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Deep convection and upper-tropospheric humidity: A look from the A-Train

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[1] This work investigates the links between deep convective clouds and upper-tropospheric humidity. We collocate data from AIRS, CloudSat, and the GDAS model output, and globally average and grid our results to seasonal scales for one year, 2007. The CloudSat cloud scenario retrieval is used as a reliable identifier of deep convective events, during which we extract the nearest 300-mb humidity from AIRS and GDAS data. The zonal averages of thus screened data clearly show significant increase in the humidity, and suppression of the all-sky outgoing long-wave radiation. **Citation:** Savtchenko, A. (2009), Deep convection and upper-tropospheric humidity: A look from the A-Train, *Geophys. Res. Lett.*, *36*, L06814, doi:10.1029/2009GL037508.

1. Introduction

[2] The relationship between the deep convection (DC) and the humidifying of the upper troposphere has been given attention since early days of TOVS, given the importance of this problem in the assessment of the greenhouse effects, [*Soden and Fu*, 1995; *Intergovernmental Panel on Climate Change*, 1990]. The establishment of the A-Train formation [*Stephens et al.*, 2002] gives an opportunity to look at this problem from many new, much more detailed, aspects. A-Train is rich on vertical sounders, yielding unprecedented data on the horizontal and vertical structure of clouds and atmospheric water content, and atmospheric radiative properties. For instance, the Cloud Profiling Radar on CloudSat opens qualitatively new window of opportunity to look at cloud regimes on global scales [*Zhang et al.*, 2007]. AIRS on Aqua is pioneering global coverage of temperature and humidity profiles, in the presence of multiple cloud formation, of radiosonde accuracy [*Auman et al.*, 2003; *Tobin et al.*, 2006]. Even though the radiative feedback of the tropospheric water vapor has been in general well understood, there are still uncertainties in the interplay of various factors that can modify the moisture content. The deep convective clouds and their intensification from such factors as aerosol load [*Rosenfeld et al.*, 2008] or warmer sea surface temperatures [*Lin et al.*, 2006] is just one example. Here we present early results from utilization of data from A-Train, that we hope will help to better constrain global circulation models with regard of frequency of occurrence of deep convection on global scales, and the role it plays in bringing moisture to upper troposphere, and potential feedbacks of that moisture.

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2. Data

[3] In our analysis, we use only a small portion of A-Train-available retrievals – the cloud scenario from the Cloud Profiling Radar (CPR), and the standard retrieval, AIRX2RET data type of version 5, from the Atmospheric Infrared Sounder (AIRS), all at Level 2 processing.

[4] CPR and AIRS are flying on correspondingly CloudSat and Aqua satellites, about a minute apart. Both instruments have very different, but nicely complementing, characteristics. While AIRS is a cross-track scanning, infrared (IR) hyperspectral radiometer, the CPR is a nadir-looking microwave (94 GHz) radar. Numerous articles exist that exhaustively describe the instruments and related algorithms. For instance, see *Auman et al.* [2003] for AIRS, and *Stephens et al.* [2002] for CPR science missions descriptions. A fundamental strength of AIRS is its ability to retrieve globally vertical profiles of water vapor and temperature under clear and partially cloudy conditions. AIRS cloud-clearing methodology allows larger yield of retrieved profiles, which is shown to have acceptable accuracy at cloud fractions of up to 80% [*Susskind et al.*, 2003]. With its cross-track scanning, resulting in a swath width of 1650 km, AIRS achieves global coverage in two days. On the CloudSat side, CPR is uniquely situated to retrieve vertical profiles of cloud characteristics with unprecedented sensitivity and horizontal and vertical resolution. In contrast to AIRS, CPR is single-track instrument that has a swath width of 1.4 km. CPR profiles are reported every 1.1 km along its track, with 250-m vertical sampling.

[5] The viewing geometry of both instruments is very different, Figure 1. The AIRS standard retrieval at Level 2 processing results in 30 fields of view (FOV), and 45 lines, across- and along-track correspondingly, per granule. The exact area of the FOV is a complex result of retrievals that use IR and microwave radiances from correspondingly AIRS and Advanced Microwave Sounding Unit (AMSU), and it is a function of the scan angle as well. Assuming for brevity a constant representative 45-km diameter for the FOV, it is clear from Figure 1 that CPR transects only 45 out of the 30 $\times$ 45 AIRS FOV per granule. Indeed, we allow only one AIRS FOV per line to be closest to the CPR track, and comment on the possible issues below.

[6] We use water vapor Mass Mixing Ratios (MMR) at 300 mb, and all-sky and clear-sky Outgoing Longwave Radiation (OLR) from AIRX2RET. The MMRs, one at “normal” (H2OMMRStd), and one for equilibrium phase (saturation, H2OMMRSat) conditions, can be used to estimate relative humidity (RH) in accordance with the World Meteorological Organization definition: RH = H2OMMRStd/H2OMMRSat. This will facilitate the comparisons with the modeled RH output.

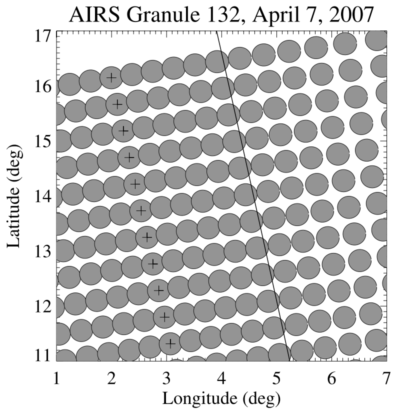

Figure 1. CPR ground track (solid line) transecting idealized 45-km FOVs from a portion of ascending AIRS AIRX2RET granule. The circles marked with crosses indicate AIRS FOV #15 (closest to nadir).

[7] The model output we exploit is from one of the operational systems at the National Centers for Environmental Prediction (NCEP) - the Global Data Assimilation System (GDAS), [*Kanamitsu*, 1989; *Parrish and Derber*, 1992]. The GDAS is the final run in the series of NCEP operational model runs; it therefore is known as the Final Run at NCEP and includes late arriving conventional and satellite data. It is run 4 times a day, i.e., at 00, 06, 12, and 18 UTC, on a 1 × 1 deg climatological grid. Model output is for the analysis time and a 6-hour forecast. The GDAS RH model output was extracted at 300 mb as well. AIRS standard retrieval has no dependency on this model (e.g., the initial guess is coming from a different model).

[8] For brevity of the presentation, we only consider two distinctively different seasonal averages, the winter and summer, of 2007.

3. Approach

[9] Our approach relies on the cloud scenario from CPR, which is used to identify and locate the events of DC. The cloud scenario pixels are screened for "determined scenario" quality only, and thus screened output serves as geolocation reference of the deep convective pixels, for each CPR orbit. The closest to them by time and arc-distance GDAS grid cells, and AIRS fields of view (FOV) are then retrieved, and quality-filtered. The accepted values of quality indicators (Qual_H2O, Qual_Cloud_OLR, Qual_clrolr) for the respective AIRS parameters are 0 and 1.

[10] While "0" indicates the entire profile is of best quality, "1" needs more careful consideration. According to the product documentation from the AIRS Science Team, when Qual_H2O = 1, the moisture profiles are still "best" from the top of the atmosphere down to pressure level Pbest, where 300mb < Pbest < Surface. PBest also intimately relates to the temperature profile, and is used in the same context there. Hence, the level of our focus, 300 mb, remains within the best range when Qual_H2O = 1. Indeed, further sophistication of quality screening does not substantially change our results, and the impact of various combinations of quality criteria would be out of scope and space-demanding. Possible impacts of quality screening on AIRS accuracy has been extensively studied by *Tobin et al.* [2006].

[11] Thus screened data are binned to 1 × 1 deg daily grids. The daily grids serve as the source for further temporal and spatial aggregates. In particular here, 3-monthly, 2 × 2 deg grids are used in the final analysis. Frequency of DC (FDC) is derived as the ratio of the number of Deep Convective CPR pixels, per all CPR pixels, that fall in 2 × 2 deg cell, per three-month period. Presently, our collocation approach is a conservative one – the output is a collocated track which is one FOV-wide for AIRS, and one grid cell-wide for GDAS. Only one AIRS FOV per scan line will be accepted, given it is not farther than 40 km from the CPR track and meets the quality criteria. The 40-km constrain is a relaxation from the strict collocation which otherwise would use half-width (~22.5 km) of the AIRS FOV. However, the 40-km radius of tolerance is a good trade off for a better yield of AIRS MMR and clear-sky OLR retrievals that may not be available in the strictly collocated "deep convective" FOV, where cloud fractions may easily be larger than 80%. The adjacent FOVs, however, where the chances of acceptable cloud fraction are better, are still close on the scale of possible horizontal mixing scales driven by the DC at 300 mb.

4. Results and Interpretation

[12] Let us first address certain sampling concerns that are typical for any polar orbiting mission, and A-Train in particular, where conservative collocation of wide-swath (AIRS) with very narrow-swath (CPR) instruments, is involved. As a polar orbiter, CPR samples the same grid cell within tropical latitudes (where the majority of DC occurs) every 16 days. The fine spatial resolution and sophisticated detection allow CPR to identify roughly 30% of all profiles in that cell as DC, Figure 2. During the collocation with CPR, most of AIRS pixels are dis-

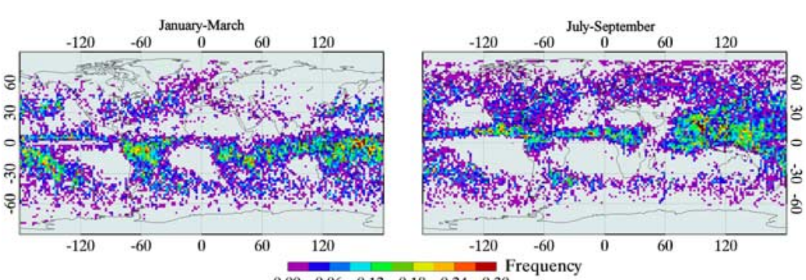

Figure 2. Frequency of Deep Convection, as derived from the CloudSat's cloud scenario.

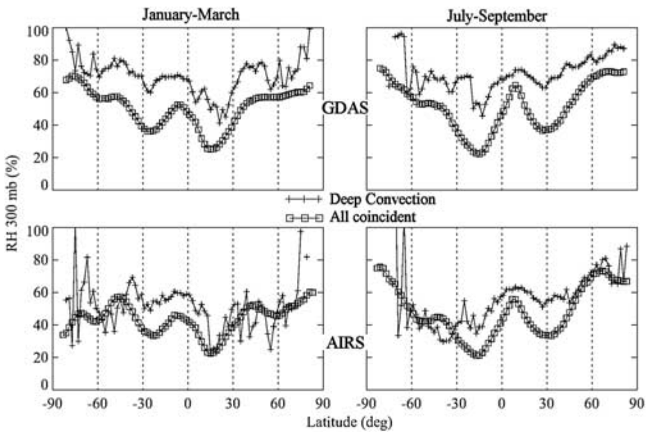

Figure 3. Zonal averages of RH at 300 mb from (top) GDAS and (bottom) AIRS, from all coincident with CPR pixels, and from those collocated with deep convective events only.

missed (Figure 1), and the ones that are collocated may not have valid water vapor retrieval due to the excessive cloud cover in the vicinity of DC. Indeed, in fractional terms, of all AIRS FOV that coincided with the DC detected by CPR, only 30% passed the quality criteria for valid water vapor retrieval. In absolute terms, the number of valid water vapor FOV at DC drops with latitude, naturally following the same tendency in the FDC (Figure 2). The resultant small yield necessitates long aggregation times as a first order of business, and lengthier consideration of implications in a more detailed publication format. Even though we present our results globally for completeness, the focus should be confined to latitudes equatorward of 45 degrees. While AIRS reports water vapor at 300 hPa over the pole, it is likely that some of those data poorly represent the true state of the atmosphere.

[13] For now, Figure 2 is elected from our available material to demonstrate that the global patterns of DC as seen by CPR are realistic (e.g., note the distinct presence of the Indian monsoon), and are in agreement with similar analyses [*Zhang et al.*, 2007]. The FDC here should be interpreted as fractional amount of deep convective CPR profiles in the particular grid cell, per all profiles in that cell, for the three-month period. Thus our FDC is "linear", i.e., along the CPR track. In contrast, *Soden and Fu* [1995] give their FDC as "spatial" fractional amount – the number of deep convective pixels, size of 5–8 km, sampled to 30-km spacing in a 2.5° × 2.5° latitude-longitude grid cell that can contain total of ~64 samples. This, and the much finer CPR resolution, should be kept in mind if relating head-to-head FDC from here with *Soden and Fu* [1995], or other wide-swath originating, results.

[14] The zonal averages of RH at 300 mb during convective events, and overall baseline, from the GDAS model and AIRS, are shown in Figure 3. Both clearly manifest enhanced RH during the deep convective events within the tropics. What's interesting though is that outside of the tropics AIRS shows that the RH seems to be indifferent to the DC, which contrasts the model output. It would be interesting to further investigate whether the model tends to give values closer to equilibrium phase (saturation), or

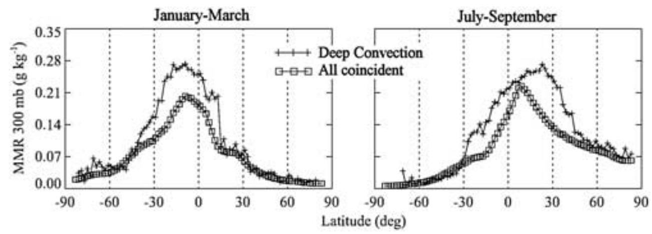

Figure 4. Zonal averages of AIRS MMR at 300 mb, from all coincident with CPR pixels, and from those collocated with deep convective events only.

AIRS exhibits dry bias in the vicinity of DC, perhaps because of low yield under excessively large cloud cover, or AIRS insensitivity at higher latitudes. Figure 4 may lend further evidence to this case. While the absolute amounts of moisture (MMR) at 300 mb are elevated during DC in the tropics, there is no indication of this taking place at higher latitudes. The tropical peak of the DC MMR moves seasonally from the southern to the Northern Hemisphere. The entire zonal pattern of the DC in the boreal summer (July–September) migrates to higher latitudes than in the austral summer (January–March). In the boreal summer, the mean of the zonal DC pattern of MMR is around 18° north, whereas in the austral summer it is only at 8° south (Figure 4). It is likely to be attributed to the larger land masses (in the Northern Hemisphere) where particularly strong convective storms, especially during monsoon months, occur.

[15] One of the most important indicators addressing the radiation budget for clouds and water vapor feedbacks is the OLR. AIRS allows considering both effects, from clouds and water vapor, separately by providing correspondingly all-sky and clear-sky OLR. The zonal averages of both OLRs, collocated with DC and overall along the CPR track, are presented in Figure 5. These results reveal substantial suppression of all-sky OLR by DC clouds, which implies a potent green house effect. The clear-sky OLR are closer related with the water vapor absorption. The collocated with DC clear-sky OLR are suppressed too, but this occurs to a much gentler degree, and the effect is constrained to tropical

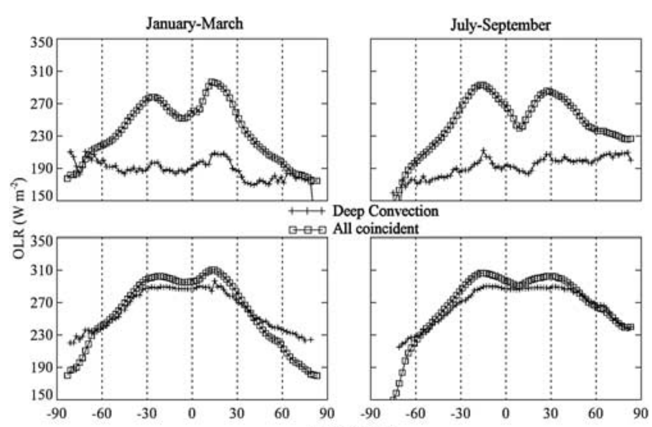

Figure 5. Zonal averages of AIRS (top) all-sky and (bottom) clear-sky, OLR from all coincident with CPR pixels, and from those collocated with deep convective events only.

latitudes, Figure 5. This constraining is consistent with Figures 3 and 4, and perhaps for the same reason. AIRS manages to give some 30% clear-sky fractional yield in the vicinity of DC, but in absolute terms the yield drops with latitude (FDC) thus possibly causing dry bias and loss of accuracy.

5. Summary

[16] The global patterns of Deep Convection are realistically revealed by the CloudSat cloud scenario retrieval that benefits from the fine CPR spatial resolution, and sophisticated decision tree algorithm. CPR, and collocated with its track GDAS model and AIRS data offer unambiguous evidences that the Upper Troposphere is humidified by the Deep Convection, predominantly within the tropical latitudes. The humidification shows patterns of seasonal variability, particularly well presented in the 300 mb MMR from AIRS. The mean of the zonally-averaged MMR during DC clearly gravitates to the Hemisphere where the summer is (following the solar heating). However, in the boreal summer it is more than twice as farther off the equator (18N) as in austral summer (8S). Hence in the Northern Hemisphere, the water vapor injected into the upper troposphere during DC can potentially have stronger impact on the radiation budget over moderate and polar latitudes, than in the Southern Hemisphere. AIRS cloud clearing helps in identifying valid water vapor retrievals in the vicinity of DC. The fractional yield of these "clear-sky" retrievals is 30% (apparently due to overwhelming cloud cover) and the latitudinal drop of the absolute yield may be impacting our extratropical results by biasing them towards drier representation. While AIRS reveals substantial suppression of all-sky OLR by DC clouds, the clear-sky OLR are modestly suppressed. Nevertheless, this is just another indication that the DC events have the potential to exert positive radiative forcing (enhance greenhouse effect) by enhancing the moisture content in the upper troposphere.

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