"Deep convective clouds at the tropopause"
Anonymous reviewer #1 (questions quoted in italics)

General Question: Can this be done over land?

Yes, but for this paper we restricted the data collection and analysis to tropical ocean, defined as AIRS footprints with less than 1% land fraction between 30S and 30N. We are considering contrasting the land and ocean results in a follow-on paper.

P16479, L20-30. This paragraph needs more explanation....

We agree. AIRS has 2378 channels, but for most of them the radiation from the troposphere is cut off by DCC. All but the strongest co2 and water absorption channels become window channels. The four channels selected in our study capture most of the information (since we are not discussing Methane of Ozone). This approach of focusing on key channels is typical for the analysis of hyperspectal data.

P16479, L20-30. A spectrum from AIRS showing these lines and what they mean would help. This could be used to better explain the geophysical inferences.

We agree, but a figure with 2378 channels, six of which will be used in the analysis, will not show much. (e.g. Kahn et al 2008, Figure 1). For this reason we described the water channel, bt1419, (P16478, L5) under tropical clear conditions as 65 to 85K colder than bt1231. We described the co2 channel, bt712, (P16478, L12) as equally cold relative to bt1231. The bt961 and bt790 channels are described as window channels (P16478, L15) For the observation of the ocean these channels have close to same brightness temperature as bt1231. The geophysical interpretation of the channel differences is at present deferred until the section discussing the results.

We plan to add the following sentence to the manuscript after (P16478, L16).
" Details on the geophysical interpretation of these differences are given at the end of the following section. We also use AIRS channels at 679.9 and 668.2 cm-1 to characterize the temperature structure between 40 and 2 hPa.".

P16480, L1-2: Again, what do DT, DW and DC mean....
Same as above. The terms are defined mathematically, but not geophysical until later in the text.
The following clarification is proposed, starting at P16480, L2.

" Under tropical ocean clear conditions DT is typically +65 to +85K due to water vapor absorption, DW is typically 60K due to strong co2 absorption, DC is typically +4 K due to weak water continuum absorption. Under DCC conditions the signal from the tropopause is cut off and the DT and DW can be as small as minus 10K, due to the radiation from co2 and water vapor in the stratosphere. The three window channels now penetrate the top of a cloud and measure a temperature where the cloud optical depth reaches unity. The exploitation of AIRS 8-13 micron window channels for the characterization of thin cirrus clouds is well known (e.g. Kahn et al. 2008): For a water/ice cloud, the cloud optical depth increases slowly between 1231 and 961 cm-1, but increases very rapidly between 961 and 790 cm-1 and is strongly particle size, shape and density dependent. In the presence of water/ice clouds well below the tropopause, DT is typically a few degree K, but DC can be 10-20K, since in the presence of a negative lapse rate the 790 cm-1 channel reaches unity optical depth sooner (lower pressure) than the 961 channel. This optical depth dependence can be used to relatively accurately define the cloud top relative to the tropopause cold point. If the clouds were to significantly reach into the region of positive lapse rate in the stratosphere, the strong cloud absorption at 790 cm-1 can make DC<0. A numerical evaluation require model calculations, which are described later."

P16480, L17: What is the additional information and what does it tell us?
Same as above.

Figure 1-3: For the scatter plots, some estimate of the significance needs to be shown to reflect scatter.

Figure 1a on P16480, L12, defines the red line (the scatter diagram ridge line) of the data. The probable error in the definition of the ridge line is the width of the dots of the bins. Adding the following sentence on P16480, L14, should help to clarify this:

"For a scatter diagram from a large data set, where each point is plotted with a fixed size, the points start to overprint, giving outliers a visually disproportionate weight. For Figure 1a the scale is so large that it not a significant issue. For this reason the scatter in Figure 1b shows the range of possible models, not uncertainty of the data."

Figure 2a: In order to show the significance of scatter, we show the ridge line and a Probable Error, PE, in the mean for each bin. In Figure 2a we show two additional lines spaced by PE above and below the ridge line. The cases used in the model calculations are intended to capture the mean and the potential variability of model parameters, not the variance of real data.

Figure 3a shows the ridge lines for both channels to show that at very cold cloud tops one shifts colder, the other shifts warmer, i.e. the cold bulge. To clarify this the data are re-plotted in Figure 3b in terms of the stratosphere lapse rate for AIRS and AMSU. Each bin mean in the plot has a +/-1 PE error bar.

P16482, L7. (Figure 4): Based on the large scatter, what is the significance here?

In Figure 4 the red ridge line of the scatter diagram shows that the correlation between the rain rate and DT is very significant. This is why we show the +/- 1 PE uncertainty in the ridge line. This is stated in the figure caption. The small PE shows that the ridge line uncertainty is small, increasing to only about 10% for very large rain rates. The correlation between rain rate and cold 11 micron window channel brightness temperatures has been known for a long time in the form of the GOES Precipitation Index (P16486, L24). When plotted as function of DT it shows the steep increase as DT<-5.

I don't know how "maybe red line with +/- black line?" was left in the caption. This will be removed.

P16483. L1. You got into this a bit later, but looking at where the clouds are un-physically high (tops with P<80 hPa or so) would be useful ....

1) It is not clear how high clouds could be propelled in a non equilibrium conditions. We stopped at 50 hPa.
2) This would be more of an issue, if the models using very high clouds would produce spectra consistent with the data. However, the spectral signature of clouds much above 100 hPa is not seen in the data, even if it was a physically realizable state.

P16484, L10. The other work should be noted here....

Liu&Zipser 2005 is referenced in the introduction and the discussion (P16477, L19 and P16487, L15). Gettelman et al. 2002 is listed in the references, but a sentence, which should have gone on P16484 L12 with the Gettelman reference was left out. It should read: "As an example, Gettelman et al (2002) found that about 0.5% of the [cold] clouds **appear to be colder** than the mean tropopause." This is reasonably consistent with our observations. The cloud tops are indeed colder than the mean tropopause, but not the local tropopause, which is distorted by the very strong convection, detected with AIRS as DCC.

P16484, L.16: Why does the BT difference separate these cold cloud tops?

Figure 2a shows that there were no observations with DC<0, while there are lots of cases in the model spectra in Figure 2b with DC<0 (the blue dots). However, the blue dots are cases where the cloud tops are more than 10 hPa higher than the local tropopause cold point. This is explained in P16484 L22 and following. If the cloud tops were indeed above the tropopause, one should see DC<0 But we don't.

P16484, L25. again, it is not clear what the physical explanation of DC is.

The physical explanation of DC was given in line L.22. Both 790 and 961 are window channels, but the scattering opacity at 790 is larger than at 961. This means that the radiation for 790 comes from higher in the cloud. If the cloud are well above the tropopause, the inversion causes the temperature to be higher at 790 than at 961, i.e. DC=bt961-bt790<0.

P16486, L24 This seems like pure speculation without foundation. A cold bulge is a hydrostatic response to convective heating below.

Gettelman et al (2002) stated very carefully that a small fraction of the cold clouds "appear to be colder than the mean tropopause". The uncertainty of the location of the tropopause in the presence of strong convection relative to the tropopause given in the reanalysis was also pointed out in one of Zipser's papers. The reanalysis tropopause refers to mean conditions, not the very strong convection associated with DCC. We show this distortion directly using AIRS and the independent colocated AMSU sounding channels at 40 hPa and a 2 hPa. We compared the temperature at 40 hPa under clear, cloudy and DCC conditions and found that under DCC conditions it is on average 2 K colder than under clear conditions. Under the same set of conditions, the temperature at 2 hPa is about 2 K warmer. (Figure 3a.). This is seen independently in the AIRS and AMSU stratosphere sounding channels. Under DCC conditions the tropopause cold point is therefore considerably colder than under average conditions where the cloud top is well below the tropopause (bt1231=225K and warmer) and under clear conditions. The local tropopause is therefore at a higher elevation than under mean (clear and cloudy) conditions . This is what we define as a "cold bulge". Figure 3b shows the effect in terms of a stratospheric gradient.

It does not appear that there is mass transfer going on at all there. You would have to have some mechanism for that.

The tropopause cold point is at the top of the cold bulge. The Protruding Convective Bubbles (seen by GOES as almost explosive events in time lapse images and deduced from the DT<-5K AIRS data) reach close to the top of this bulge, transporting whatever ice particles and pollutants they may carry along. When the strong convection dies out, the cold bulge disappears as the tropopause cold point returns to it average elevation. But the cirrus ice trapped below what used to be the tropopause cold point at the top of the bulge stays at the same elevation, but now this elevation is above the mean tropopause, i.e. in the lower stratosphere. The end result is what appears to be mass transport above the mean tropopause. This is consistent with observations of transport of pollutants into the lower stratosphere in the presence of strong convection, e.g. Randel et al. (2010), although not the mechanism.

P16487, L8. I do not think you have shown any evidence of mass transport into the lower stratosphere in these bulges ....

We hope that the AIRS data with the DCC related cold bulges are convincing evidence.

References

Kahn, B. K., C. K. Liang, A. Eldering, A. Gettelman, Q. Yue, and K. N. Liou (2008) "Tropical thin cirrus and relative humidity observed by the Atmospheric Infrared Sounder Atmos. Chem. Phys., 8, 1501–1518, www.atmos-chem-phys.net/8/1501/2008/