Radiative Control of Deep Tropical Convection

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Outline

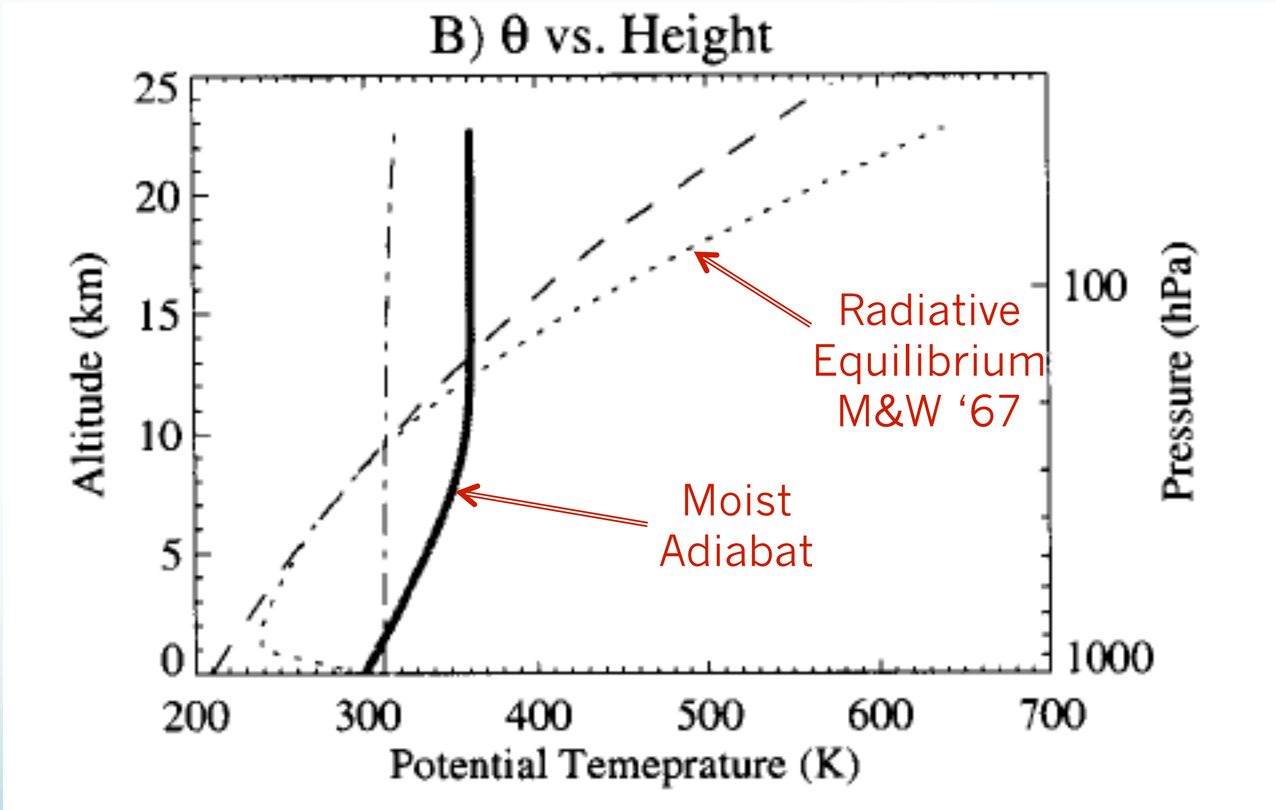
- Review Tropical Transition Layer
- Observed response of clouds to Tropical SST
  - Evidence of upward shift of radiatively driven convergence and clouds.
- Numerical experiments with radiative-convective equilibrium in a tropical CRM
  - The role of water vapor
  - The role of ozone
- Conclusions

The Tropical Transition Layer

- Controls the pressure depth of the general circulation.
- Important for cloud feedback.
- Important for stratospheric water vapor.

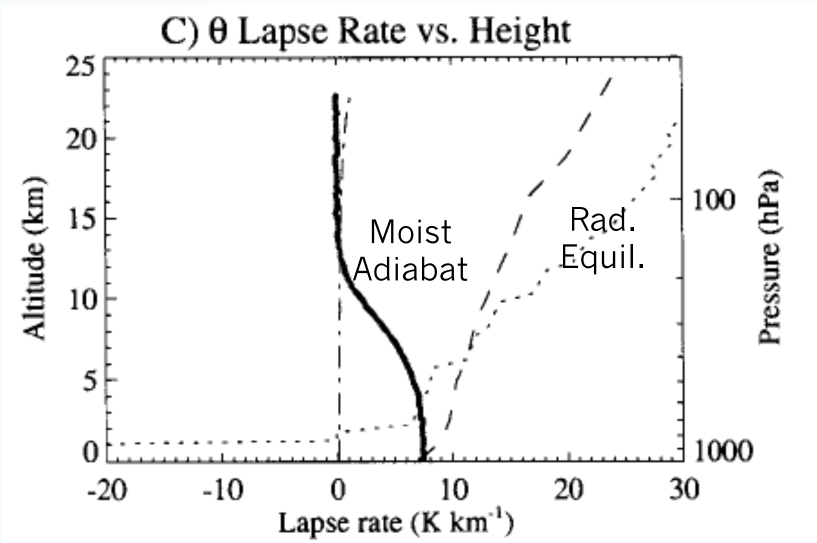
TTL Definitions

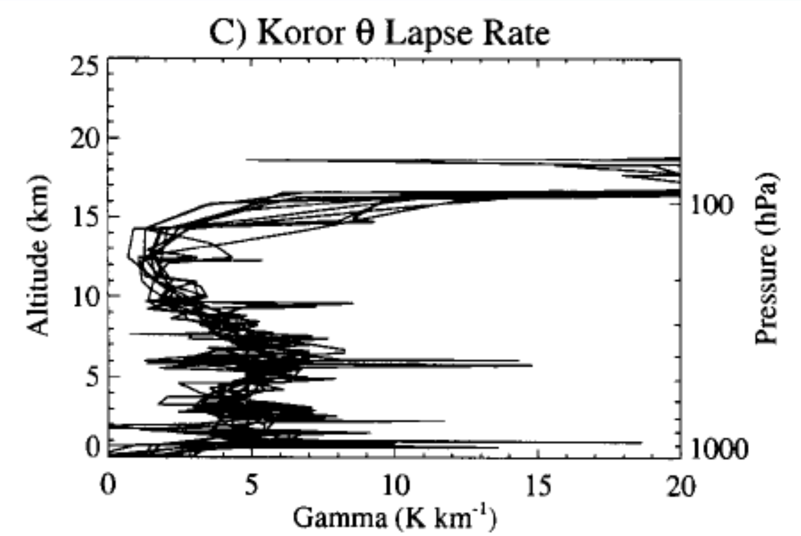
- Gettelman and Forster (2002): Minimum Lapse rate of Potential Temperature definition of base of TTL.

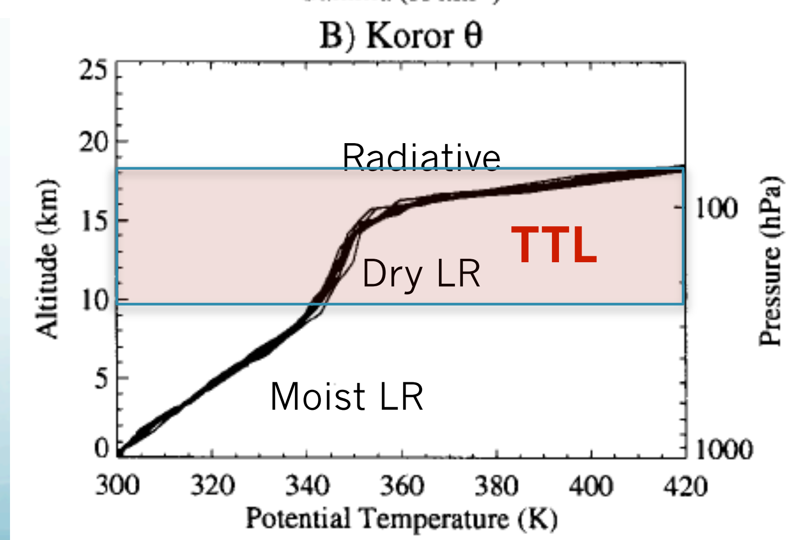


TTL Definition Contd.

- Observations show a minimum in theta lapse rate







Gettelman & Forster
(2002) JMSJ

The Mixing Barrier

- Folkins, GRL, 1999, looked at Samoa, barrier below cold point.

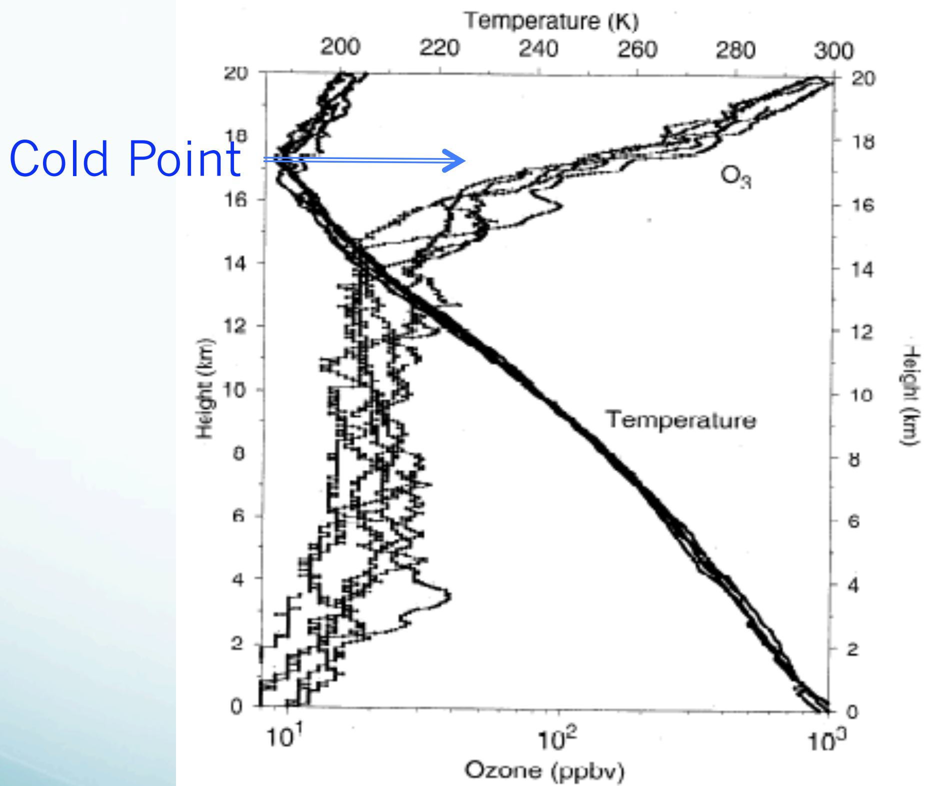


Figure 1. Profiles of temperature and O_3 taken from five ozonesondes launched Samoa in March 1996.

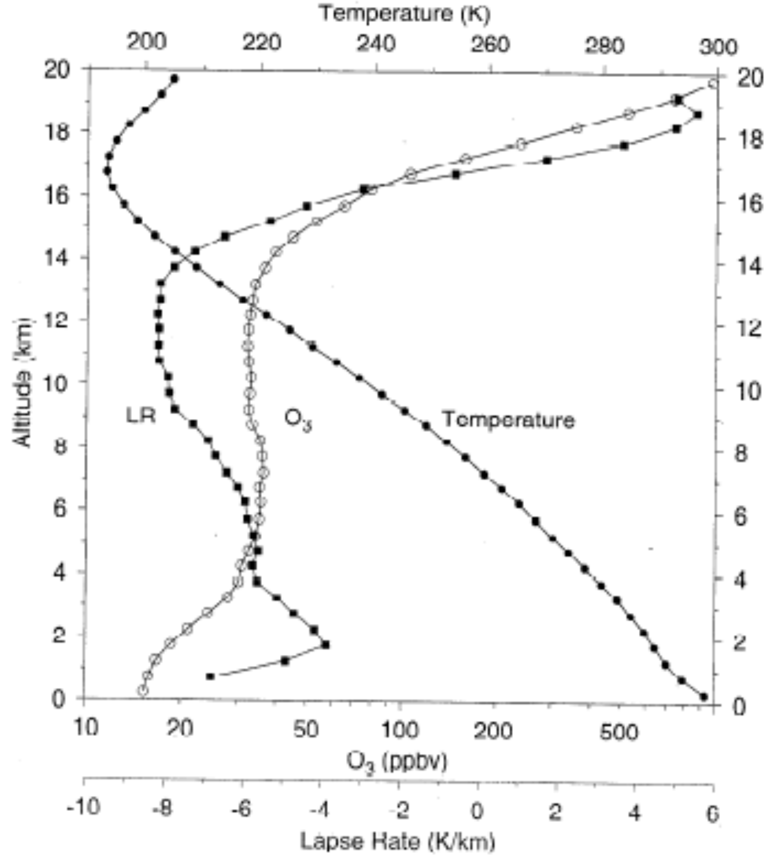
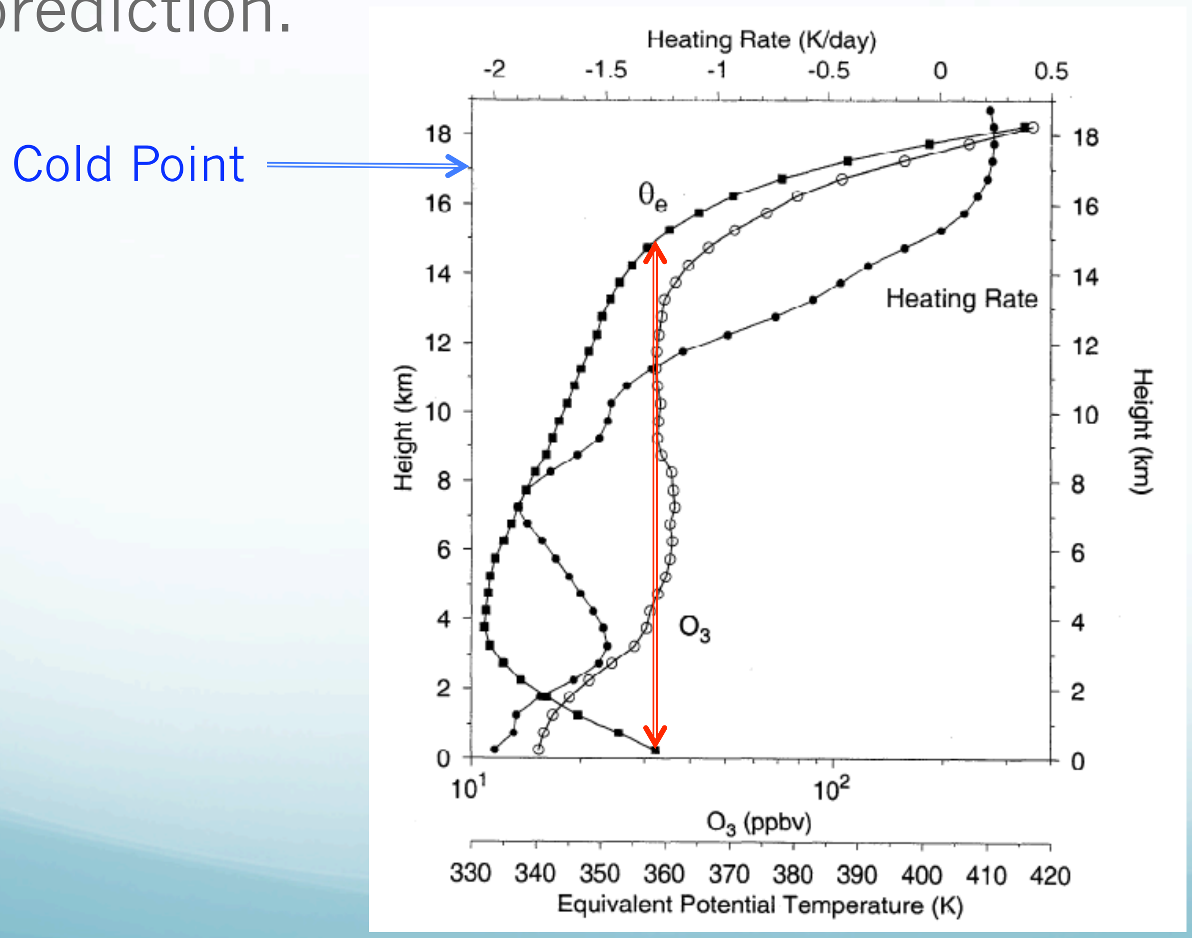


Figure 2. Average profiles of temperature, O_3, and lapse rate(LR) from all 108 Samoan ozonesondes.

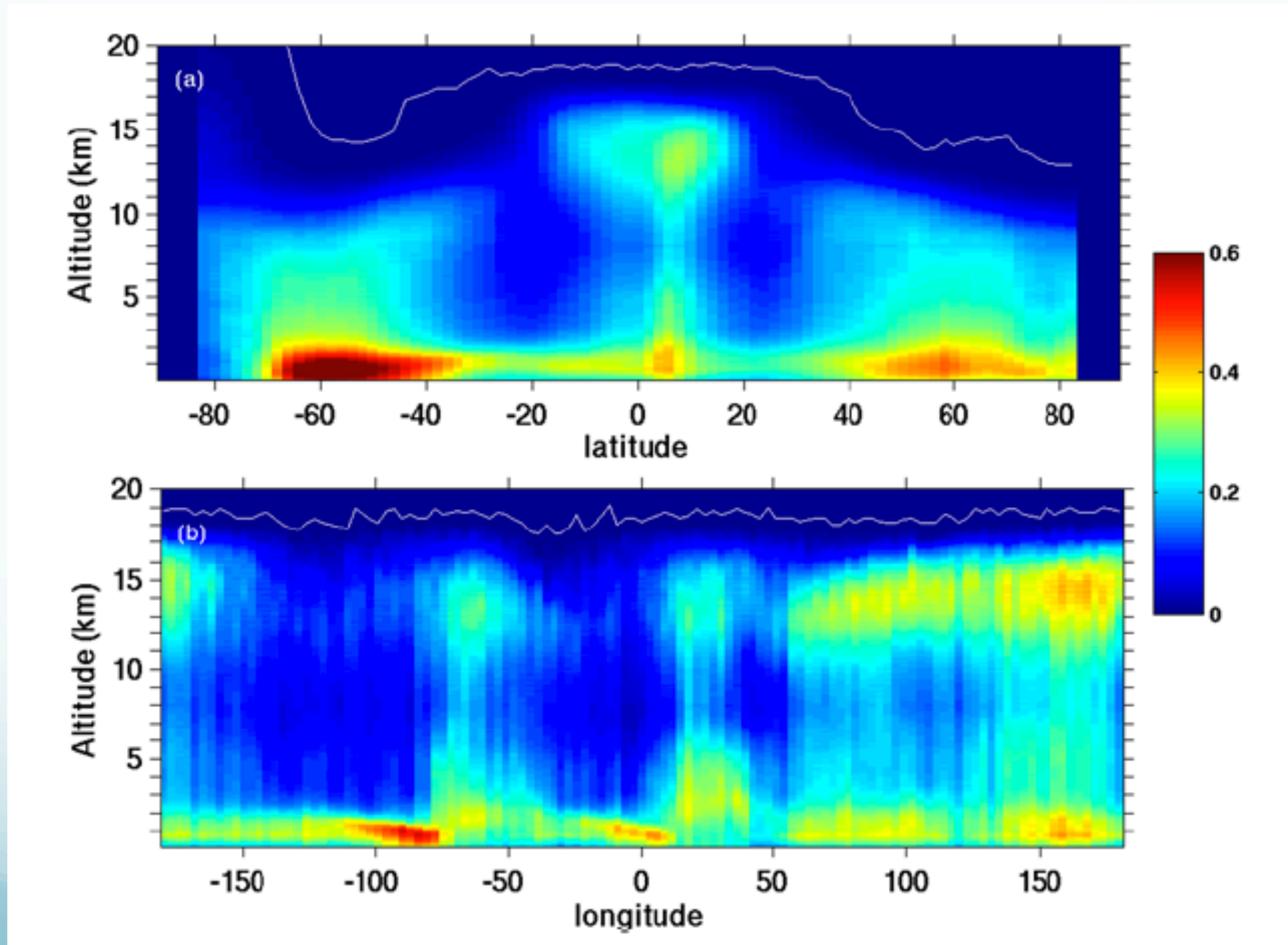
Folkins '99 "Explanation"

- Predicted mixing layer depth with Theta-E profile.
- I would say this is a consistency statement, not a prediction.



Clouds

- CALIPSO lidar, most sensitive cloud instrument.

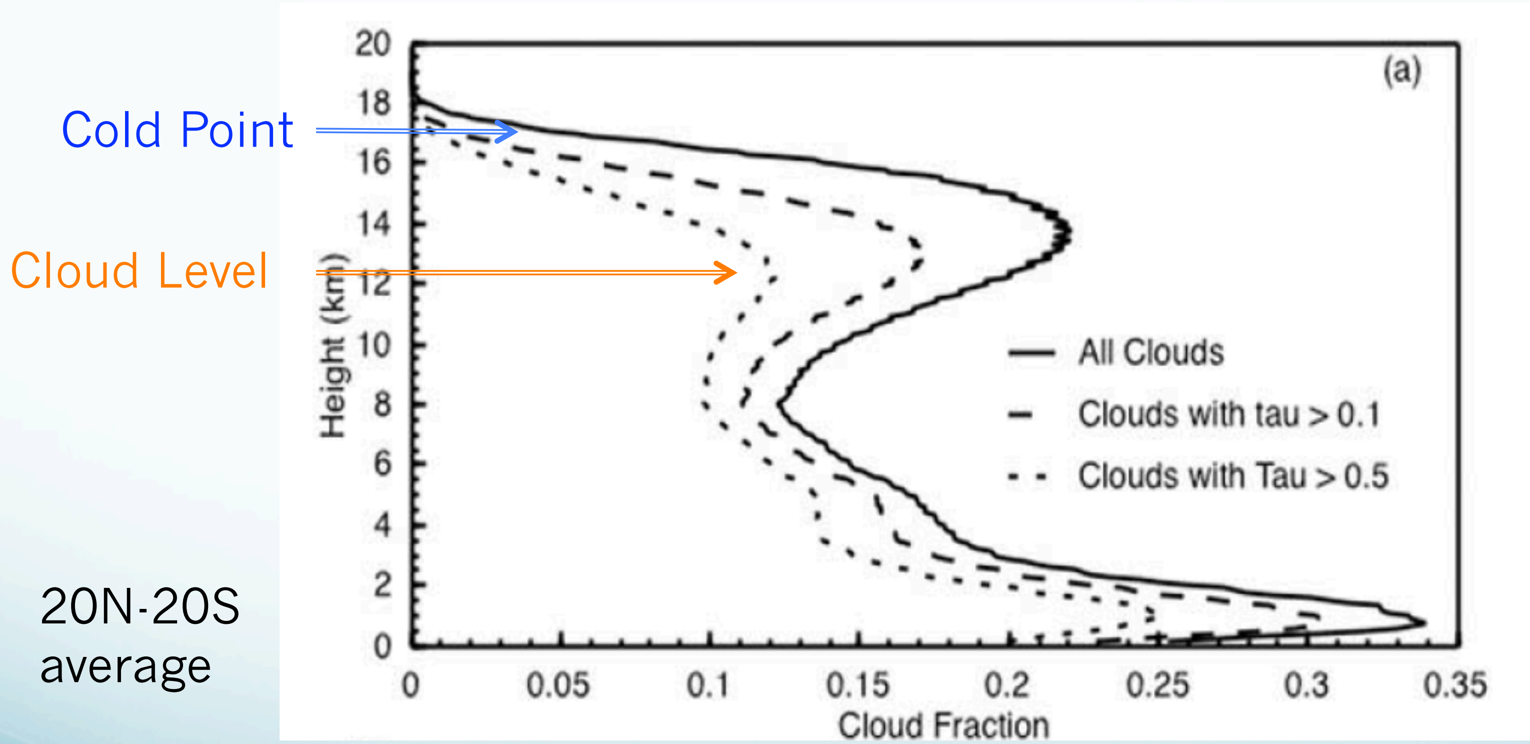


20N-20S average

Fu, Hu and Yang, GRL, 2007

Clouds

- CALIPSO lidar: Thin clouds everywhere in Tropics, but main cloud deck ~12km



20N-20S average

Fu, Hu and Yang, GRL, 2007

The Fixed Anvil Temperature (FAT) Hypothesis

Hartmann & Larson, GRL (2002)

- The detrainment level of tropical clouds is set by clear-sky radiative processes
- Specifically, active convection ceases where the air becomes so cold that water vapor becomes inefficient at radiating away energy provided by convection.
- This marks the top of the actively convecting layer.
- Since water vapor depends only on temperature, the top of the actively convecting layer and the clouds associated with it, will remain at the same temperature if the surface temperature changes.

The Fixed Anvil Temperature (FAT) Hypothesis

- Diagnosis:
  1 Compute the clear-sky radiative cooling,
  2 the large-scale subsidence required to provide the adiabatic heating to balance the radiative cooling,
  3 and the convergence of the vertical velocity.
  4 This gives us the **Clear-Sky Convergence**
- Compare the observed cloud fraction and the clear-sky convergence as functions of pressure or temperature.
- Compute the **sensitivity** of the cloud fraction and clear-sky convergence to tropical mean SST.

Observed cloud and Clear-Sky Convergence

Based on period from 2002-2011

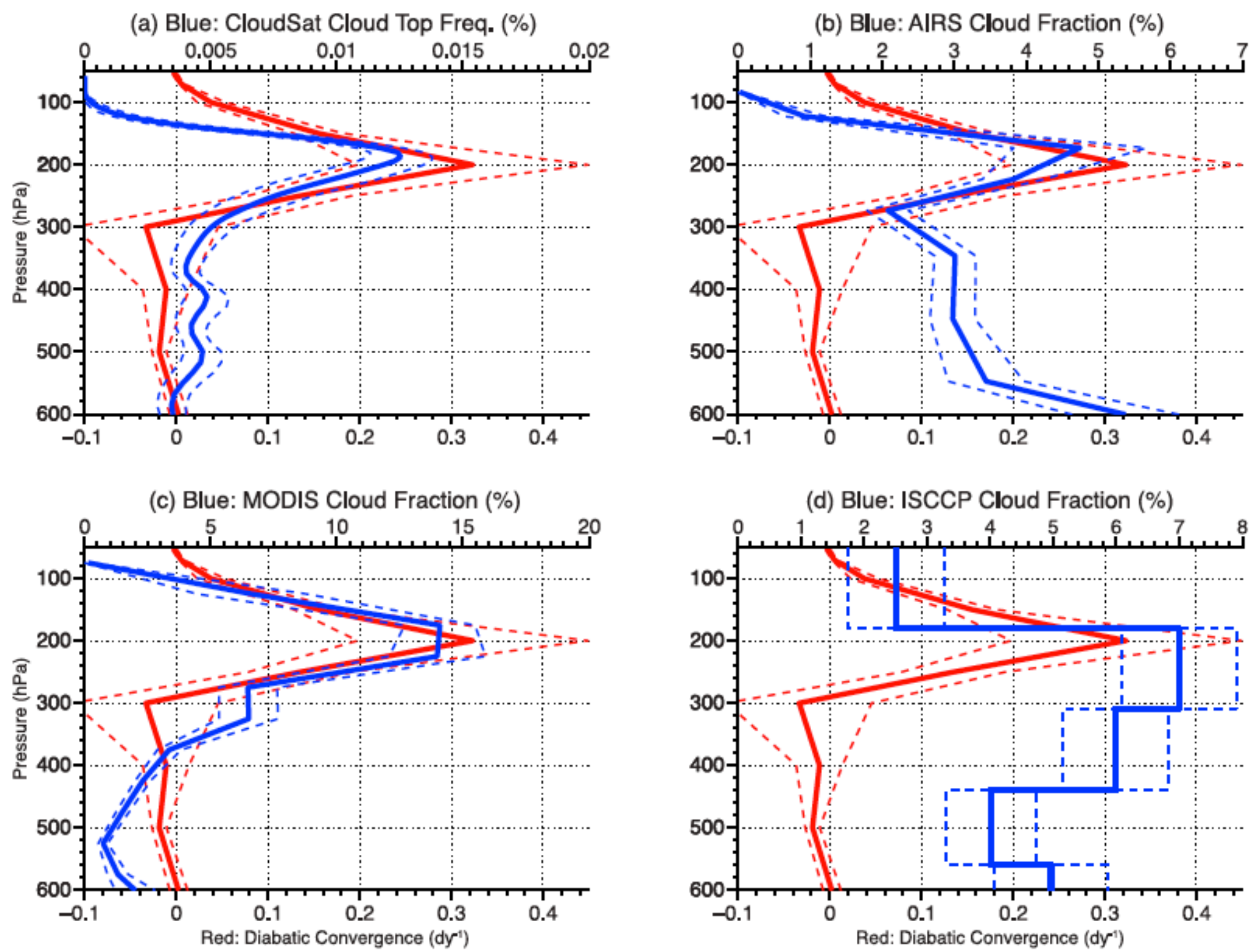


Figure 3. Tropical mean (a) cloud top frequency of occurrence from CloudSat and cloud fraction from (b) AIRS, (c) MODIS, and (d) ISCCP (blue). MODIS cloud fractions are plotted at the geometric mean pressure of the cloud top pressure bins. Only clouds with $\tau \geq 1.3$ are included in the ISCCP cloud fraction plot. Overlain red lines show the diabatic convergence repeated from Figure 2f. The dashed lines represent the 2σ range of monthly tropical average quantities. Note that the range of values on the upper x axis varies.

Tropical-Mean Conditions

Cloud Fraction – BLUE

And convergence associated with large-scale subsidence necessary to balance clear-sky radiative cooling - RED

Zelinka & Hartmann, 2011

Sensitivity to SST

In pressure Coordinates

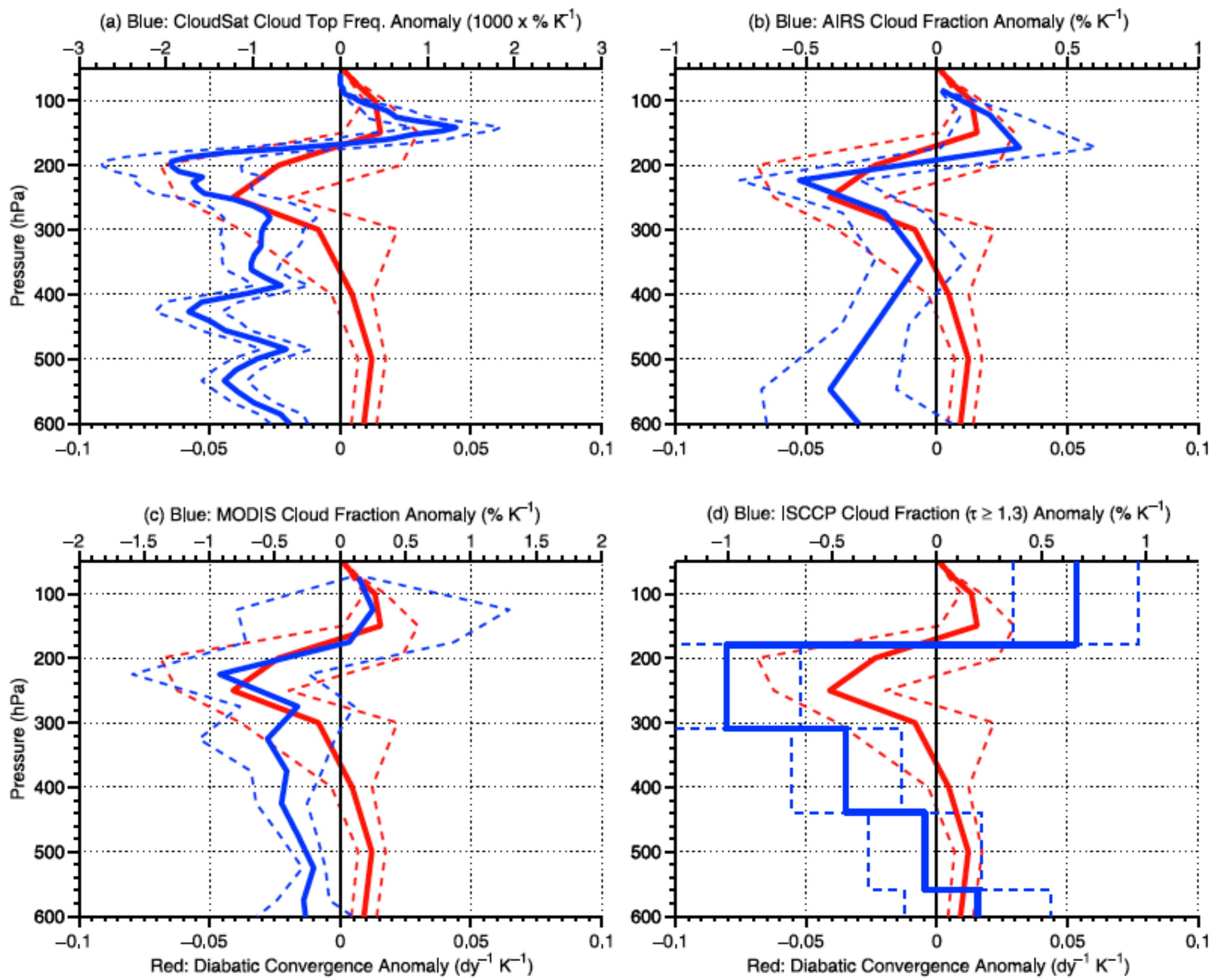


Figure 7. Sensitivity of (a) tropical mean cloud top frequency of occurrence from CloudSat and cloud fraction from (b) AIRS, (c) MODIS, and (d) ISCCP to tropical mean surface temperature (blue). Only clouds with $\tau \geq 1.3$ are included in the ISCCP cloud fraction plot. Overlain in red is the sensitivity of diabatic convergence to tropical mean surface temperature as shown in Figure 6f. Note that the range of values on the upper x axis varies. The dashed lines represent the 95% confidence interval of the regression coefficients computed using a bootstrapping method as described in the text.

Sensitivity to tropical mean SST for

Cloud Fraction – BLUE

And clear-sky convergence – RED

Both move to lower pressure as SST warms

Zelinka & Hartmann, 2011

Mean and Sensitivity

In temperature coordinates

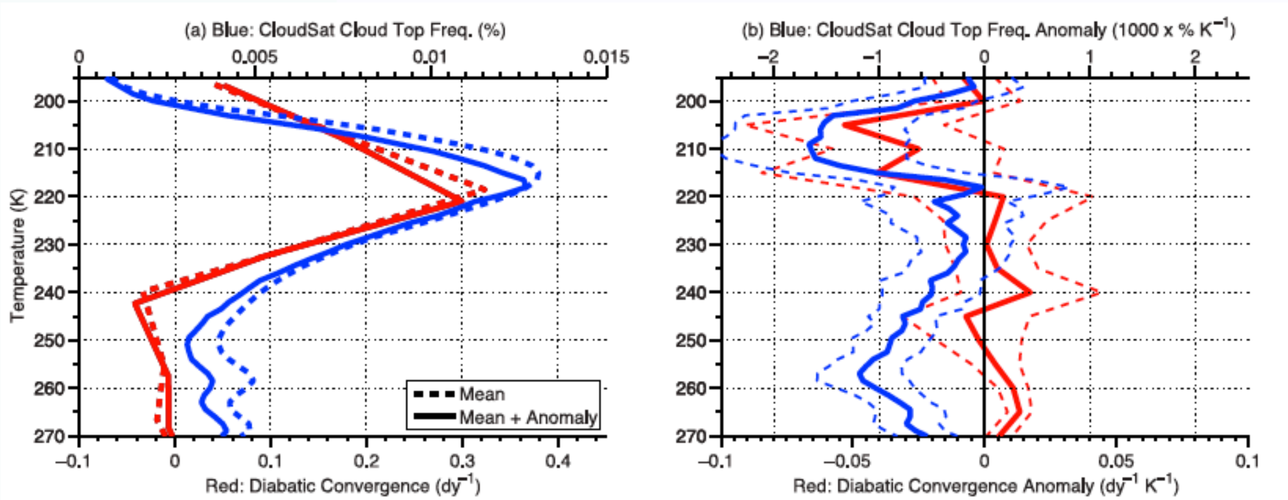


Figure 9. (a) Tropical mean CloudSat cloud top frequency of occurrence (blue) and diabatic convergence (red). The dashed lines represent the mean profile, and the solid lines represent the sum of the mean and perturbation profile shown in Figure 9b. (b) Sensitivity of tropical mean CloudSat cloud top frequency of occurrence (blue) and diabatic convergence (red) to tropical mean surface temperature. The dashed lines represent the 95% confidence intervals of the regression coefficients computed using a bootstrapping method as described in the text.

Mean (left panel) and Sensitivity to tropical mean SST (right) for

Cloud Fraction – BLUE

And convergence associated with large-scale subsidence necessary to balance clear-sky radiative cooling - RED

Zelinka & Hartmann, 2011

In temperature coordinates the cloud and clear-sky convergence show **no change of temperature**, but the **magnitude of the convergence and the amount of cloud both decrease** at temperatures between 200 and 215K. **If this is robust, why does it occur?**

Tropical Convection in a Box

- Kuang and Hartmann (2007) used SAM CRM to compute radiative-convective equilibrium response to fixed SST in a tropical box: 64x64 1km horizontal resolution, 96 layers, single moment microphysics, GCM–style CCM3 radiation.
- Showed remarkable insensitivity of cloud temperature to SST and robustness of cloud temperature to ozone, CO_2, stratospheric circulation (BDC), and stratospheric water vapor.

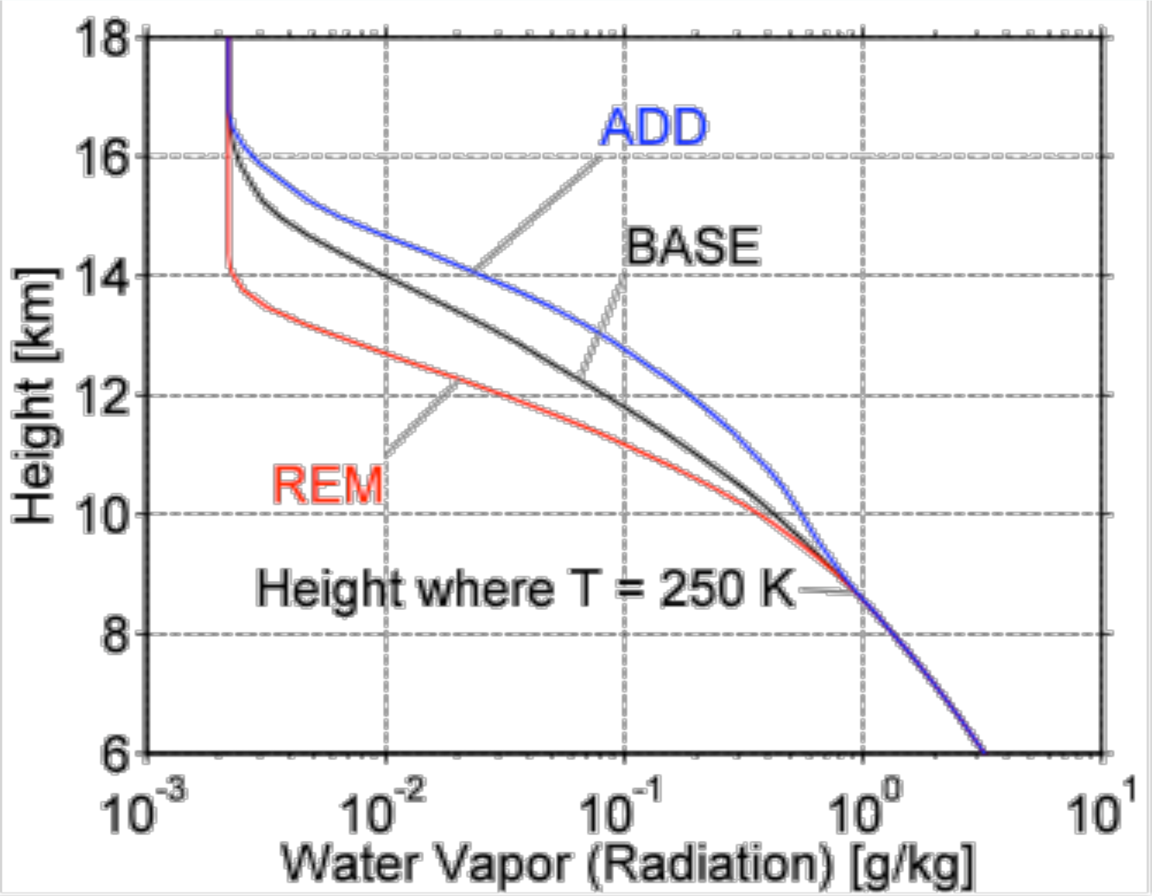
Tropical Convection in a Box

- Harrop and Hartmann (2012) same setup as Kuang and Hartmann (2007) except used RRTM radiation code, and also used a 3km horizontal resolution to test sensitivity to self-aggregation.
- Specifically test role of water vapor by changing water vapor concentrations seen by radiation code (no change to microphysics)
- Further investigate role of other trace gases, especially ozone.

Water Emissivity Experiments

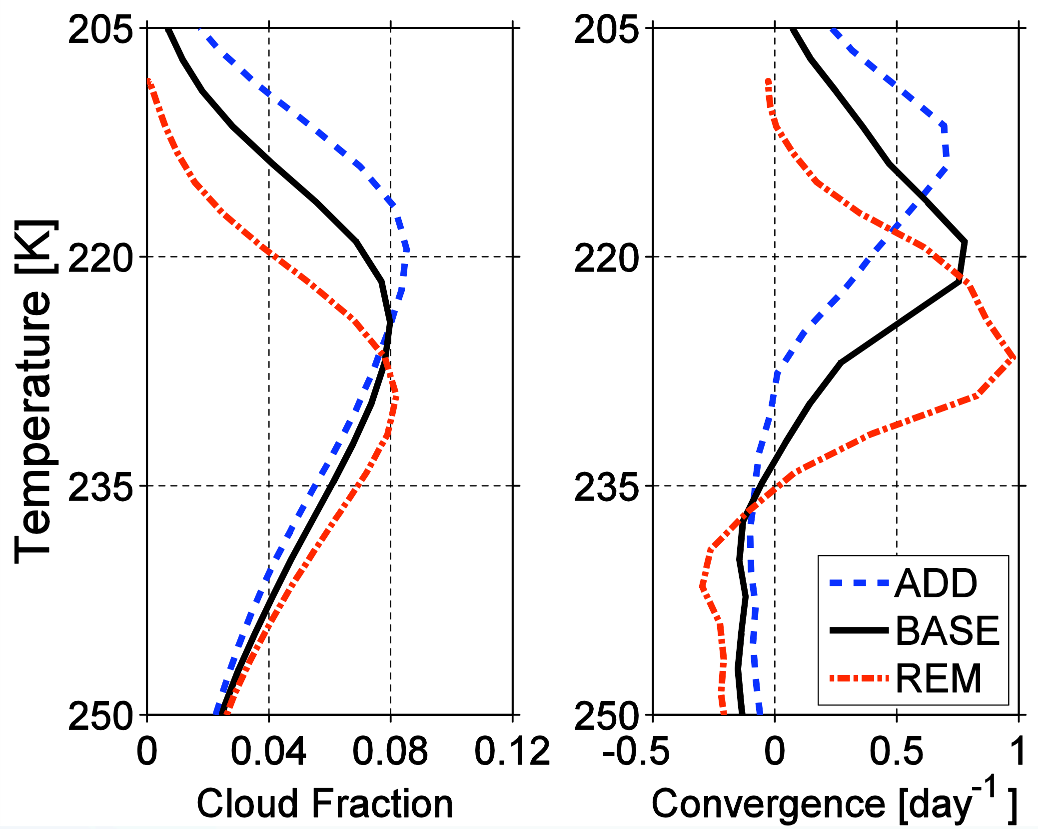
- To test the hypothesized control of cloud top temperature by water vapor's radiative effect we,
- Change the emissivity of water vapor in the upper tropical troposphere.
- Hypothesis: Less water emissivity, warmer clouds
  More water emissivity, colder clouds
- Rather than change the radiative code, we just change the water vapor seen by the radiation code, leaving the predicted water vapor alone, but "adjusting" it as it goes into the radiation code.

Emissivity Experiments

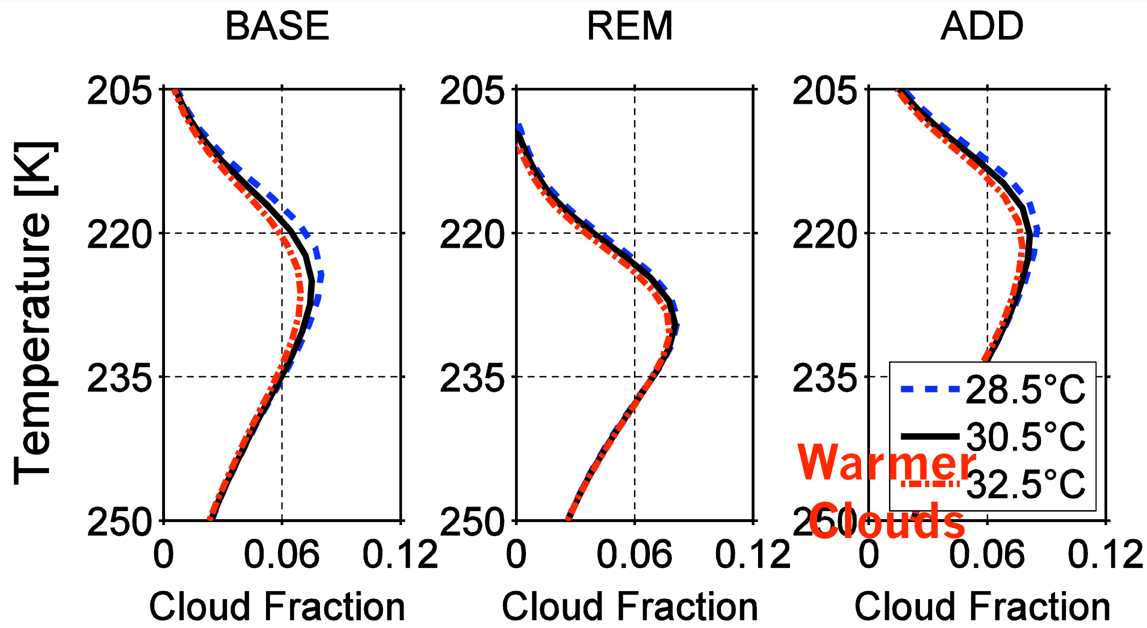


Cloud Fraction Clear-Sky Convergence

Results



Water Emissivity Experiments



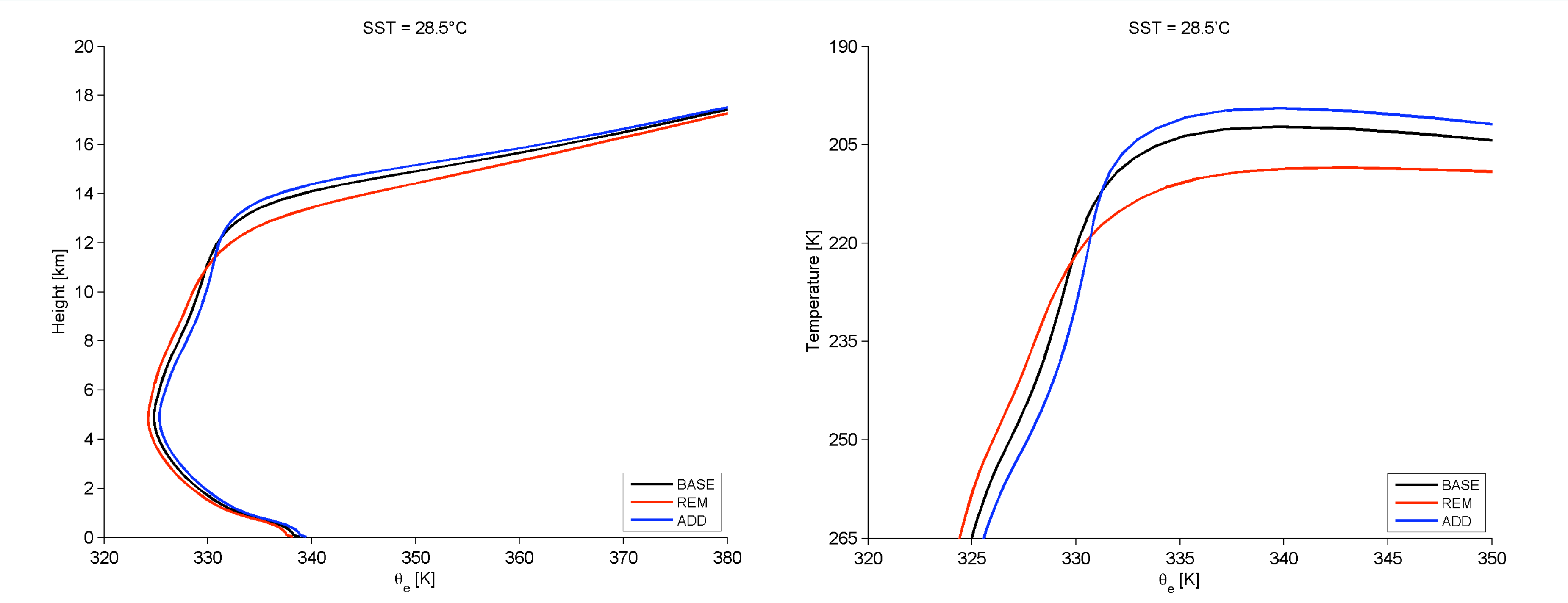
Colder Clouds

Water Emissivity Experiments

- If we increase the water vapor emissivity in the upper tropical troposphere we can make the cloud tops colder, and vice versa.
- Conclude that the radiative effect of water vapor and its dependence on temperature is the primary explanation for insensitivity of cloud temperature to surface temperature in radiative-convective equilibrium.

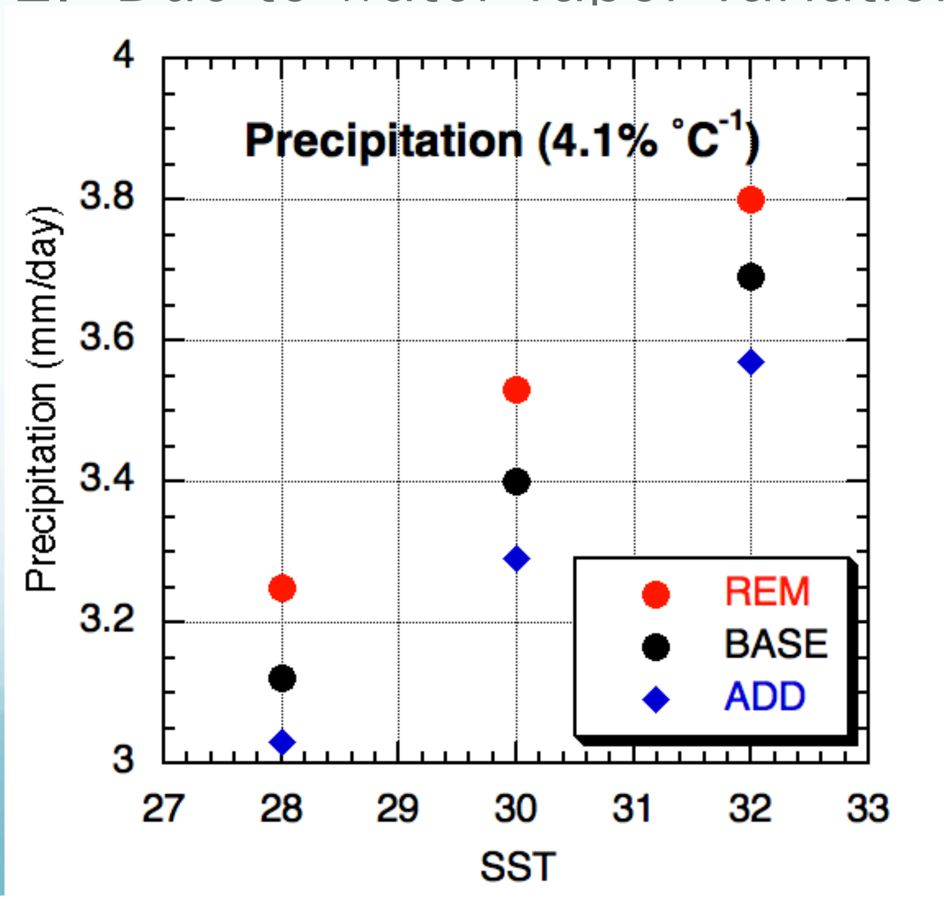
Water Emissivity Experiments

- What about Ian Folkins' ThetaE argument?
- Adding water vapor at the top you cool more at low temperatures and pressures, so you decrease thetaE near the top, but increase it below.



Water Emissivity Experiments

- How does precipitation change?
- 1. Due to SST, ~+4.1%/°C.
- 2. Due to water vapor variations REM, BASE, ADD?

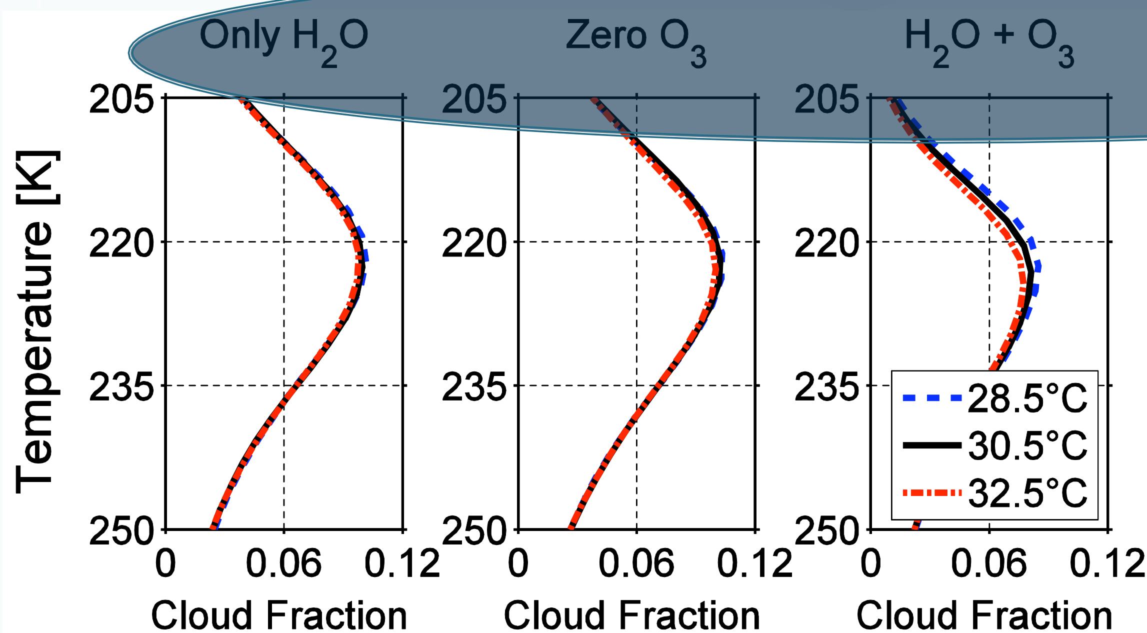


Reducing upper tropospheric water emissivity reduces greenhouse effect and causes emission to come from warmer layers, cooling atmosphere more efficiently and increasing precipitation rate. ThetaE is reduced at surface to support greater heating from the ocean.

Ozone Experiments

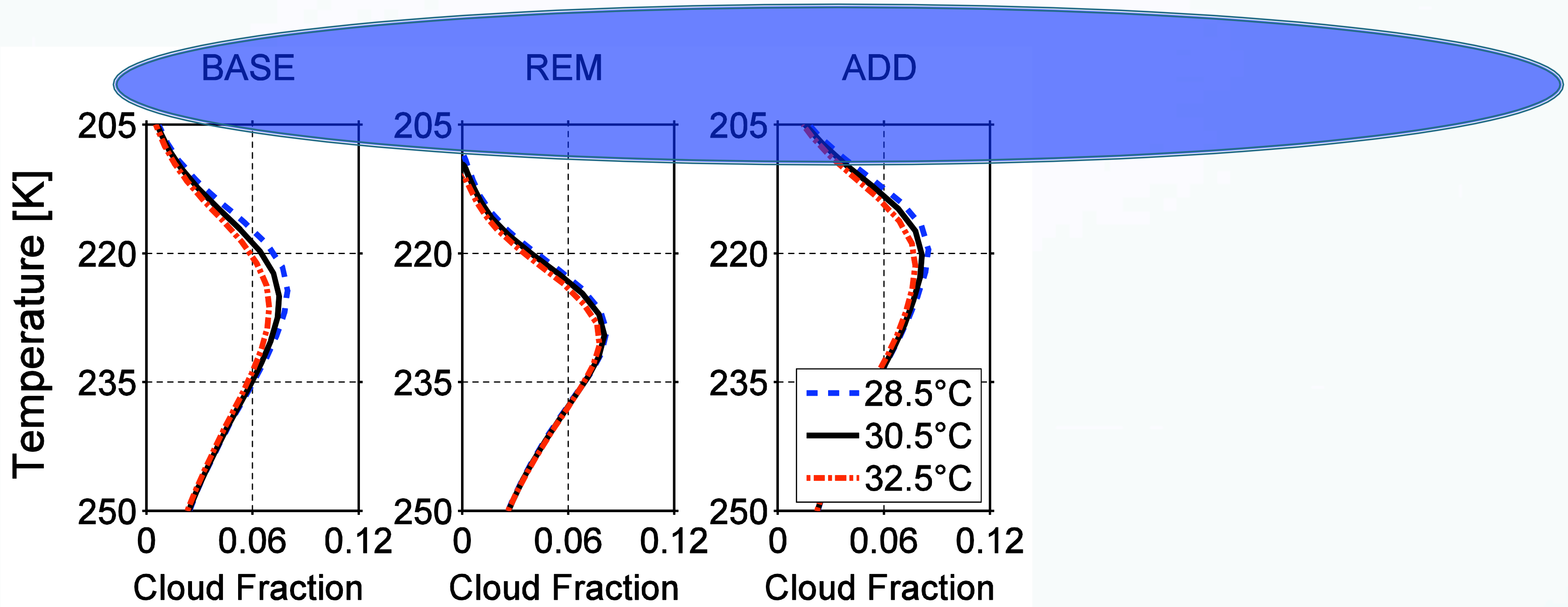
- Contrary to the expectations of the Fixed Anvil Temperature Hypothesis the **clouds warm slightly with SST** and cloud fraction decreases.
- We will now show that **this is because ozone is fixed** as a function of pressure in these experiments.
- As the surface warms and the convection rises to higher altitudes (lower pressures), the clouds are increasingly influenced by ozone, which heats the atmosphere and increases stability in the upper troposphere.

Ozone Experiments



In the absence of ozone, both cloud temperature and cloud amount are very insensitive to SST

Water Emissivity Experiments



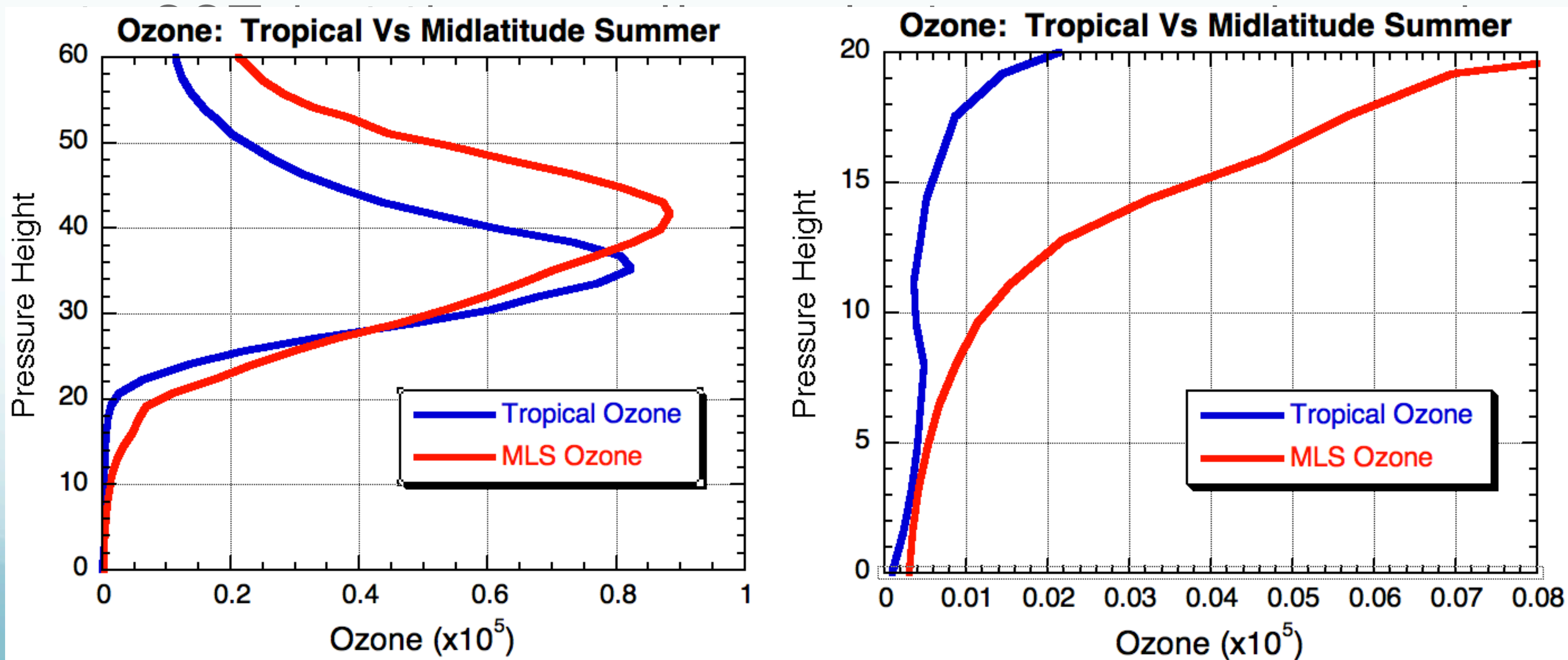
In the absence of ozone, both cloud temperature and cloud amount are very insensitive to SST

Water only case

- Cloud fraction AND cloud temperature are independent of SST.
- **Cloud mass flux declines** since more water is carried by same mass flux and condensation heating can only proceed at rate of radiative cooling
- But smaller mass flux carries same amount of water upward and yields same cloud fraction.

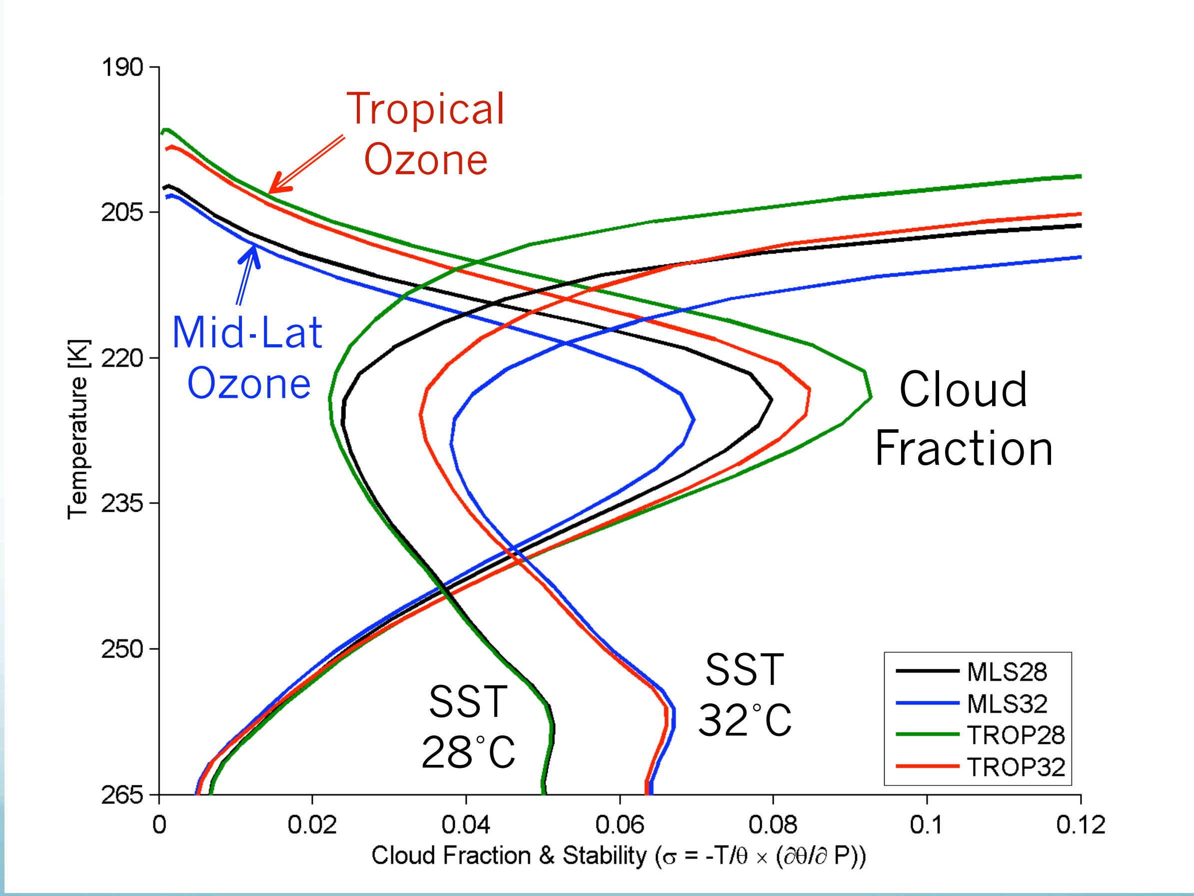
Ozone Profiles

- We inadvertently used a midlatitude summer ozone profile for most of the results you've just been shown.
- If we use a tropical profile the clouds move up a bit and the cloud top temperature is even less sensitive



Response to Tropical versus Midlatitude Summer Ozone Profile

- Ozone and Temperature both have strong effects on cloud fraction, but somewhat less effect on temperature of the most abundant cloud.



Summary

- Tropical Radiative Convective Equilibrium in a box supports that hypothesis that the radiative effect of water vapor gives clouds with temperature independent of SST.
- Warming of clouds (modest effect) and reduction in cloud area (more significant effect) arises from ozone that is fixed in pressure.
- If water vapor is only radiatively active gas present, then neither the cloud fraction or the cloud temperature change with SST.
- Very little evidence of expected cloud fraction response to SST/dry static stability without ozone.

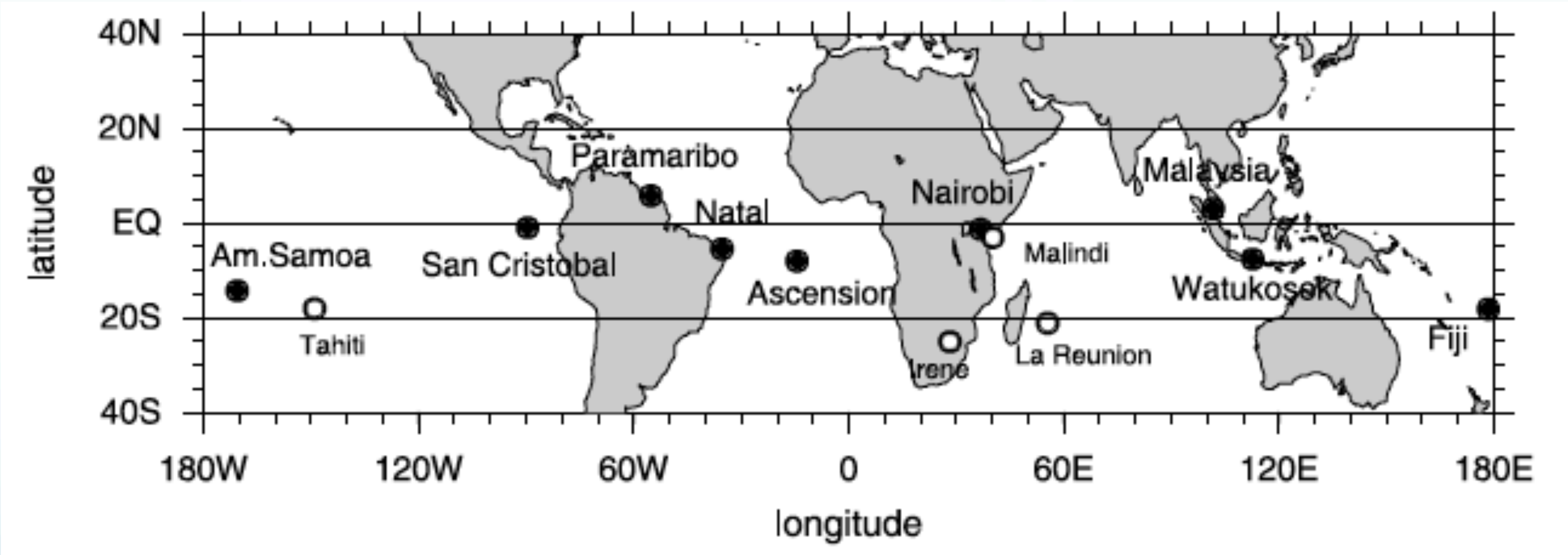
Implications

- Warming of high clouds and reduction in high cloud area arises from ozone that is fixed in pressure.
- Ozone effect on high cloud fraction response to SST is much stronger than any process related to moist thermodynamics, dry static stability or dynamics
- Since tropical cold clouds interact strongly with tropical ozone, one needs to predict ozone in the troposphere to predict cloud properties.
- Thanks!

More Ozone Data (SHADOZ)

Takashima and Shiotani (2007)

- SHADOZ network of Ozone Sondes



More Ozone Data (SHADOZ)

Takashima and Shiotani (2007)

- Climatological Ozone minimum rather subtle.

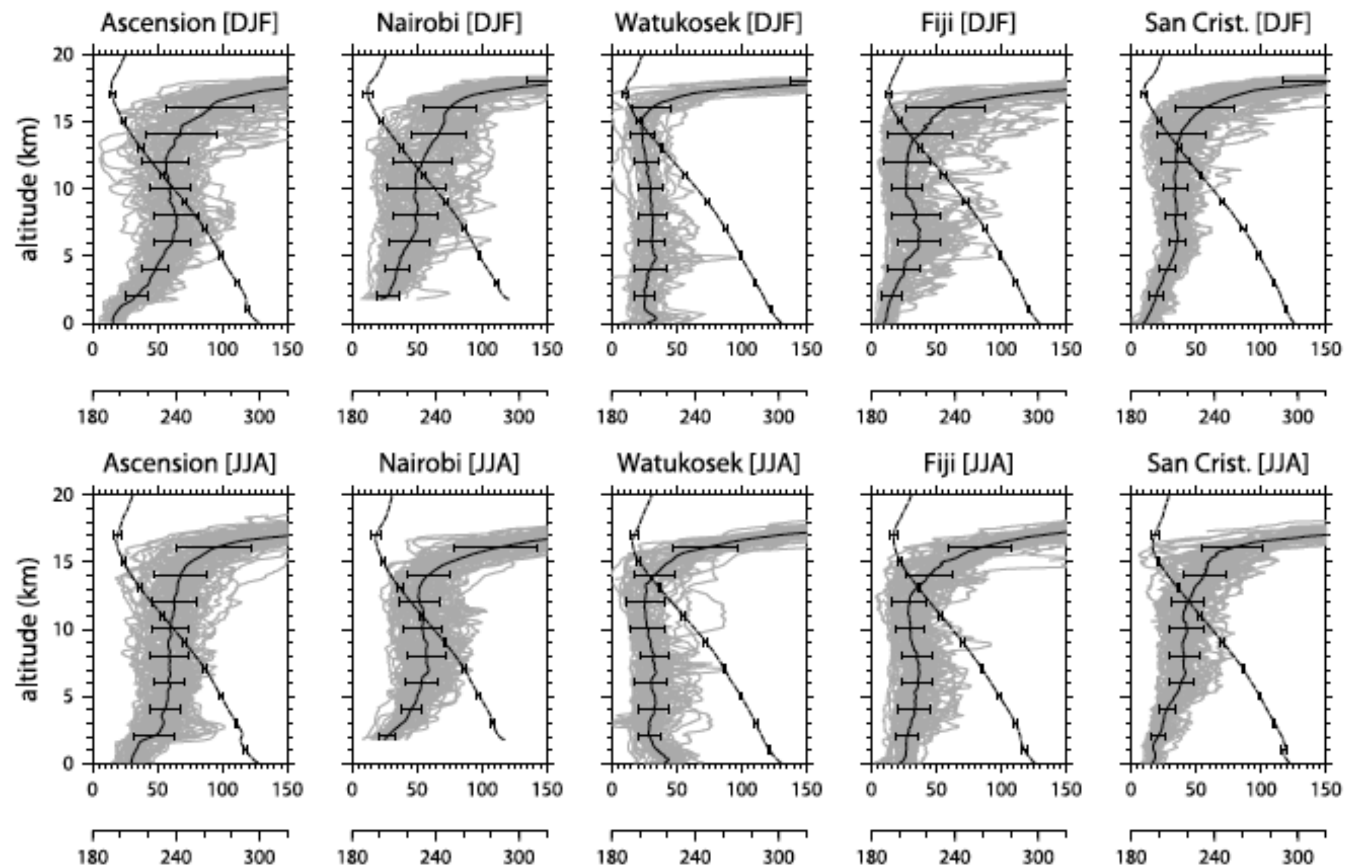
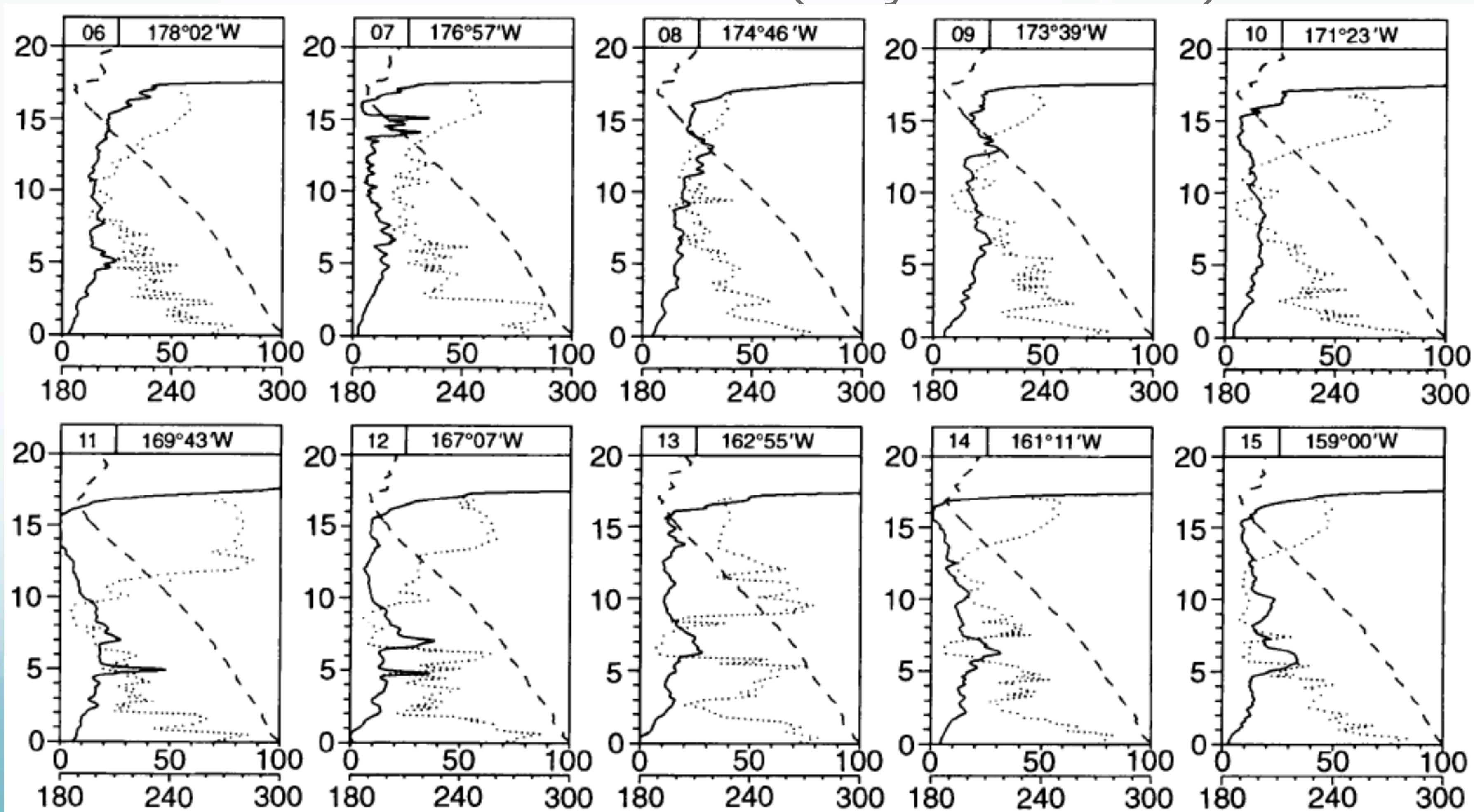


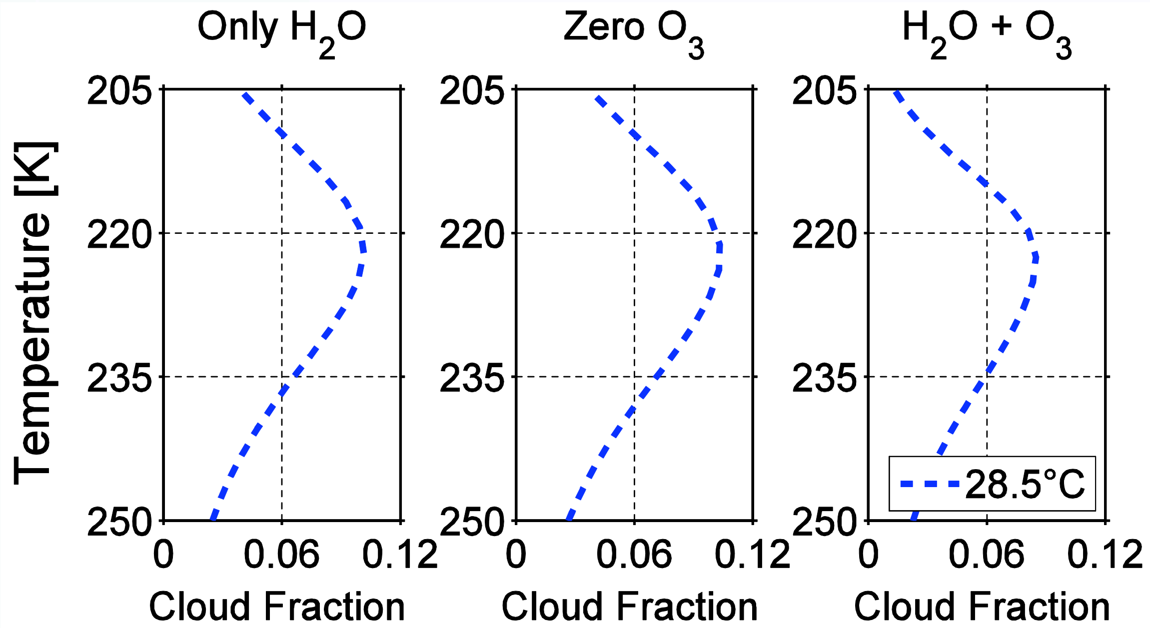
Figure 2. Vertical profiles of the ozone mixing ratio (solid line in parts per billion by volume; upper scale) and the averaged temperature (dashed line in kelvin; lower scale) for December–February (top) and June–August (bottom) at Ascension, Nairobi, Watukosek, Fiji, and San Cristóbal. Thick lines indicate averaged ozone profiles. Error bars indicate ±1 standard deviations.

Composition Data

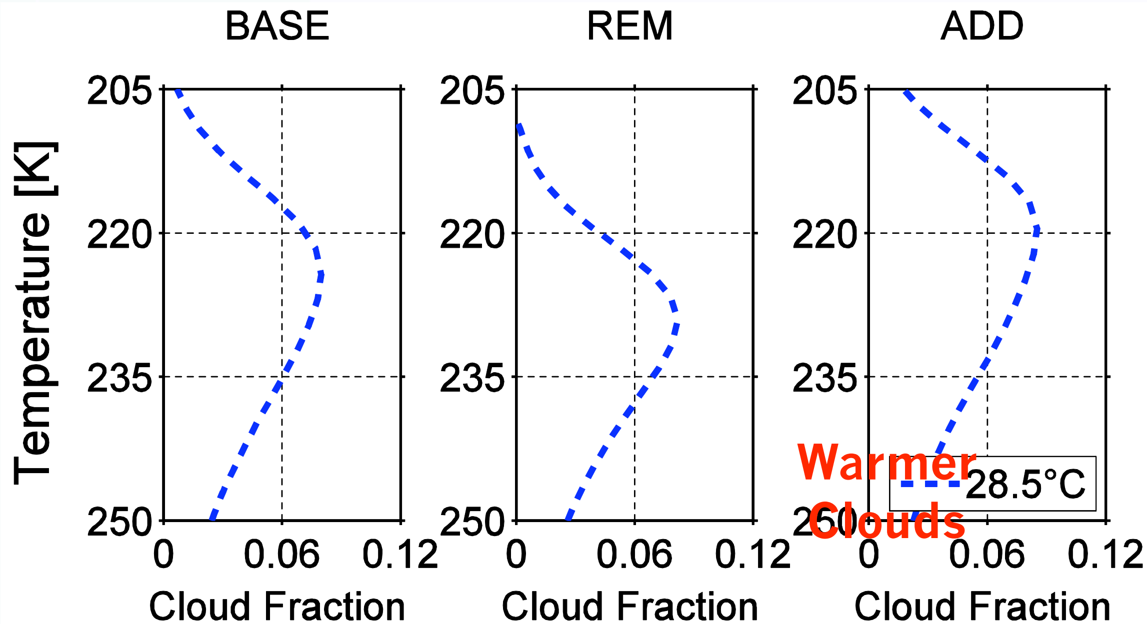
- In convective regions, the TTL can be associated with a minimum in ozone. (Kley et al. 1996)



Ozone Experiments



Water Emissivity Experiments



Colder Clouds