"Deep convective clouds at the tropopause"

Author's comments to Anonymous reviewer #2 (questions quoted in italics)

The authors seem to forget that most readers are not familiar with even the physical principles working behind these techniques. I recommend that the authors completely rewrite the paper ....

We appreciate the comment, but think that the reviewer overstated the case. Although we use the AIRS hyperspectral data, the basic techniques used in this paper have been known from the lower spectral resolution GOES and Meteosat data for decades. We propose to add more references which explain the techniques. Details are imbedded in the response to other questions.

1. Show an example figure to explain what "inverted spectrum" is.

Since this is the same suggestion made by Reviewer#1, 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.

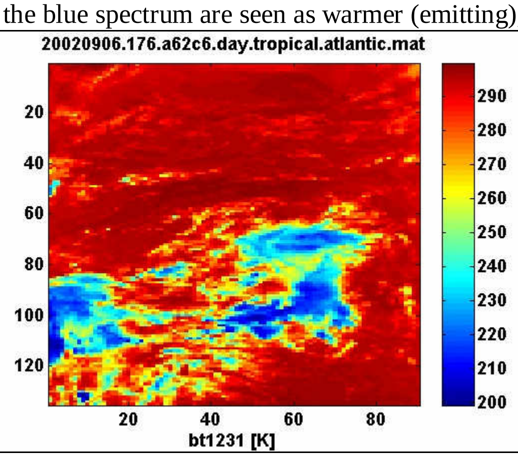

Figure 1a shows the brightness temperature in the 1231 cm-1 window channel for a typical tropical ocean AIRS data granule.

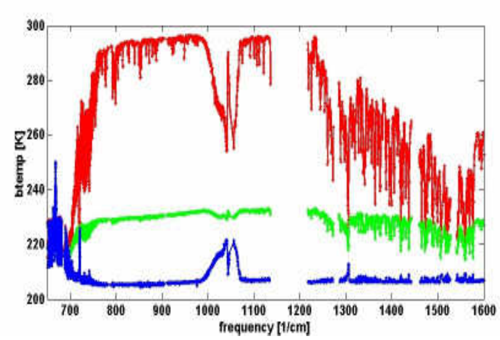

Figure 1b shows typical absorption spectra (red=clear), high clouds (green) and inverted spectra (blue) from the data on the left.

2. Explain why it is useful to use AIRS, AMSU and AMSRE data together.

We pointed out in the manuscript (p.16478 line 20), that the three instruments are on the same satellite, which assures spatial and temporal measurement simultaneity, which is key to making sense of highly variable effects like clouds and rain. We also pointed out that the microwave AMSU data are much less effected by clouds than infrared AIRS data (p.16482 line 14).

3. What would DW, DT and DC tell us about cloud properties....

Since this is the same comment as made by anonymous#1, we propose to add the following sentences to the manuscript after P16478, L16 and at P16480, L2.

Starting at P16478, L16 add:

Details on the geophysical interpretation of these differences are given at the end of the following section. We also use AIRS temperature sounding channels at 679.9 and 668.2 cm-1 to characterize the temperature structure between 40 and 2 hPa.

Starting at P16480, L2 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 (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."

4. A typical example of ....

Much of this is covered in 3) with the proposed clarification starting at P16480, L2. We are trying to sort out what we see using the forward algorithm (i.e. guess the clouds and the temperature water vapor profile and calculate what we should see). With AIRS and the co-located AMSU data we may have enough information for a formal retrieval, but this is work in progress not ready to be described in detail.

Specific comments:

1) Line 10. P 16477

Agreed. Change to "has the potential to force..."

2) Setvak et al. 2008.

We added on Page 16488 Line 12:

More recently Setvak et al. (2008) studied their association with deep convective storms over Europe.

Conceptually the scatter plots shown in Figure 4 Setvak et al (2008) and our Figure 1a are similar. There are also some interesting differences. Setvak (2008) defined BTD as the brightness temperature difference between the 6.2 μm and 10.8 μm bands in Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI) above the tops of deep convective clouds, assuming a thermal inversion above the cloud top level. With the help of model calculations, Setvak interprets BTD as the signal of water vapor into the lower stratosphere. Our paper does not explicitly address water vapor in the LS, however, a paper on water vapor in the LS above DCC is in preparation. BTD is conceptually analogous to bt1419-bt961. Numerically BTD rarely is larger than 1K, while we have seen bt1419-bt961 as large as 12K. Water vapor weighting functions are very sensitive to temperature. Retrieval of water vapor in the LS is therefore fairly tricky, since the temperature structure in the LS is modified by the presence of the DCC. This is why we used bt712 instead of bt1419. The availability of the AIRS and AMSU stratospheric temperature and water sounding channels gives us lots of leverage compared to SEVIRI data. We defer to a comparison with Setvak et al. 2008 until we publish our findings on LS water vapor and correlations with DCC.

References to be added:

Inoue, Toshiro (1987) "A Cloud Type Classification With NOAA 7 Split-Window Measurements" JGR, VOL. 92, NO. D4, pp3991-4000, 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.