"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 hyperspectral 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. A similar request was made by Reviewer#2. we propose to add the following figure and text at page16480 line 5.:

The data are saved in groups of 135 scan line, corresponding to 6 minute data granules containing 90x135=12150 spectra. Figure 1a shows a 90x135 pixel image from a typical tropical Atlantic granule, granule 176 from 6 September 2002. The brightness temperature in the 1231 cm-1 window channel, bt1231, is shown color encoded between 199K and 300K. Of the 12150 pixels, 5016 (41%) are so clear that the observed bt1231 agrees with the expected value based on the sea surface temperature forecast by the National Centers for Environmental Prediction (NCEP) within 2 K. The average clear spectrum between 650 and 1600 cm-1 region of the spectra is shown in red on the right in Figure 1b. For 600 pixels (5%) bt1231 is between 225K and 240K, indicating moderately high clouds, shown in light blue in Figure 1a, the average spectrum is shown in green on the right. Imbedded in regions of high clouds are some extremely cold cloud tops. For 73 pixels (0.6% for this granule) bt1231<210K, with the average spectrum shown in blue in Figure 1b. The ozone region (near 1050 cm-1), the co2 lines below 780 cm-1, the CH4 at 1305 cm-1 spectrum and the water lines between 1300 and 1600 cm-1 are now warmer than the window channels, i.e. instead of the lines seen as colder (absorbing), as for the case of the clear sky spectrum (red), the lines in the blue spectrum are seen as warmer (emitting), or inverted from the clear sky case.

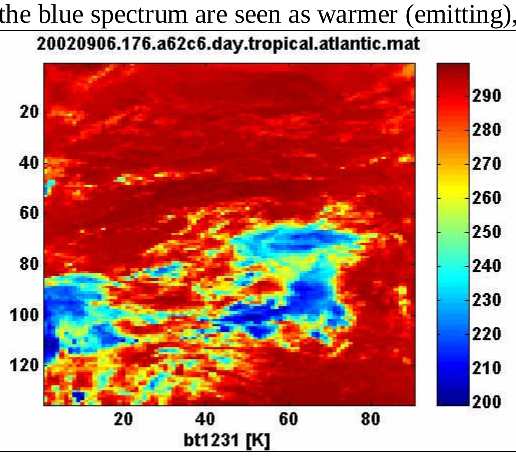

Figure 1a shows the brightness temperature in the 1231 cm-1 window channel for a typical tropical ocean AIRS data granule.

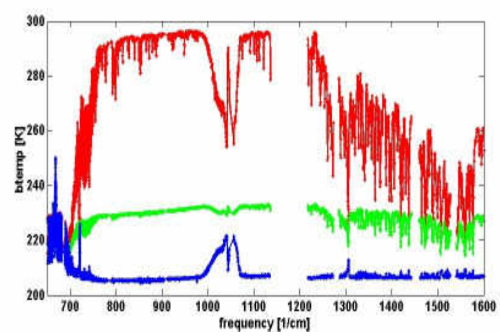

Figure 1b shows typical spectra under clear (red), high clouds (green) and inverted spectra (blue) from the data on the left.

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.

Starting at P16480, L2 we propose to add

The difference between a 10 μm window channel and a 6 μm water channel has been used with GOES and Meteosat IR imagers to identify convective cloud tops (e.g. Schmetz et al. 1997). However, this technique is sensitive to the amount of water vapor and the temperature in the lower stratosphere. In fact, Setvak et al. (2008) have evaluated the use of this difference for the measurement of water vapor in the lower stratosphere. With AIRS we have much higher spectral resolution and the option of using a strong co2 absorbing channel to avoid the water vapor ambiguity. Under tropical ocean clear conditions DT=bt1231-bt712 is typically +60 K due to strong co2 absorption, DW=bt1231-bt1419 is typically 60 K to +85K due to water vapor absorption. Under DCC conditions the signal from below 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 lower stratosphere.

The exploitation of the gradient across the 10 micron window channel has been used to characterize cloud properties for many years (e.g. Inoue 1987, who defined BTD as the difference between the 11μm and 12 μm window channels). In the case of AIRS we have many window channels in a much larger spectral region, which have been used for the characterization of cirrus clouds (e.g. Kahn et al. 2008). We focus on three window channels, which penetrate the top of a cloud and measure a temperature where the cloud optical depth reaches unity. For a water/ice cloud, the cloud optical depth increases slowly between 1231 cm-1 (8.1 μm) and 961 cm-1 (10.4 μm), but increases very rapidly between 961 and 790 cm-1 (12.6 μm). The 790 cm-1 channel reaches unity optical depth sooner (lower pressure) than the 961 cm-1 channel, and measures a lower temperature, as much as 20 K, for cloud tops below the tropopause, i.e. in the presence of a negative lapse rate. Since the optical depth is strongly cloud particle size, shape and density and emissivity dependent, the physical interpretation of observed differences require scattering 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 and the +/- 1 PE uncertainty in the ridge line shows that the correlation between the rain rate and DT is very significant. 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 very cold clouds and high rain rate has been known for a long time in the form of the GOES Precipitation Index (P16486, L24).

The correlation between rain rate and DT=bt1231-bt712 is very important. From a single brightness temperature threshold alone we would not be able to distinguish between optically thick very cold anvil clouds and optically thick cold clouds propelled by intense convection to the tropopause. Deep Convection is typically identified by the rain rate >1.6 mm/hr in 1 degree lat/lon bins (Zelinka and Hartmann 2009). Figure 4 shows the rain rate as function DT increases steeply for DT<-2 and even steeper at DT<-5. The DT=bt1231-bt712<-2 K threshold separates anvil clouds from deep convective clouds at the tropopause.

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." The cloud tops may indeed colder than the mean tropopause, but not the local tropopause, which is distorted by the very strong convection, detected with AIRS and AMSU data.

We propose to add

Setvak et al. (2008) studied the association between upside down spectra identified with deep convective storms over Europe.
Inoue (1987) was first to use the 10um split window technique, conceptually similar to out bt961-bt790, to characterize clouds.

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. This is not observed.

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 only way this can happen, excluding a measurement error, is a local cold bulge due to deep convection, which is not in the reanalysis. 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

Inoue, Toshiro (1987) "A Cloud Type Classification With NOAA 7 Split-Window Measurements" JGR, **92**, D4, pp. 3991-4000, April 20, 1987.

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.

Setvák, M., D. T. Lindsey, R. M. Rabin, P. K. Wang, A. Demeterova (2008) "Indication of water vapor transport into the lower stratosphere above midlatitude convective storms: Meteosat Second Generation satellite observations and radiative transfer model simulations", Atmospheric Research 89 (2008) 170–180.