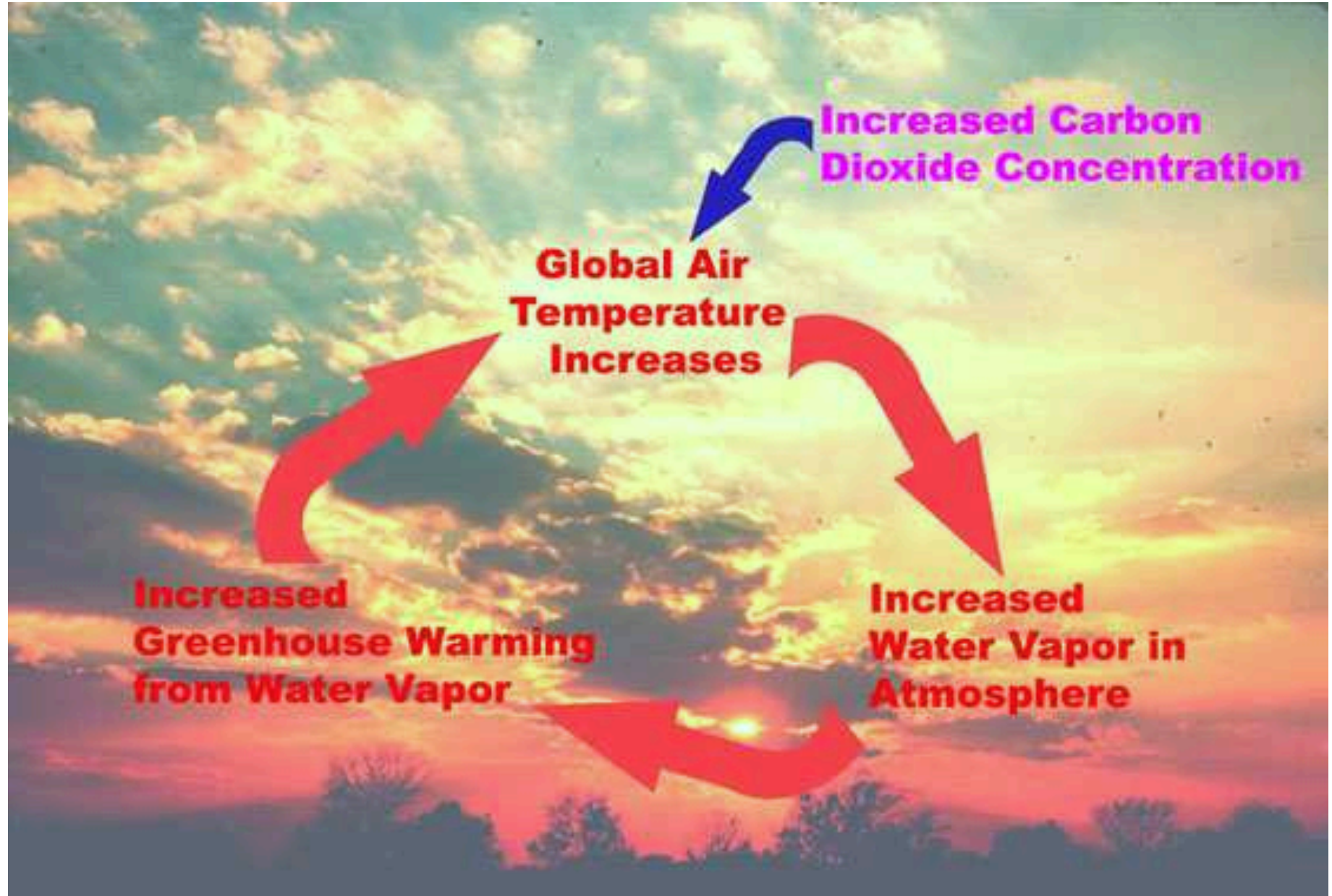


Moist – HW4

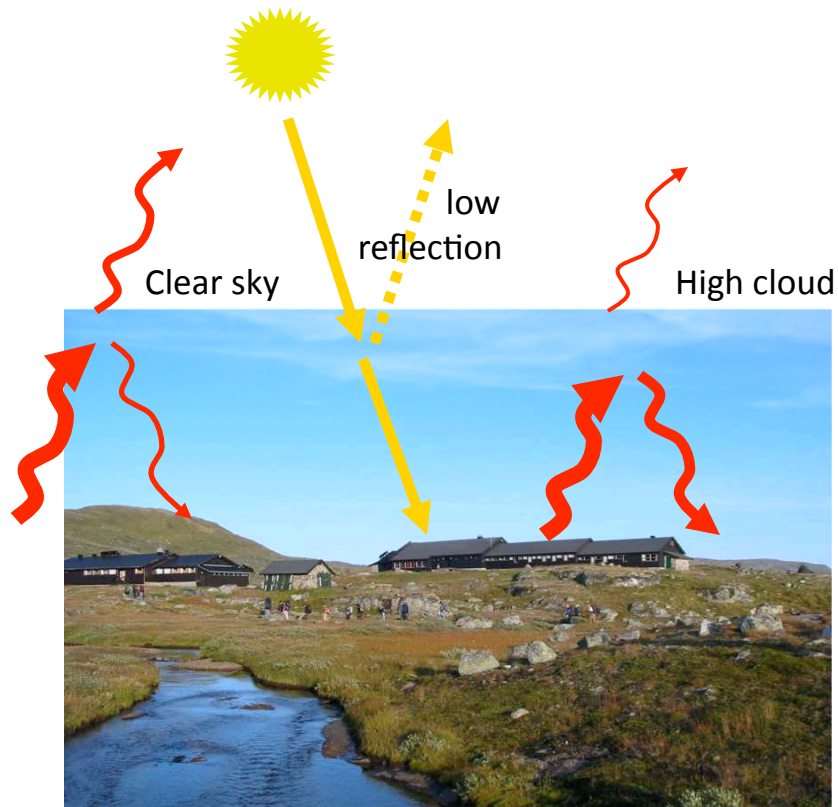


See the horizontal waves have developed about the same in both models.
And yet the vertical motion is MUCH greater in the moist case.

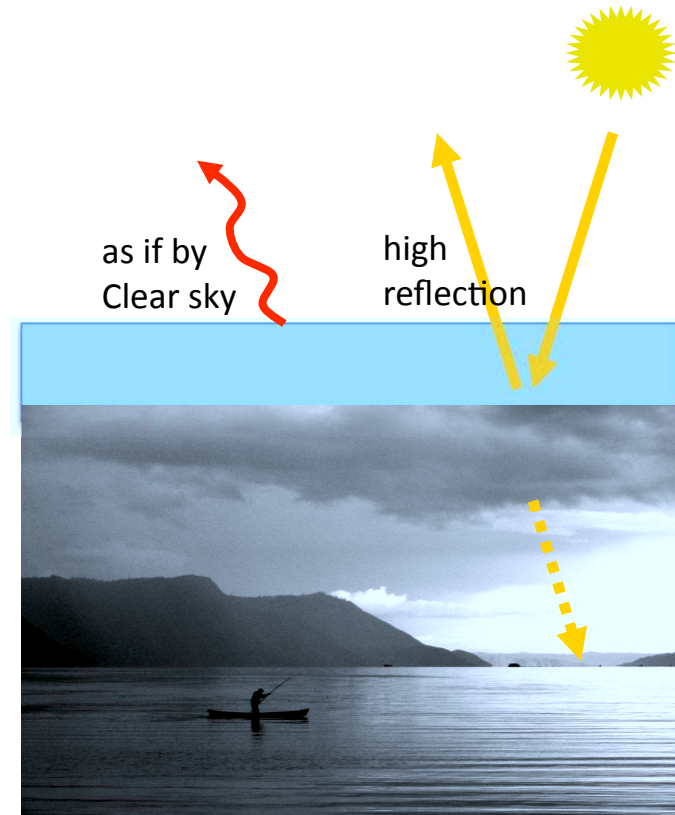
Water vapor positive feedback (more about this later)



Clouds and Climate



High (thin) Clouds Warm



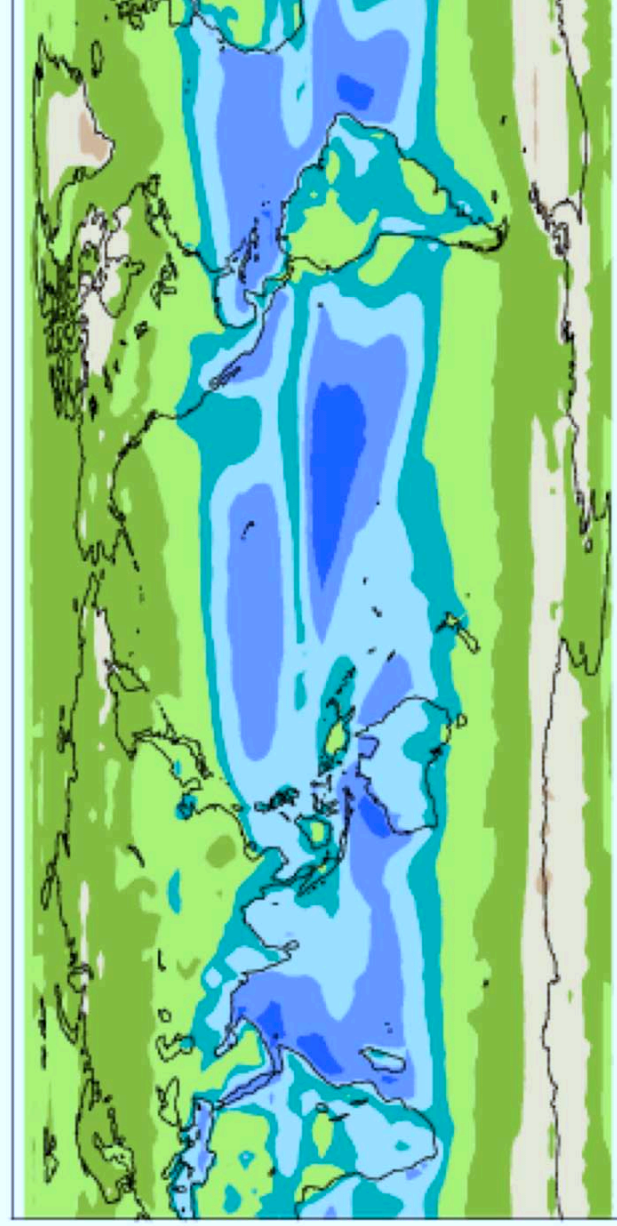
Low (thick) Clouds Cool

In today's climate, *the net effect of clouds is to cool the planet* (albedo affect wins over greenhouse effect)

TOA albedo

mean= 0.31

dimensionless



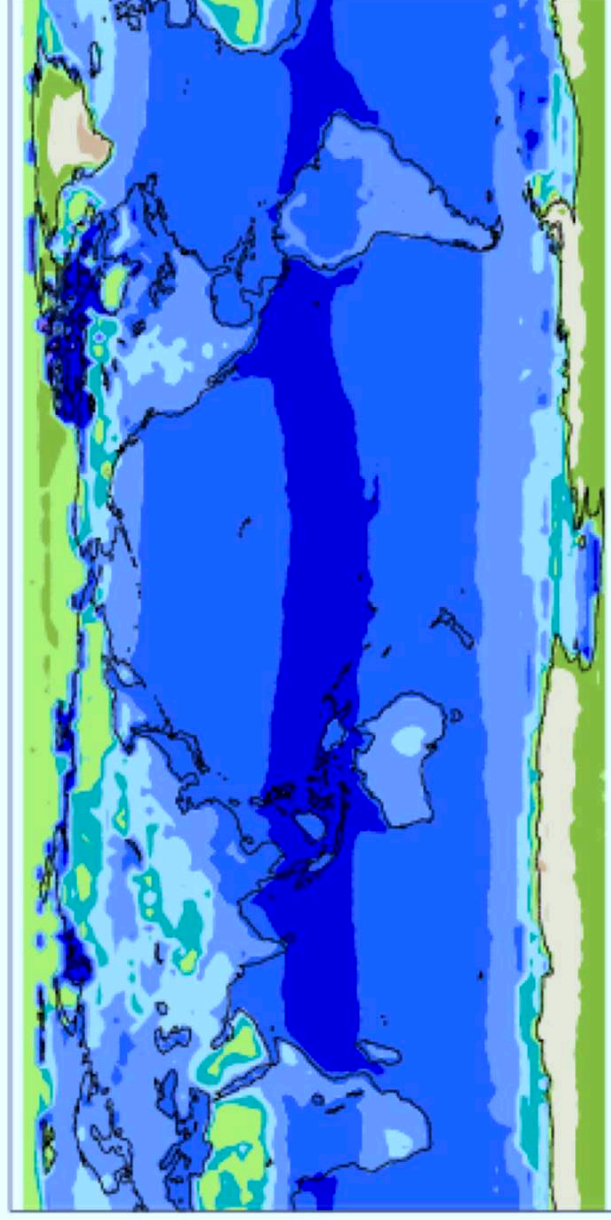
Min = 0.12 Max = 0.68



TOA clearsky albedo

mean= 0.15

dimensionless



Min = 0.03 Max = 0.67



Cloud feedback from global warming?



More of these

...and/or...



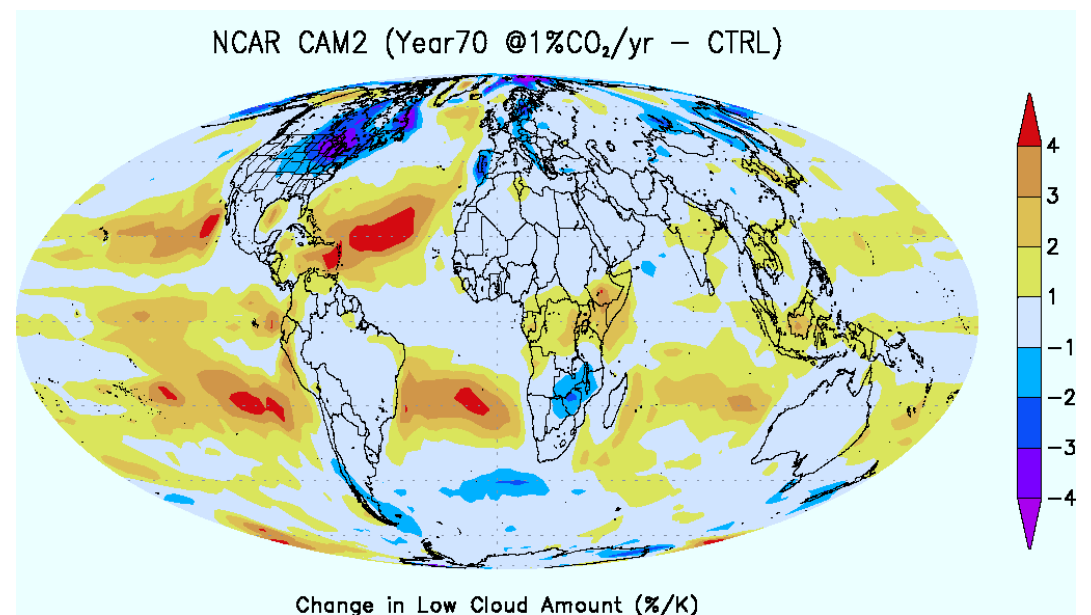
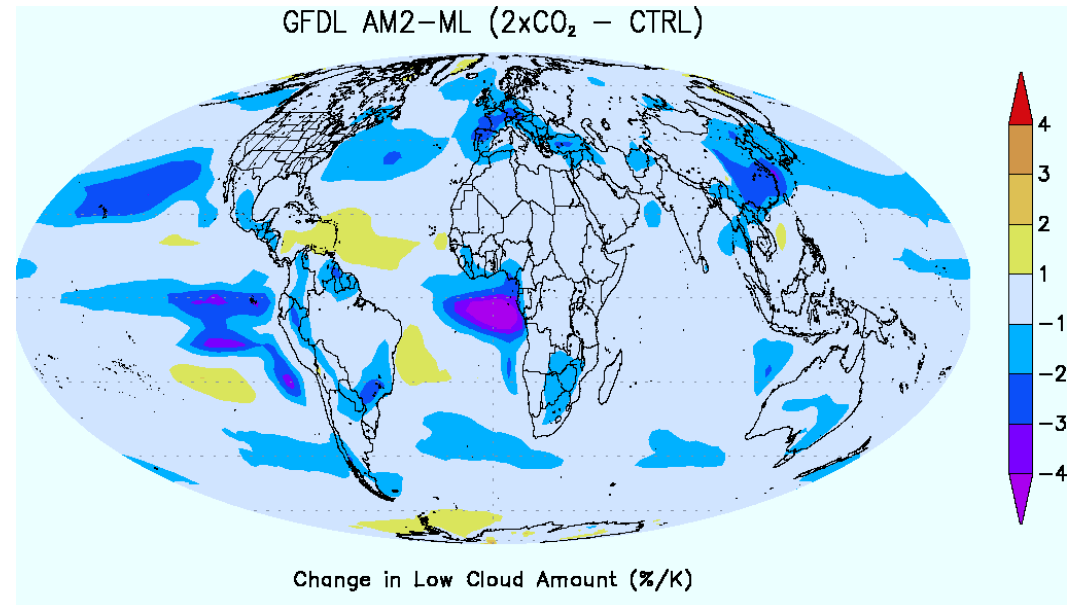
... less of these?

Near agreement that low clouds cool less as CO_2 rises, which makes a **positive** feedback. But amplitude is very uncertain.

The cloud feedbacks problem agreement is fairly recent
In 2003 two prominent models were wildly different

These figures show low cloud change from doubling CO₂

- decreased in GFDL AM2
(positive albedo feedback)
global warming = 4.5 K
- increased in NCAR CAM2
(negative albedo feedback)
global warming = 1.5 K



Cloud Fraction is a fairly phony concept in a model that does not resolve clouds (hence all weather and climate models). It is useful in a relative sense and as a diagnostic concept.

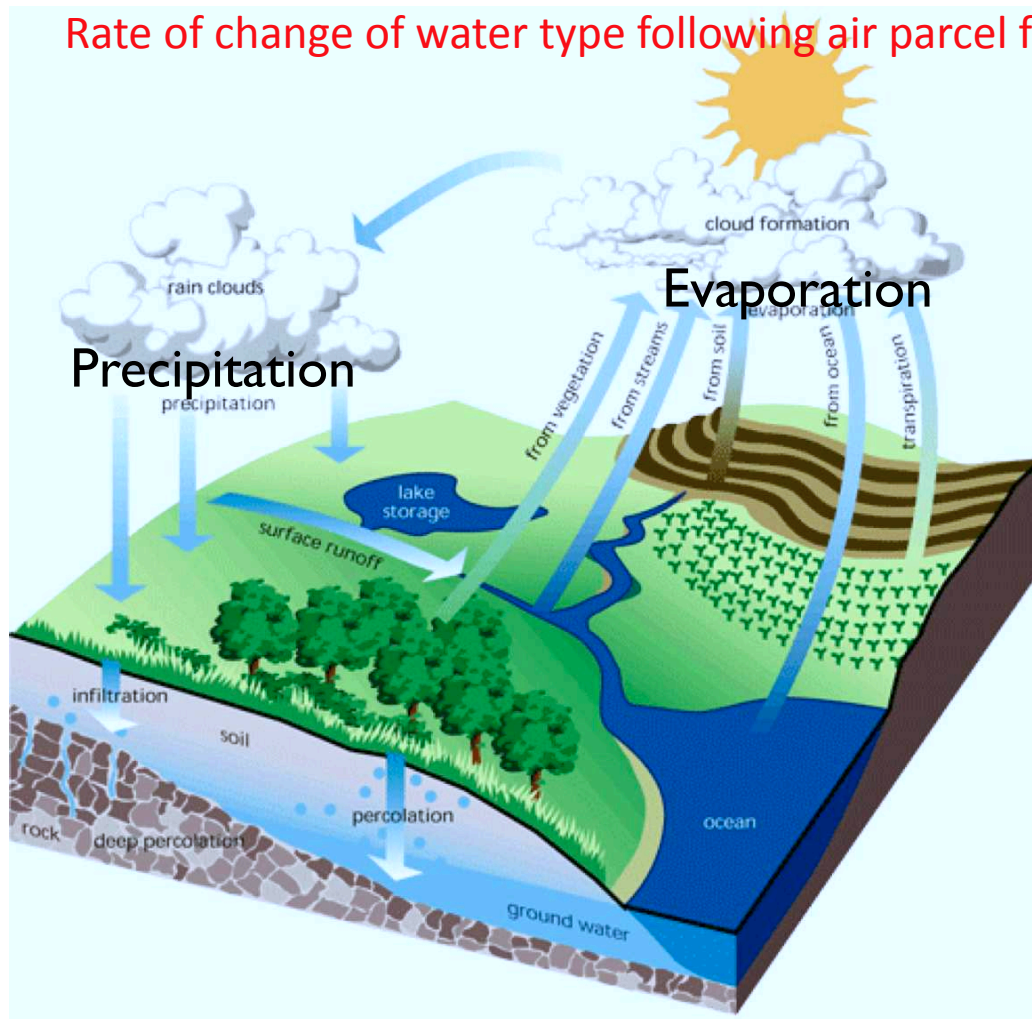
It does not follow any conservation law. But a good cloud scheme doesn't have condensate without cloud fraction about zero.

If a cloud fraction parameterization is modified to give higher cloud fraction, the cloud condensate will be more dilute and generally have a smaller radiative impact in the cloud. This compensation means that the more fundamental concern is with conservation of water type, rather than the parameterization of cloud fraction.

Threshold needed in RH for presence of cloud because grid cell area is too large to expect such a large area to be cloud free before it reaches 100% RH. Instead a fractional cloud coverage forms at a lower RH. In all cases water is conserved!

Conservation of water

Like the continuity equation for the flow of air, we also have a **continuity equation for the flow of water in EVERY form** it occurs: water vapor, liquid condensate, and ice condensate.



In the global average
Evaporation = Precipitation

$$E = P$$

Conservation of water

For example for water vapor

Sources of water vapor:

- Evaporation at the surface (or sublimation if surface is ice)
- Evaporation from liquid cloud condensate
- Sublimation from ice cloud condensate

Sinks of water vapor:

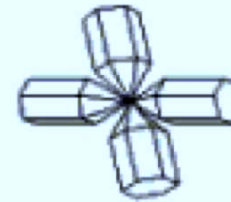
- Condensation at the surface (or frost deposition if surface is ice)
- Condensation to liquid cloud condensate
- Deposition onto ice cloud condensate



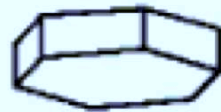
Dendrite



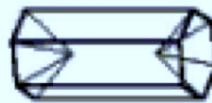
Aggregate



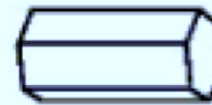
Bullet Rosette



Plate



Hollow Column



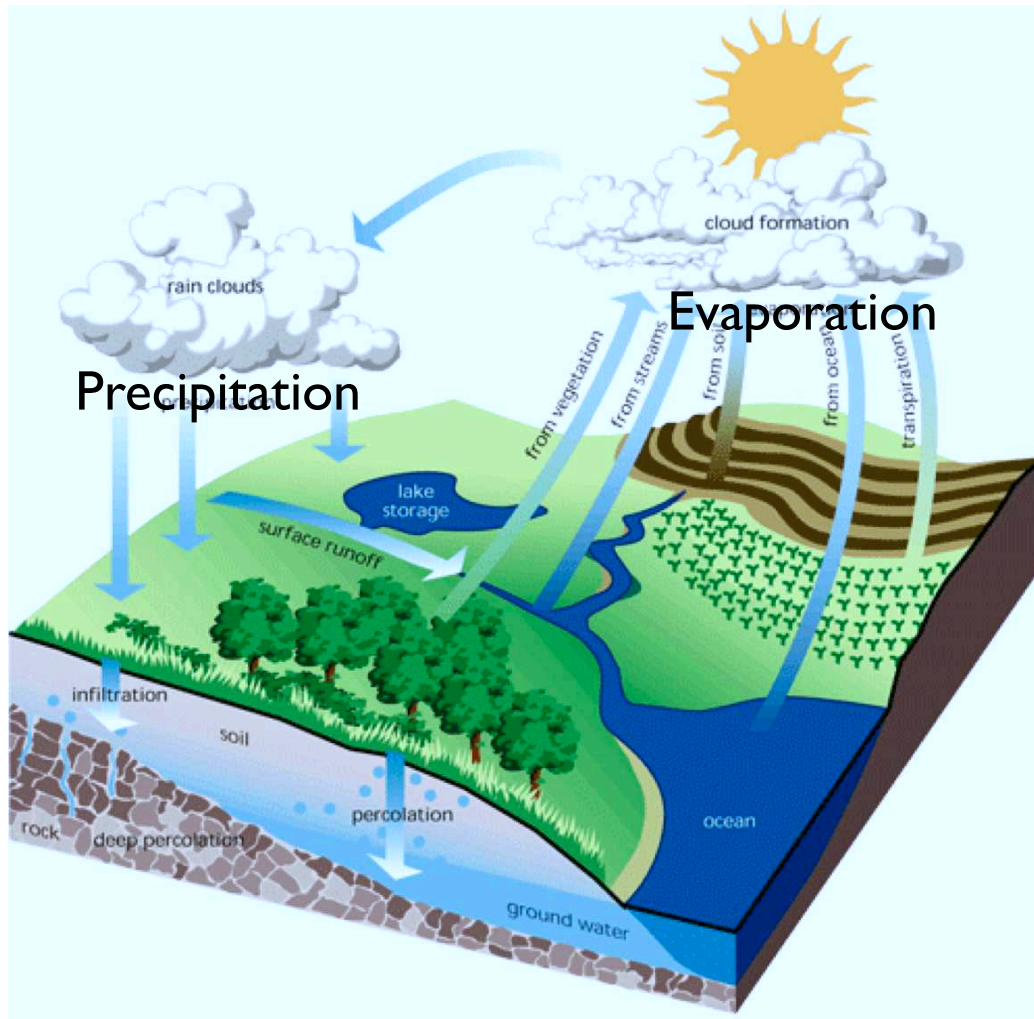
Solid Column

Fig. 17-1. Idealized ice particle shapes or "habits". Spheres are not shown.
(Courtesy P. Yang)

<http://stratus.ssec.wisc.edu/streamer/userman/clouds.html>

Wednesday Feb 3, 2011

What determines H₂O concentration?

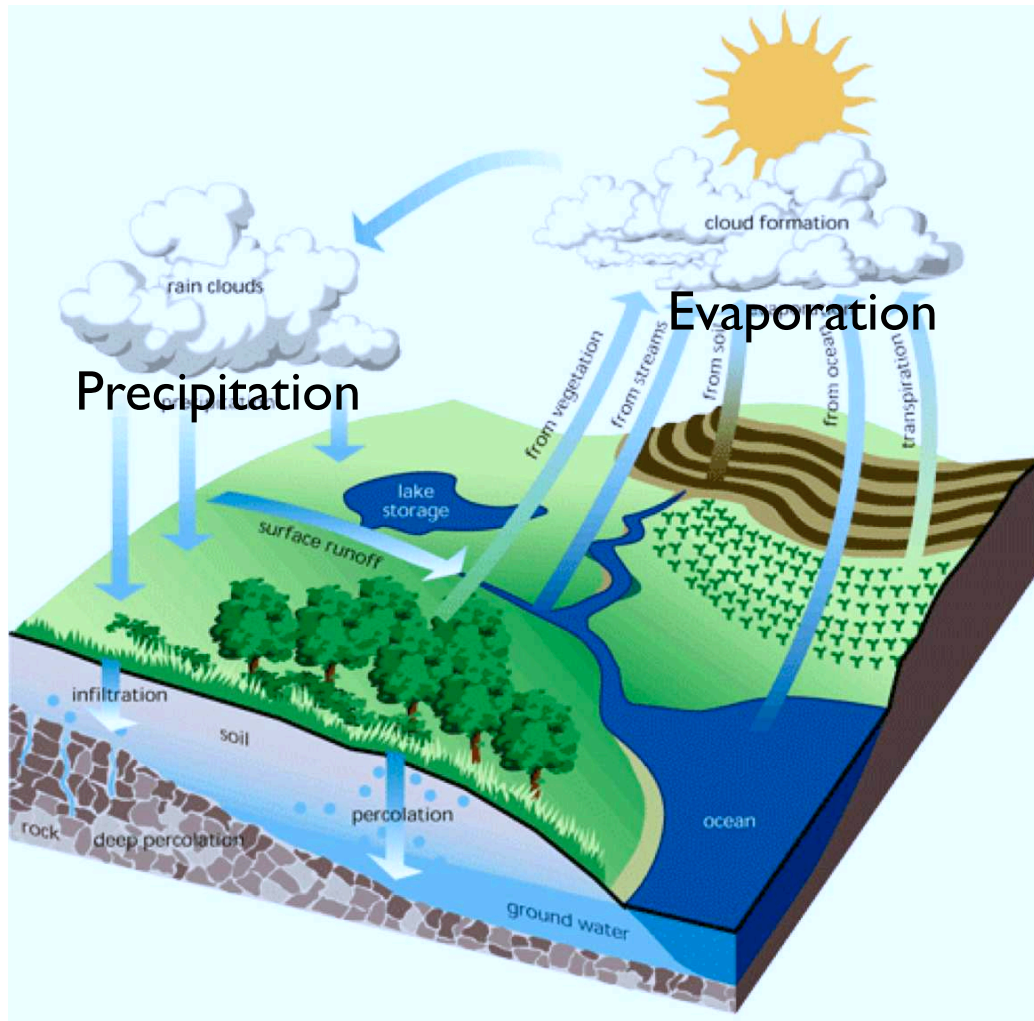


Take all the water vapor out of the atmosphere. What happens at first?

Precipitation, $P = 0$ (no rain)

Evaporation, E is big because the air is dry

What determines H₂O concentration?



The air is moistening, but not yet back to normal. Now what?

$$E > P$$

Water vapor is part of a Feedback,
it is not Forcing

Human activities do not directly influence water vapor.

We do not consider it a “forcing”

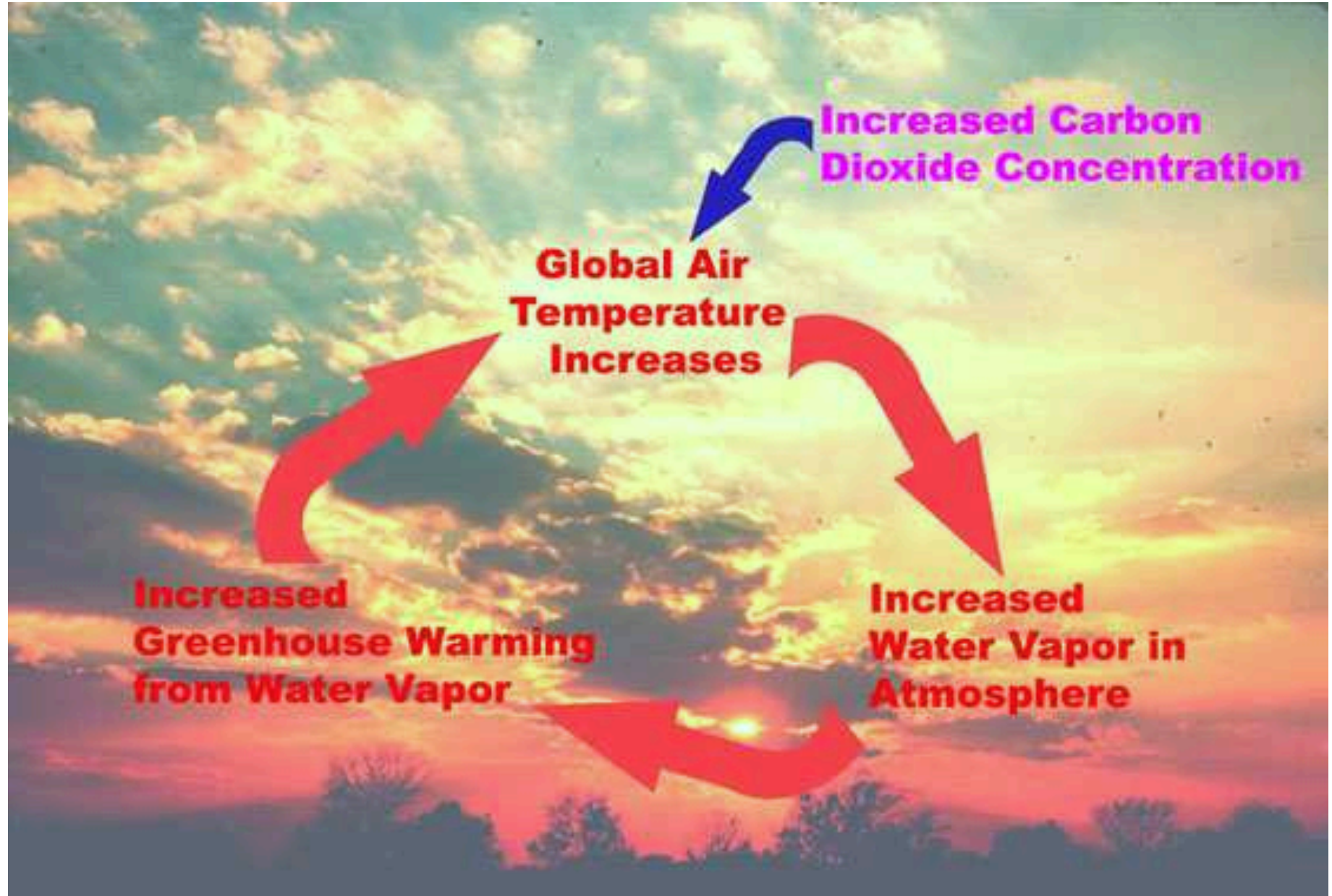
It is part of the system...

For your homework 4

How long does it take for $E=P$?

You know $E=P$ when the humidity is no longer changing much!

Water vapor positive feedback



What determines H₂O concentration?

Leaky bucket analogy



source is evaporation

bucket is the atmosphere, containing water vapor

leak is precipitation

How full the bucket is matters

Imagine a partially full bucket, pictured here as a glass.
This represents the present climate.

The fraction it is full is like the **relative humidity**

$$= \frac{\text{actual water vapor concentration}}{\text{water vapor concentration at saturation}}$$



If the glass were full, the atmosphere would be saturated.
In reality it is not full.

So what happens under global warming?

As the climate warms the concentration at saturation increases at a rate of 7% per degree C according to the Clausius Clapeyron Relation

This increase in capacity is like making the glass bigger.



But will it contain more water???

So what happens under global warming?

Will there be more water in the glass - by which we mean more water vapor in the atmosphere - just because the capacity is greater?



Constant relative humidity
assumption



Constant Water Vapor Concentration
assumption

H₂O in the atmosphere as Positive Feedback



Constant relative humidity
assumption

If warming increases the amount of water vapor in the atmosphere, the Earth will warm even more, because water vapor is a GHG too.

Planetary Energy Balance

At Equilibrium (a steady climate):

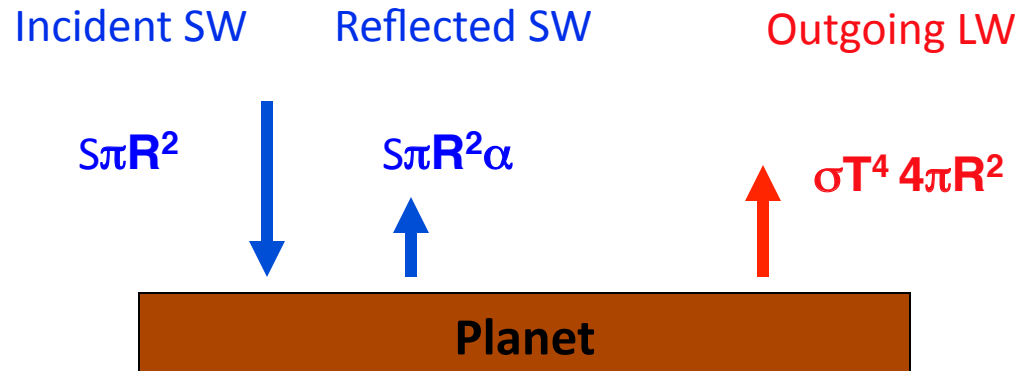
Energy Flux in = Energy Flux out

Absorbed solar energy = Heat energy lost to space

$$F_{\text{IN}} = F_{\text{OUT}}$$

If something knocks a planet out of energy balance,
the planet WILL warm or cool to eliminate the imbalance.

Model of Planet with No Atmosphere - Model A



$$F_{\text{IN}} = F_{\text{OUT}}$$

$$S\pi R^2 (1-\alpha) = \sigma T^4 4\pi R^2$$

Balance of total Fluxes

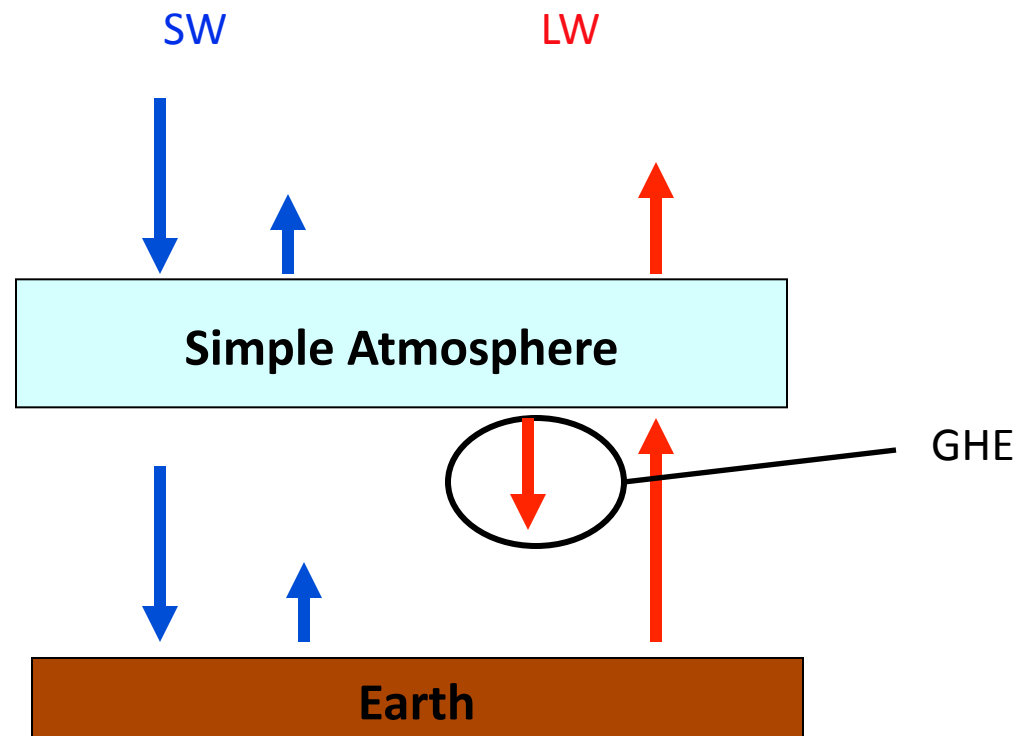
$$\frac{S}{4} (1-\alpha) = \sigma T^4$$

Balance of Fluxes per unit area
Model A

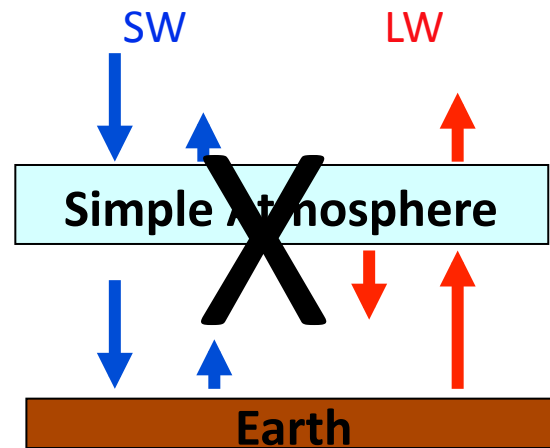
$$T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma}}$$

Model A, solved for T

Earth with a Simple 1-Layer Atmosphere Model B



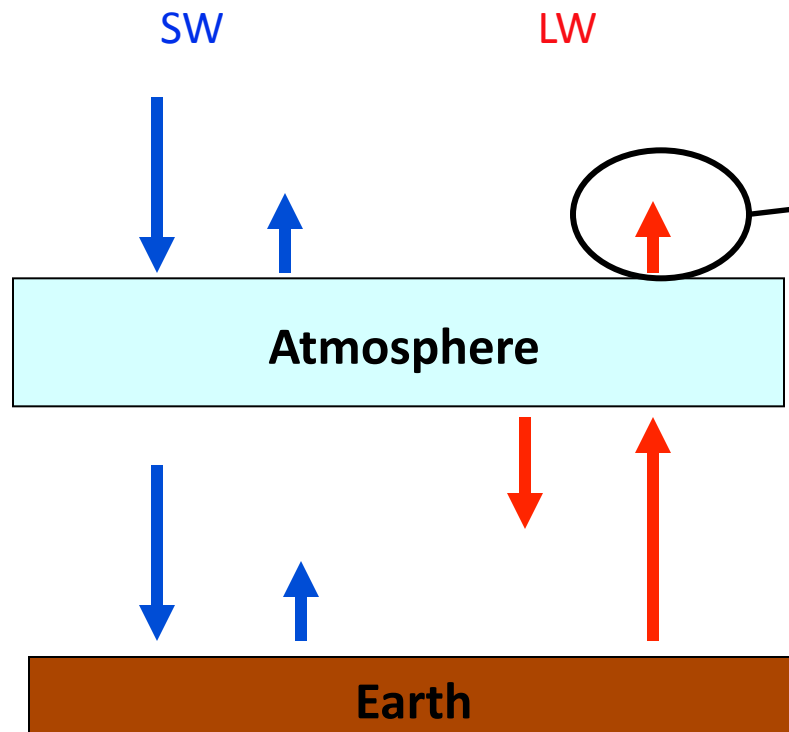
Enhanced or Anthropogenic GHE



Even Model B is too simple because it doesn't change if there are more GHGs

Because the atmosphere is emitting the same longwave flux up and down. In reality it doesn't because there is a temperature and density profile.

Earth with Multi-Layer Atmosphere Model C



Adding More Greenhouse Gases initially reduces Outgoing Longwave Radiation (OLR)

Causes an energy imbalance and the planet has more heat entering than leaving.

Nature abhors energy imbalances. Warming acts to eliminate it by raising OLR back to balance net absorbed solar.

Imagine the CO2 Level Doubled Instantly

Less heat escapes, so

F_{OUT} decreases

“Radiative Forcing”

$$\Delta Q = F_{IN} - F_{OUT} = 3.7 \text{ W/m}^2$$

(estimated to within a few tenths)

Feedback Theory

$$\lambda \Delta T = \Delta Q$$

Note:

Δ : common symbol to refer to change in some quantity

ΔQ : radiative forcing (or instantaneous change in energy balance)

ΔT : response (change in surface temperature)

λ : total climate feedback (everything else)

λ : does not represent the wavelength of light here!

Run a Climate Model with Double CO2

$$\lambda \Delta T = -\Delta F$$

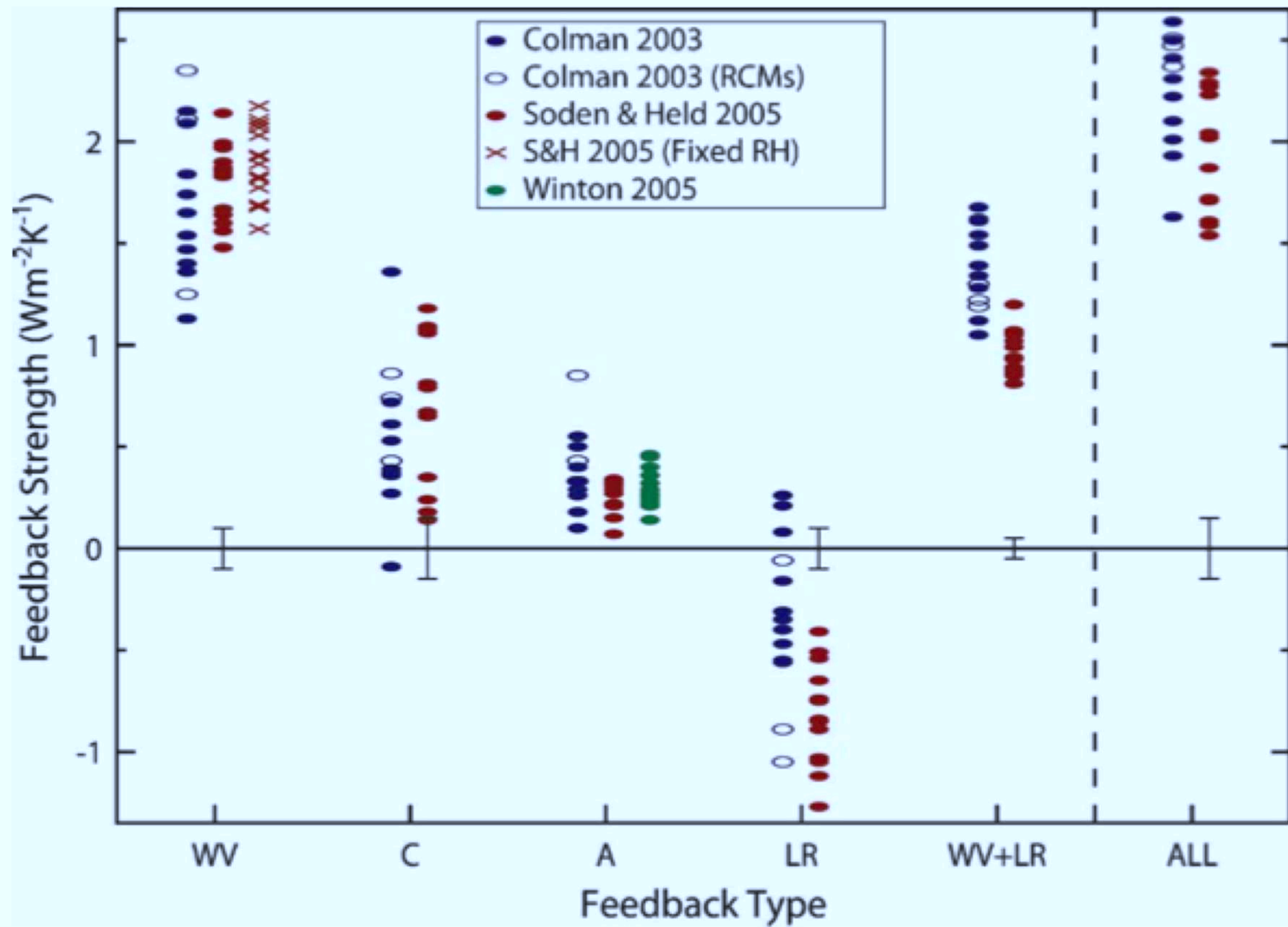
Run model until the ocean comes into equilibrium with the atmosphere and find ΔT is about 3 deg C.

So λ is ?

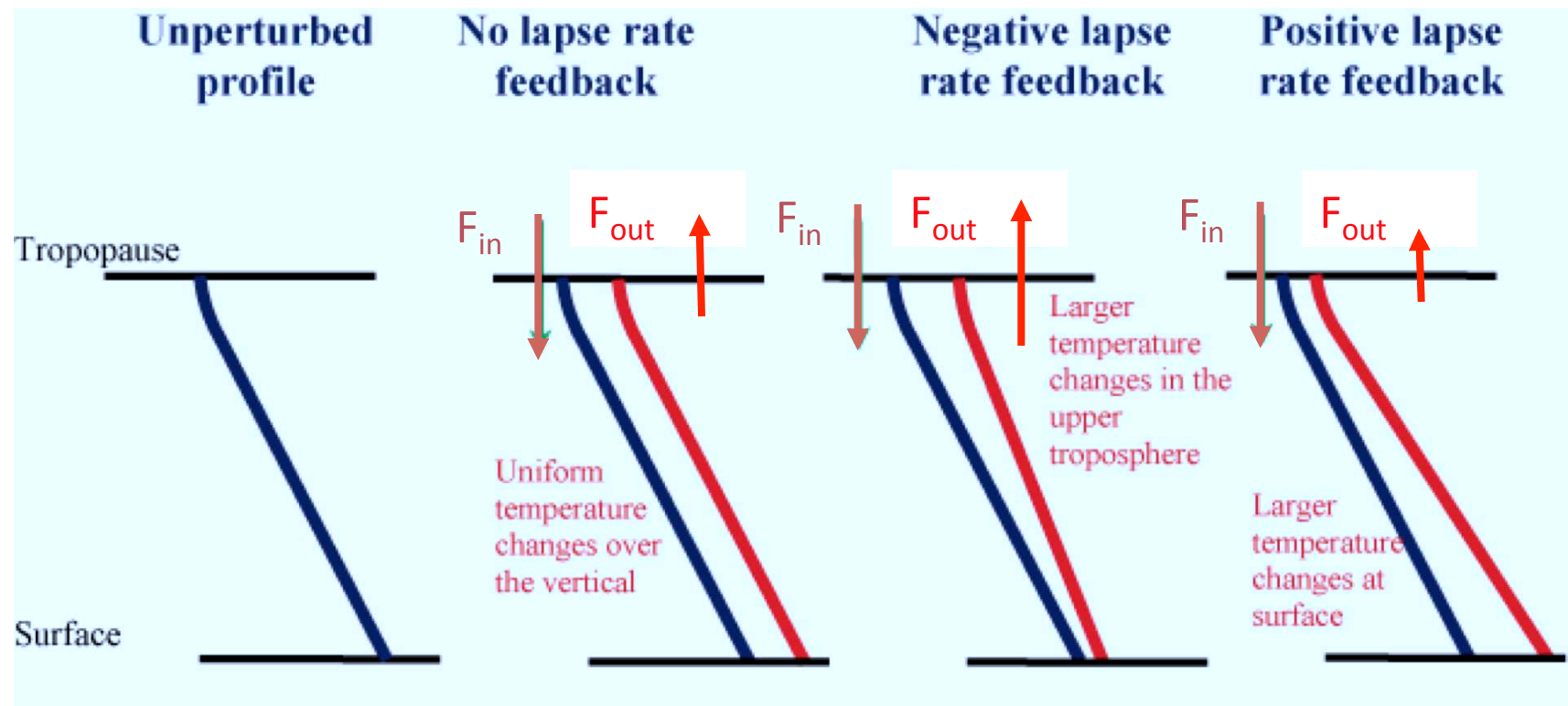
$$\lambda = -\Delta F / \Delta T = -3.7/3 = -1.23 \text{ W/m}^2/\text{K}$$

If we ignore all feedbacks except for black body radiation of the planet, then $\lambda_B = -d(\text{OLR})/dT = -4 \sigma T^3 = -3.8 \text{ W/m}^2/\text{K}$

Bony et al 2006



In which case has the planet warmed enough to remove the imbalance caused by the perturbation (eg CO2)?





Cirrus

These are real clouds.
What do model
clouds look like?



Cumulonimbus



Stratus



Cumulus

Fog



Arakawa 2004 Review on Cumulus Parameterizations

UNCERTAINTIES IN FORMULATING CLOUD AND ASSOCIATED PROCESSES

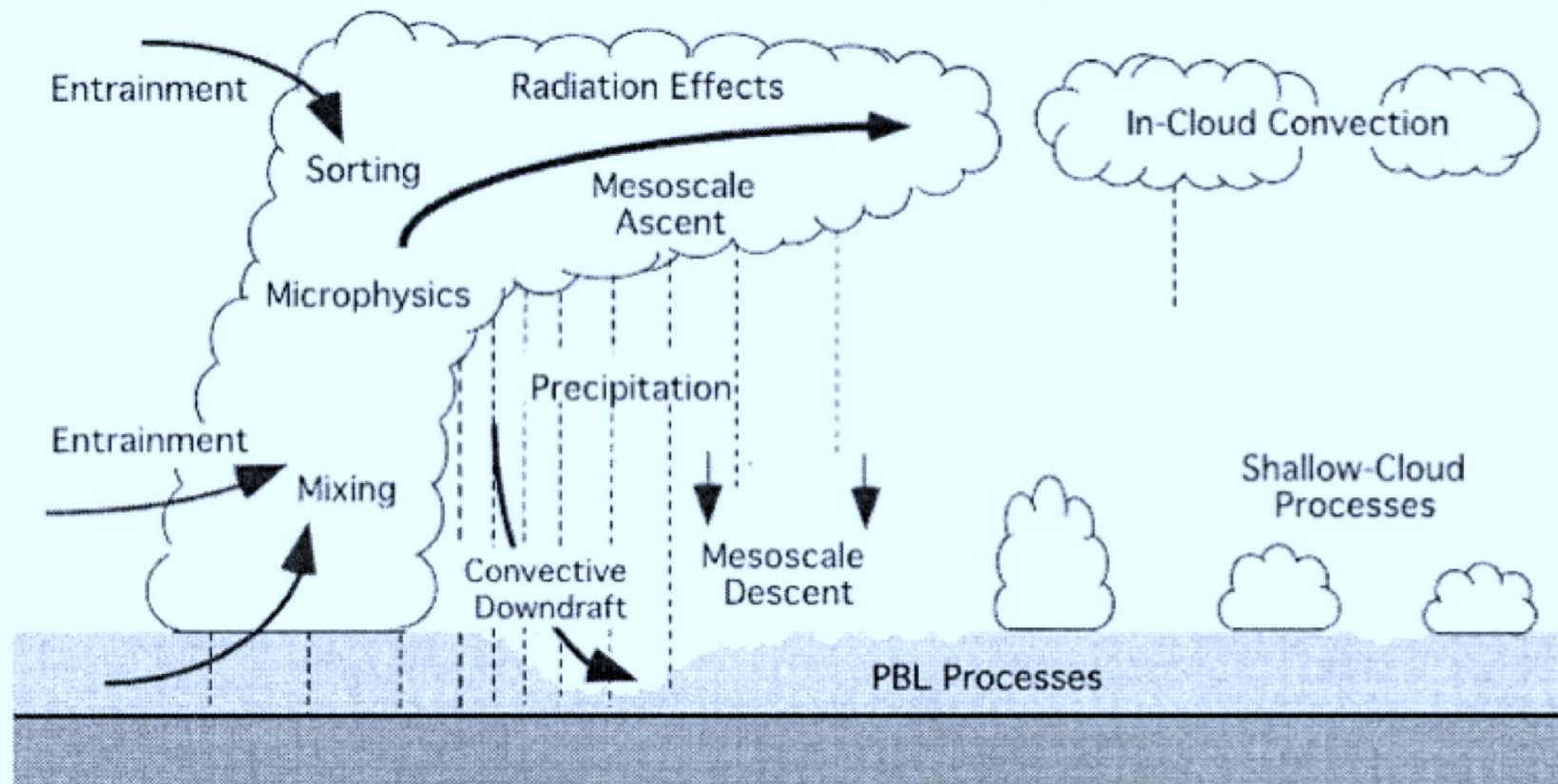
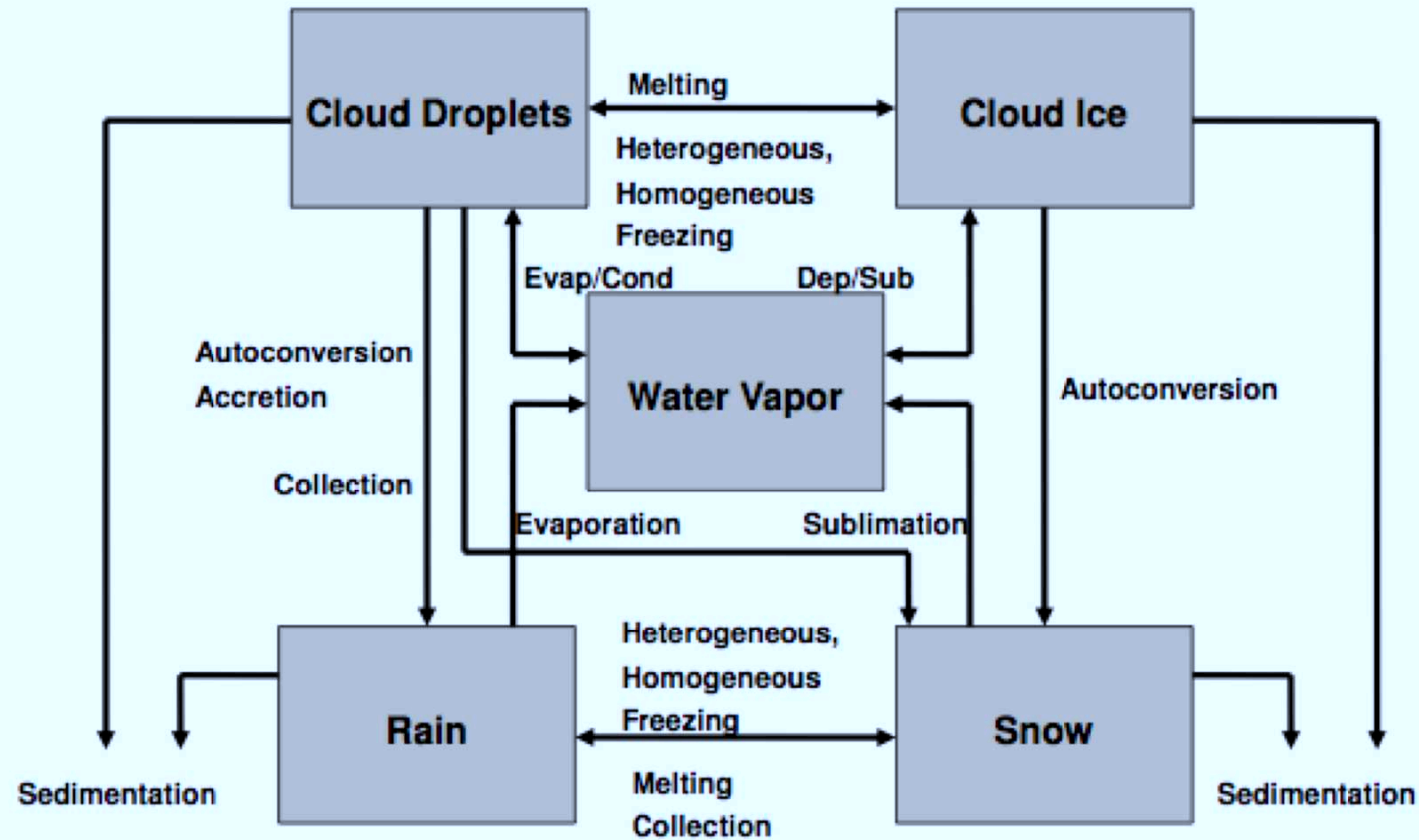


FIG. 2. Cloud and associated processes for which major uncertainties in formulation exist.

Morison et al 2005 and Saltzman et al 2010



Arakawa 2004 Review on Cumulus Parameterizations

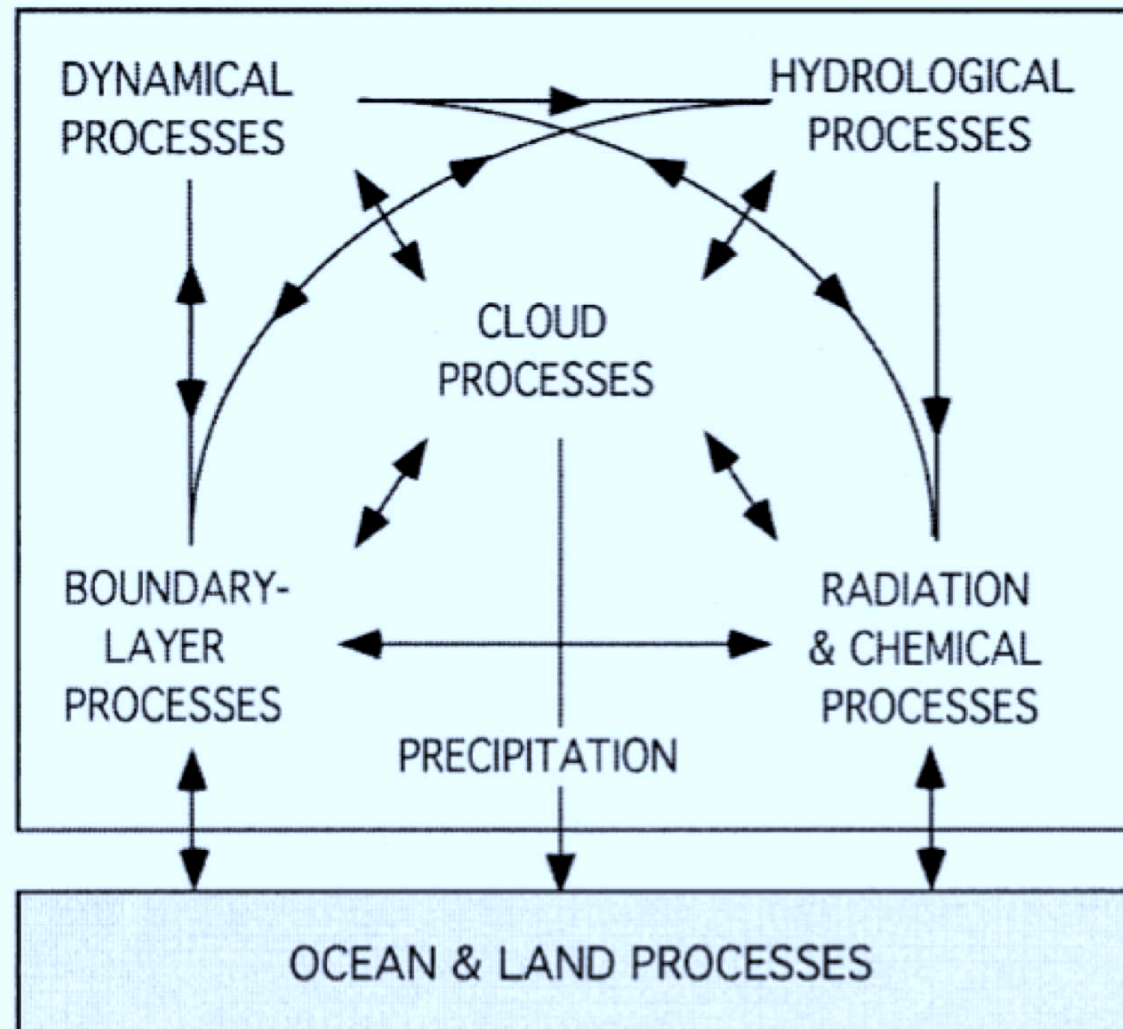


FIG. 1. Interactions between various processes in the climate system.