Robust Responses of Tropical High Clouds in GCMs

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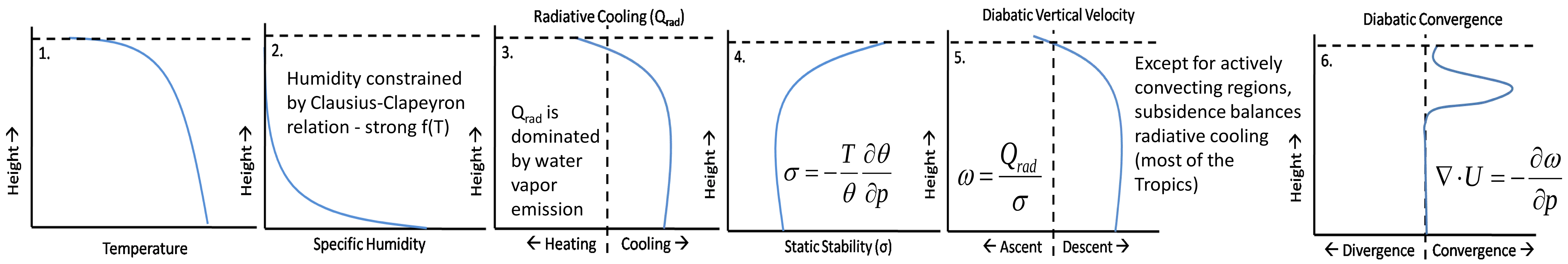
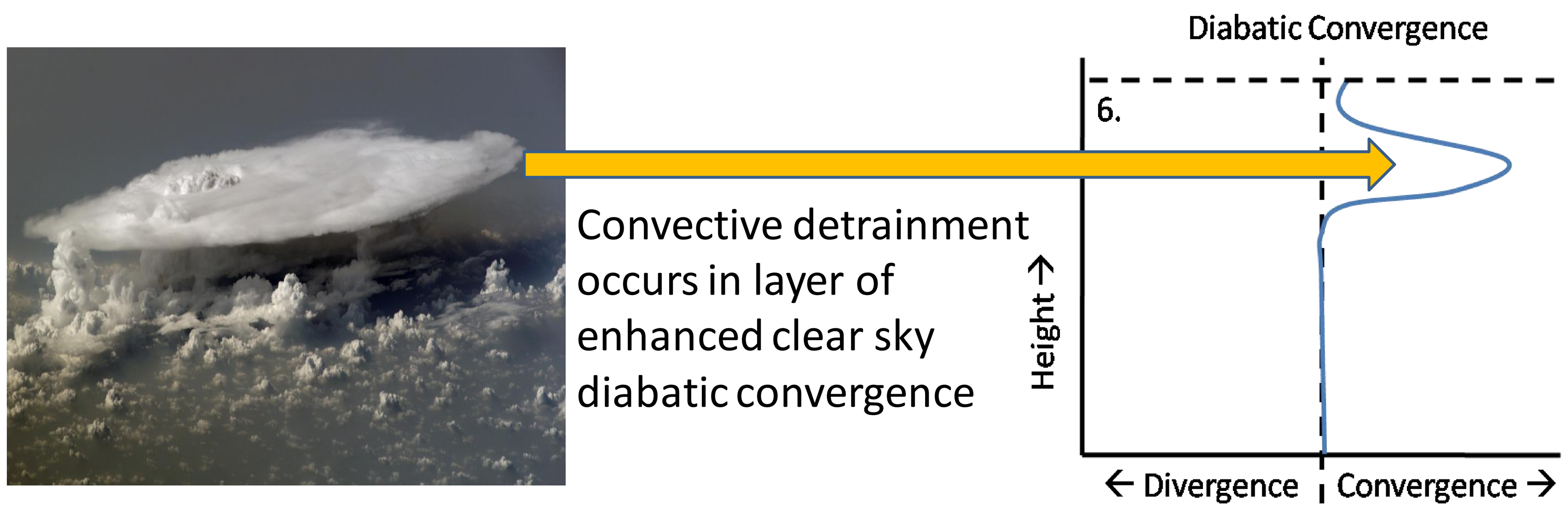
1. Motivation / Objectives

All global climate models submitted to the IPCC AR4 archive exhibit a positive longwave cloud feedback.
Here we propose that this is largely due to the fact that tropical high clouds maintain a nearly constant emission temperature.
Furthermore, we show that this feature should be expected from physical relationships that are fundamentally constrained by thermodynamics.

2. The Fixed Anvil Temperature (FAT) Hypothesis

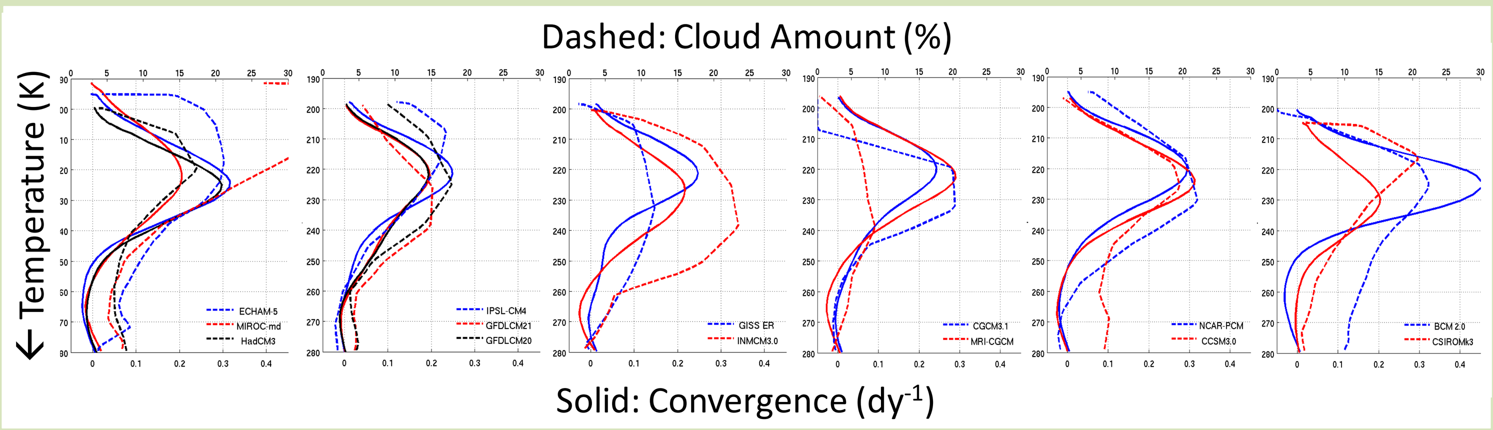
○ Hartmann and Larson (2002) hypothesized that the **altitude at which high clouds are most abundant** is where the clear-sky **diabatic convergence is largest** and that this level will remain at about the same temperature (not height!) as the climate warms.





○ **The atmosphere can only be heated by convection in regions that are balanced by radiative cooling.** Radiative cooling decreases rapidly with height beginning below the tropopause because **water vapor concentrations become so small in upper troposphere**. **Water vapor concentrations are primarily constrained by temperature** through the Clausius-Clapeyron relation; thus the temperature profile governs the height of abundant high clouds.
○ **KEY POINT**: The level of abundant high cloudiness will **remain at about the same temperature as the climate warms** because clouds will only exist where water vapor is abundant enough to radiatively cool, and this is fundamentally constrained by temperature.

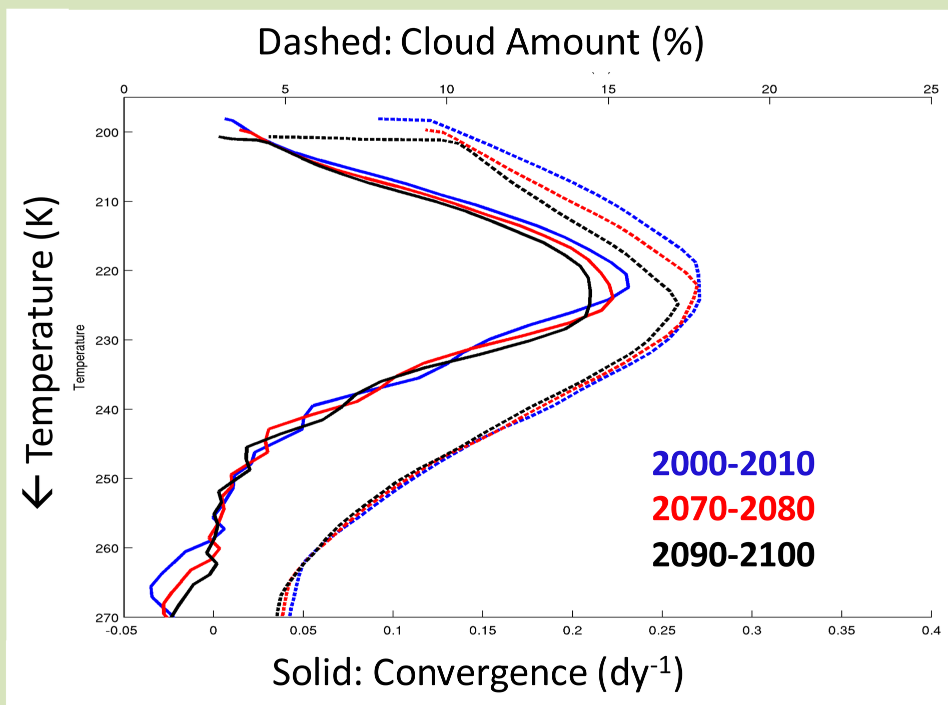
3. Correspondence Between Diabatic Convergence and High Clouds in AR4 GCMs

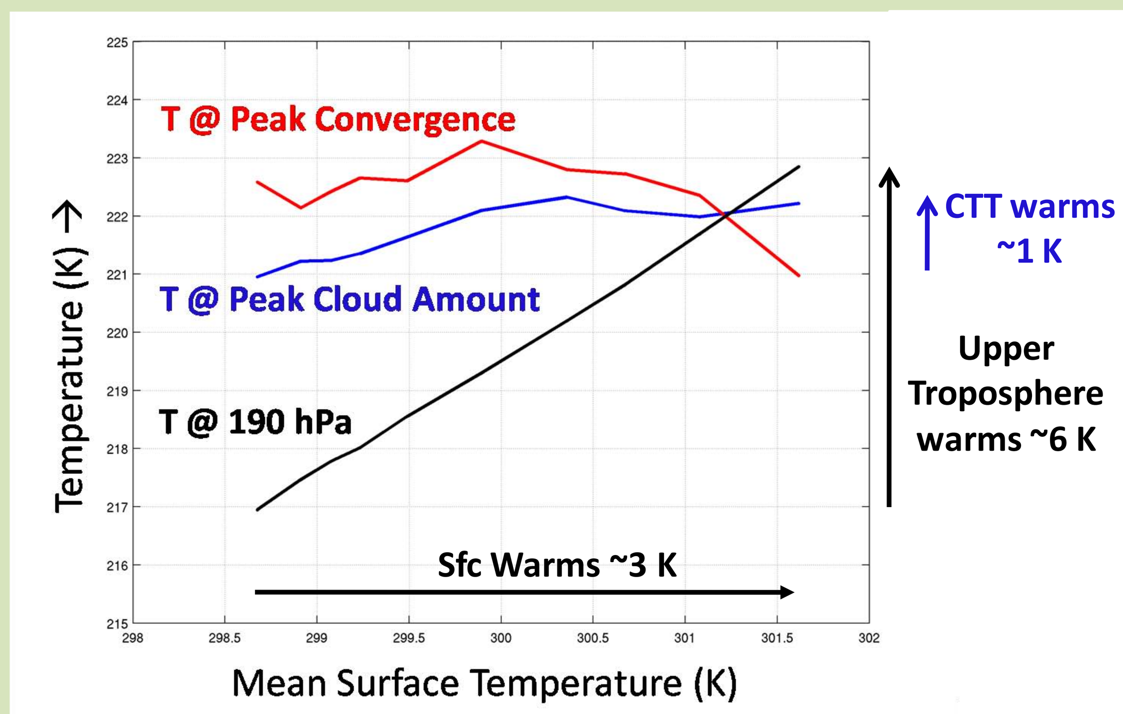


Above: Tropical-mean cloud amount (dashed) and diabatic convergence (solid) for 14 AR4 models

In all figures, diabatic convergence is calculated using radiative cooling profiles generated with the Fu-Liou 4-stream radiative transfer code. Tropical mean temperature and humidity profiles from each model are used as input to the radiation code.

4. Assessing FAT in 14 GCMs (SRES A2 Scenario)





○ **Ensemble-mean cloud amounts correspond to peak in ensemble-mean diabatic convergence**
○ The **temperature at this level remains nearly constant** as the climate warms over the 21st Century.
○ Upper troposphere warms much more than the surface (moist adiabat), **but temperature at level of peak cloud amount warms only slightly → strong positive LW cloud feedback**
○ **Slight reduction in magnitude of diabatic convergence and cloud amount**

5. Estimating the Contribution of FAT to LW Cloud Feedback

Mathematical Framework

[1] $LWCF = OLR_{clr} - OLR = f(OLR_{clr} - OLR_{cld})$

[2] $\Delta LWCF = \Delta f(OLR_{clr} - OLR_{cld}) + f\Delta OLR_{clr} - f\Delta OLR_{cld}$

Assume f and OLR_{cld} can be broken into components from high and low clouds:
[3] $fOLR_{cld} = f_{hi}OLR_{hicld} + f_{lo}OLR_{locld}$, where f_{lo} is the effective low cloud fraction

[4] $OLR_{hicld} = \sigma CTT^4$, where CTT is a cloud-weighted temperature for clouds that are between the freezing level and the tropopause

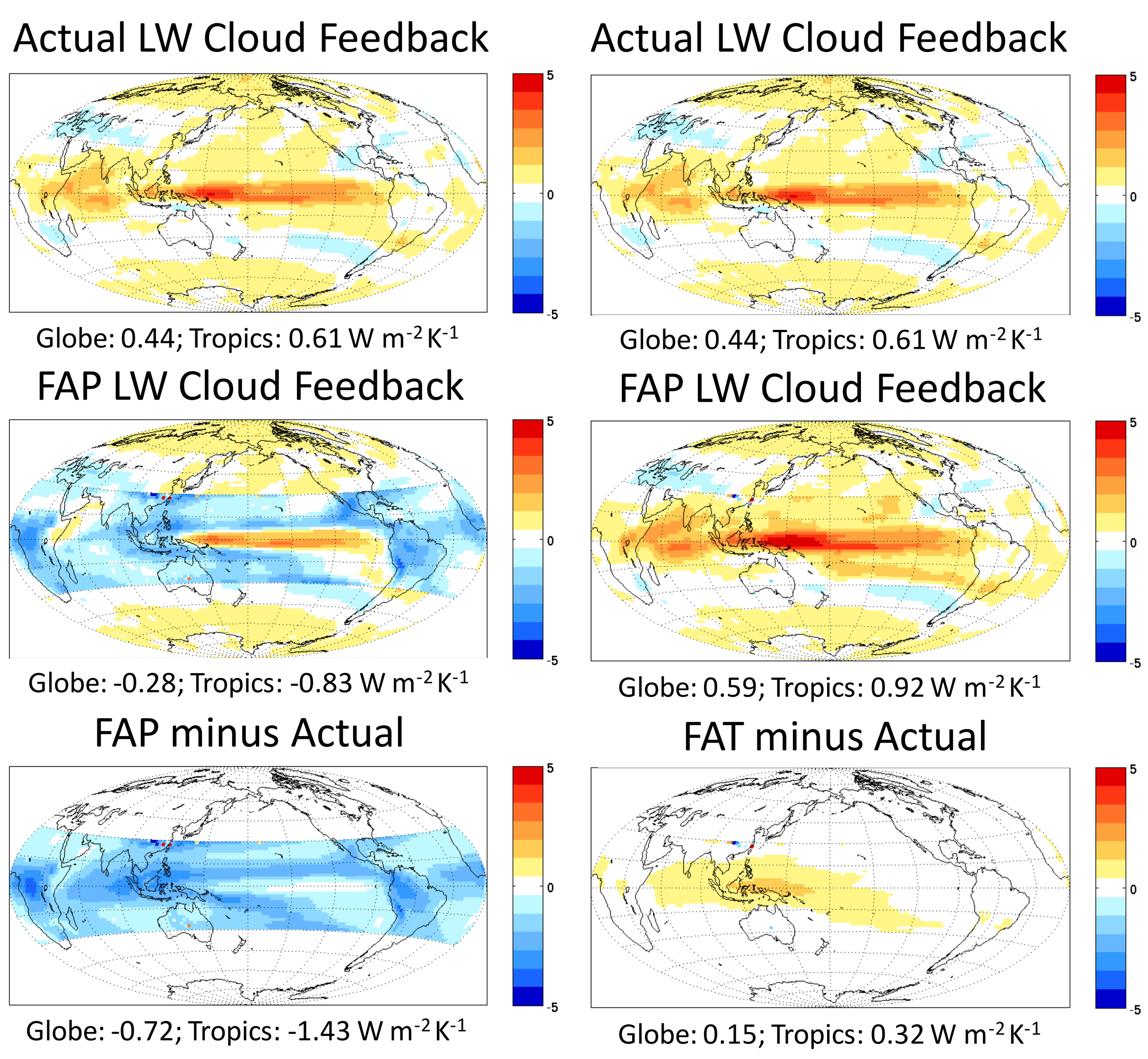
Using $f = f_{hi} + f_{lo}$, we can solve [3] for f_{hi}:
[5]
$$f_{hi} = f\,\frac{OLR_{cld} - OLR_{locld}}{OLR_{hicld} - OLR_{locld}}$$
where OLR_{cld} is given by [1], OLR_{hicld} is given by [4], and we assume $OLR_{locld} = OLR_{clr}$

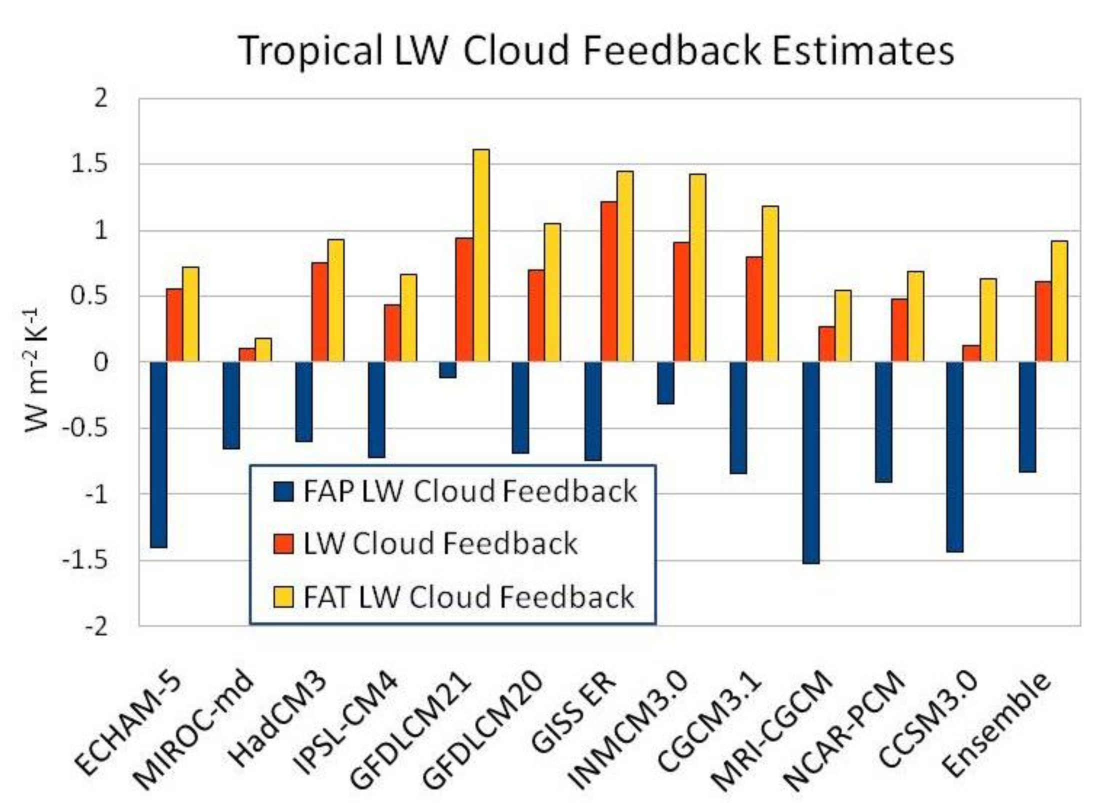
[6] $\Delta LWCF = \Delta f_{hi}(OLR_{clr} - OLR_{hicld}) - f_{hi}\Delta OLR_{hicld} - f_{lo}\Delta OLR_{locld} + f\,\Delta OLR_{clr}$

Two hypothetical scenarios, **Fixed Anvil Pressure** and **Fixed Anvil Temperature**:
[7] $\Delta LWCF_{FAP} = \Delta f_{hi}(OLR_{clr} - OLR_{hicld}) - \mathbf{f_{hi}\Delta OLR_{hicld}} - f_{lo}\Delta OLR_{locld} + f\,\Delta OLR_{clr}$

[8] $\Delta LWCF_{FAT} = \Delta f_{hi}(OLR_{clr} - OLR_{hicld}) - ~~f_{hi}\Delta OLR_{hicld}~~ - f_{lo}\Delta OLR_{locld} + f\,\Delta OLR_{clr}$

Finally, we use the radiative kernel technique (Soden et al. 2008) to convert ΔLWCF to LW cloud feedback (apply a correction factor due to clouds masking temperature and humidity changes).





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6. Take Home Points

○ The **level of abundant upper tropospheric cloudiness** in the AR4 model ensemble-mean **corresponds quite well with the ensemble-mean clear-sky upper tropospheric diabatic convergence**, however there is considerable spread from model to model.
○ The **high cloud response to global warming in GCMs is qualitatively consistent with the FAT hypothesis**: upper tropospheric convergence and the corresponding high cloudiness **remain at approximately the same temperature** as the climate warms during the 21st Century.
○ Actual LW cloud feedback is slightly smaller than that calculated assuming FAT, but is clearly underestimated by assuming that clouds remain at the same pressure.
○ The LW cloud feedback, which is dominated by the tropical cloud response, **can be closely approximated by assuming that tropical high clouds remain at the same temperature**: The actual cloud response much more closely resembles FAT than FAP. **This increases our confidence in the modeled LW cloud feedback because there is a fundamental thermodynamic constraint maintaining this cloud response, namely the dependence of water vapor abundance on temperature through Clausius-Clapeyron.**