Validation of Aqua satellite data in the upper troposphere and lower stratosphere with in situ aircraft instruments

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[1] Aircraft observations from a recent campaign spanning 0–40N latitude are compared to coincident observations from satellite sensors on board the Aqua satellite of temperature, ozone, water vapor and cloud properties in the upper troposphere and lower stratosphere. Satellite observations compare well to aircraft data; temperature is generally within ±1.5 K and water vapor is within ±25% of aircraft observations for pressures above 150 hPa and mixing ratios above ~10 ppmv. Satellite ozone has a positive bias in the upper troposphere, and clouds observed by the aircraft are qualitatively well represented in the satellite data. These data and analyses provide critical validation of satellite observations, which promise new global insights into this region of the atmosphere. *INDEX TERMS:* 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Gettelman, A., et al. (2004), Validation of Aqua satellite data in the upper troposphere and lower stratosphere with in situ aircraft instruments, *Geophys. Res. Lett.*, *31*, L22107, doi:10.1029/2004GL020730.

1. Introduction

[2] The upper troposphere/lower stratosphere (UT/LS) is a critical region for understanding the radiative balance of the climate system. The tropical UT/LS sets the chemical boundary conditions of the stratosphere [*Stratospheric Processes and Their Role In Climate* (*SPARC*), 2000]. Because of difficulties in sensors and observing platforms, observations of the UT/LS, particularly in the tropics, are of insufficient resolution to be useful for understanding complex processes such as cirrus cloud evolution and stratosphere-troposphere exchange. Radiosonde profiles of temperature and ozonesonde profiles in the tropics are sparse, despite recent efforts such as the Southern Hemisphere Additional Ozonesondes (SHADOZ) program [*Thompson et al.*, 2003]. Radiosonde humidities are not quantitative for temperatures below −35°C (~300 hPa) [*Miloshevich et al.*, 2001]. Past satellite observations of temperature and humidity (such as from TOVS/HIRS, e.g., *Bates and Jackson* [2001]) have broad vertical weighting functions that average across regions with large temperature and humidity gradients. Daily and global coverage which can resolve vertical gradients in the UT/LS is needed.

[3] A new generation of satellite sensors provides this capability. The Atmospheric Infrared Sounder (AIRS) experiment on the Aqua satellite measures temperature, water vapor and ozone profiles at horizontal resolution of 50 km and vertical resolution as good as 1–2 km from the surface through the UT/LS. The sensitivity and resolution of AIRS varies with altitude, however. The extremely low specific humidity in the UT/LS is at the edge of AIRS sensitivity of ~10 ppmv, while the sensitivity of AIRS to tropospheric ozone is largely unknown [*Aumann et al.*, 2003]. The results described here quantify the measurement sensitivity and vertical resolution of the AIRS retrieved products by comparing them with in situ observations in the UT/LS. We also compare cloud data from the Moderate resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite. Section 2 describes the satellite and aircraft data, as well as the locations of the coincidences. Section 3 describes the comparisons, and section 4 discusses the implications and suggested valid ranges.

2. Data

[4] We take advantage of a recent campaign, the Preliminary Aura Validation Experiment (PreAVE), conducted using the NASA WB57 aircraft from January 16 to February 2, 2004. The campaign was based in Houston, Texas and San José, Costa Rica. Flight latitudes ranged from ~5°S–40°N. Aircraft position is derived from Global Positioning System (GPS) sensors. Pressure and temperature data are measured by 2 Rosemount Type 102 temperature probes and a Weston DPM 7885 pressure transducer. Ozone data is described by *Proffitt and McLaughlin* [1983] and more recently by *Richard et al.* [2003]. Absolute accuracy of the ozone instrument is ±2% throughout the range of ozone values in the intercomparison. We show comparisons between AIRS and Harvard water vapor as described by *Weinstock et al.* [1994], and total water described by E. M. Weinstock et al. (Measurements of the ice water content of cirrus in the tropics and subtropics: 1. Instrument details and validation, submitted to *Journal of Geophysical Research*, 2004). Quoted uncertainty for the Harvard water vapor instrument, as validated by laboratory calibrations, in-flight intercomparisons with JLH [*May*, 1998] and in situ vacuum ultraviolet absorption is ±5%. Also analyzed, but not shown, are water vapor from the JPL Laser Hygrometer (JLH) [*May*, 1998] and total water from the Aircraft Laser

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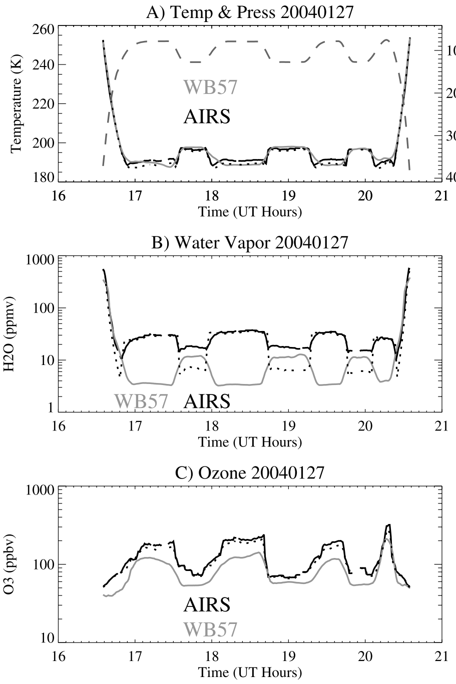

Figure 1. A) Temperature & Pressure B) Water vapor and C) Ozone along the WB57 Flight track on January 27, 2004. Gray solid line is aircraft data. Black solid line is AIRS 28 pressure level data (standard product). Black dotted line is 100 level data (support product) interpolated to the aircraft flight track. Dashed line in (a) is aircraft pressure.

Infrared Absorption Spectrometer (ALIAS) [*Webster and Heymsfield*, 2003]. A detailed comparison of these H_2O measurements is beyond the scope of this study.

[5] Satellite data is from two instruments on NASA's Aqua spacecraft. Aqua is in a sun-synchronous polar orbit, with an equatorial crossing of ~1330 local time, covering the earth twice a day. The AIRS instrument suite on Aqua is a nadir scanning sounder with combined infrared and microwave retrievals [*Aumann et al.*, 2003]. The ~2000 independent channels on AIRS permit retrieval of an entire profile in the presence of up to 70% cloud cover. Retrievals are based on optimizing the fit to a subset of these channels (147 for temperature, 66 for H_2O and 23 for O_3) using overlapping trapezoidal perturbation functions with widths in the UT/LS of ~2 km for temperature, 1–3 km for H_2O and ~3 km for O_3. This yields an effective vertical resolution of slightly less than these values [*Susskind et al.*, 2003]. AIRS retrieved products are archived at two resolutions. The standard products contain 28 levels from the surface to the mesosphere. We examine 500, 400, 300, 250, 150, 100, 70 and 50 hPa. The 100 level support products are intended primarily for radiative transfer calculations and may contain no more information than the standard product; we show below that the support product temperatures better resolve the sharp vertical gradients around the tropical tropopause which are averaged out of the standard product. We use AIRS level 2 data (version 3.0), described by *Fetzer et al.* [2003] and at http://www-airs.jpl.nasa.gov/.

[6] Cloud top pressure observations come from the MODIS instrument on the Aqua platform. MODIS has 'moderate' spectral resolution, but high spatial resolution, of 1 km at nadir for cloud properties, and 5 km in the infrared [*King et al.*, 2003]. We use version 4 of the MYD06 level-2 product, described at http://daac.gsfc.nasa.gov/MODIS/. AIRS and MODIS data are archived at the NASA Goddard Distributed Active Archive Center (DAAC), http://daac.gsfc.nasa.gov/.

3. Comparisons

[7] Satellite data were matched to the flight track by averaging all AIRS profiles on the same calendar day within ±0.5° of points every 50s along the flight track (~10 km assuming ~200 m s^{-1} aircraft velocity). This represents 6–10 profiles for each point, at 2 observation times (one within a few hours, and one ~12 hours prior). Averaged satellite profiles were interpolated to aircraft altitude. Aircraft observations were averaged over 500s (~100 km) for comparison with the satellite data. Since the aircraft is flying level or nearly level, it is not possible to average the aircraft profiles in the vertical for comparison, but we can use ascent and descent observations to infer vertical gradients.

[8] Only AIRS data which meet (1) the recommended quality checks for a successfully completed AIRS infrared retrieval as well as (2) geophysical constraints of oceanic points from 40°S–40°N latitude and no sun glint were used. Limiting the data to only the orbits near the observation time (daytime orbits) does not affect the comparisons for temperature, water vapor and ozone. For MODIS, observations were averaged over ±0.1deg (~20 km) around the aircraft location. MODIS fields are single level, and are not interpolated in the vertical.

[9] Figure 1 illustrates the flight of January 27, 2004, 16.5–20.5 UTC, from Costa Rica south to below the equator and back. The aircraft flew a series of alternating altitude legs (Figure 1a), hence the crenulated patterns in Figure 1, which reflect the vertical gradients of temperature and H_2O decreasing with altitude and O_3 increasing with altitude. AIRS overflew this track at 7.2 and 19.5 UTC. The correspondence for temperature (Figure 1a) is quite good, except for the coldest temperatures. The structure of the cold point temperatures above 100 hPa are too narrow for the standard AIRS product to resolve. The higher resolution support product (dotted line in Figure 1a) better resolves tropopause temperatures. The satellite retrieval errors for these coincidences are pretty uniform at ~0.7 K.

[10] Water vapor observed from AIRS (Figure 1b) tracks the vertical structure through most of the upper troposphere on ascent and descent. This indicates that despite the large vertical averaging kernels, AIRS can well represent the large scale (over 50 km horizontally) H_2O vertical gradient. H_2O retrieval errors are 15–25%. There are significant differences relative to the aircraft at pressures below ~120 hPa, where the aircraft measures water vapor below ~10 ppmv, the sensitivity limit of the AIRS instrument [*Aumann et al.*, 2003]. Ozone along the flight track is illustrated in Figure 1c. AIRS data tracks well the vertical structure and variability of the aircraft ozone, with the right gradient and dynamic range, but with a 20–30% positive bias.

[11] Data for all PreAVE flights is illustrated in Figure 2 for temperature, water vapor, ozone and relative humidity at

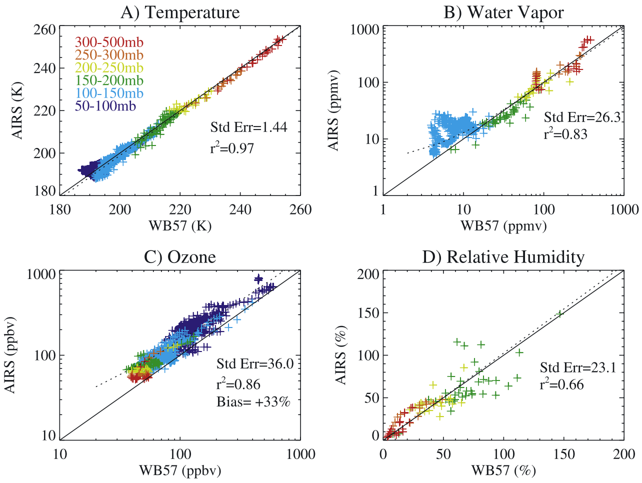

Figure 2. Comparisons between in situ WB57 aircraft observations and AIRS satellite retrievals for A) Temperature B) Water Vapor C) Ozone and D) Relative Humidity. Standard error and r^2 values are indicated. Solid lines are 1:1 line, dotted lines are linear fits.

pressures below 500 hPa, using the standard product and version 3.0 data. For temperature, there is good agreement with observations, except for some larger variations at the 100–50 hPa level in the lower stratosphere, a result of lower resolution at the tropopause noted above. The slope of a linear fit to the data at pressures above 100 hPa is not significantly different than 1 (at the 95% level). r^2 = 0.97, and the standard error (*se*) is 1.44 K. Including the 50–100 hPa level, *se* = 1.79 K. Using the 100 pressure level support product, *se* = 1.34K, indicating that the abrupt transition of the tropical tropopause is better characterized in the support product.

[12] Water vapor comparisons are illustrated in Figure 2b. For pressures above 150 hPa, satellite data appears to track well the in situ observed water vapor (which is greater than 10 ppmv). At 150–100 hPa and lower pressures, AIRS has significant wet biases, and a priori information in the retrieval biases the results. A linear fit for points at pressures greater than 150 hPa is shown in Figure 2b, with a slope not statistically different from 1, r^2 = 0.83 and *se* = 26.3 ppmv. The mean absolute percent difference between individual satellite (s) and aircraft (a) observations ($|s - a|/a$) is 23%. The comparisons are made using the Harvard water vapor instrument. Similar comparisons were performed using (1) water vapor from JLH and for clear skies (2) the Harvard total water instrument, and (3) the ALIAS total water instrument. All four instruments yield essentially the same mean absolute difference (23–27%) from the aircraft observations, despite calibration uncertainties and undetermined systematic errors inherent in all the in situ measurements, and instrument hysteresis that can affect the total water instruments. Using any of these instruments for intercomparison would not change the conclusions regarding the satellite data presented here.

[13] The positive bias in ozone for the flight of January 27th in Figure 1c is also seen in Figure 2c. There is also a loss of sensitivity at pressures greater than 300–500 hPa. A linear fit to the data indicates that AIRS ozone has a +34% bias relative to the aircraft observations, which does not appear to be a function of pressure level. For this fit, r^2 = 0.86 and *se* = 36ppbv. The mean absolute percent difference with the bias removed ($|(1 - 0.34)s - a|/a$) is 19%. The bias is not due to misregistration of the O_3 gradient in the vertical, and is also present in total column ozone.

[14] Given the fidelity of temperature (Figure 2a) and water vapor (Figure 2b), we also calculate relative humidity over ice (*RHi*) in Figure 2d. *RHi* from the observations is calculated from the 100 km average pressure, temperature and water vapor. The results indicate wide scatter, but no bias, with a linear fit having a slope not statistically different than 1, but with r^2 = 0.66, and *se* = 23% (RHi). Recent in situ observations of RHi in clear air in the upper troposphere have shown that regions of supersaturation with respect to ice are common [*Haag et al.*, 2003]. In general, AIRS does report a small number of observations with *RHi* > 100%.

[15] Finally, we investigate cloud locations from the satellite and in situ observations. While AIRS provides measurements of cloud top temperatures and pressures, a comparison with either aircraft data or MODIS cloud top temperatures indicates that the current product has significant biases. So for this study we focus on comparing MODIS cloud observations with in situ observations of ice from the aircraft. In Figure 3, evidence of condensed phase water vapor from the aircraft is compared to cloud top pressures from MODIS for the flight of January 27th, 2004. The presence of condensed phase water is identified on the aircraft using Harvard ice water content (IWC), defined as total water minus water vapor with minor adjustments for instrument hysteresis (blue crosses in Figure 3). Minimum MODIS cloud top pressures within ~10 km of the aircraft are indicated in black. Diamonds indicate where the minimum cloud pressure is below the aircraft pressure (a potential cloud at aircraft pressures). With the exception of the early part of this flight, the satellite does a good job of finding those locations with cloud. The satellite sees ice 53% of the time the aircraft does (72/134 points), and the aircraft observes ice 97% of the time it is seen by the satellite (72 of 74 points). The average IWC of the clouds seen by MODIS is 30% larger than average IWC of the points only observed by the aircraft. MODIS thus appears to miss many thinner clouds. For the other flights of the mission, fewer locations of condensation are found, and the satellite misses many of these more tenuous clouds. Some of these discrepancies are due to the timing of satellite

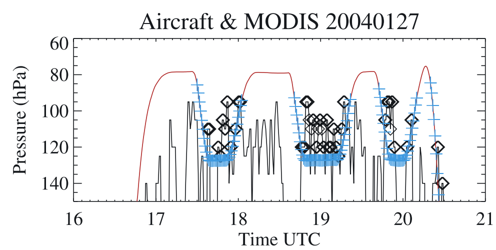

Figure 3. Solid line is the local (±0.1deg) minimum cloud top pressure from MODIS interpolated to aircraft flight track for January 27, 2004. The satellite overpass time is 19.5 UTC. Aircraft pressure in red. Diamonds indicate where minimum MODIS cloud top pressure is less than the aircraft pressure. Blue crosses indicate where aircraft total water and water vapor indicates the presence of ice.

overpasses. MODIS has better correspondence with aircraft data close to the 19.5 UTC overpass time of the satellite, indicating temporal correspondence is more important for clouds than for temperature, H_2O or O_3.

4. Discussion

[16] Aircraft observations in the UT/LS provide a valuable platform for validating satellite data. Results from the PreAVE campaign indicate that AIRS data represent temperature to within ±1.5 K up to the tropopause, water vapor within ±25% up to 200 hPa, and ozone within ±20%, with a positive bias to the AIRS ozone observations at low concentrations. Vertical gradients of averaged temperature and H_2O seen by the aircraft on ascent and descent (Figure 1) are well reproduced for all flights (Figure 2) from 500–200 hPa (representing ~250–190°K temperature and ~1000–10 ppmv H_2O). This analysis indicates that for temperature and humidity averaged at the 50 km AIRS horizontal resolution, vertical structures of 1–2 km can be resolved. Horizontal structures are well represented down to 100 km. Temperature retrievals are slightly biased around the tropopause, which can be reduced by using the higher vertical resolution support product.

[17] Quantitative relative humidity observations are possible in the upper troposphere up to 200 hPa. For relative humidity, the averaging volume is critical. Aircraft data on smaller scales are vital for interpretation of these measurements, because cloud processes do not feel the 'average' relative humidity, but a micro-scale relative humidity. AIRS cirrus cloud properties do not agree with MODIS or aircraft indications of high clouds. MODIS cloud top data does appear to characterize the conditions in which clouds are observed from the aircraft, but may miss some thinner clouds.

[18] Aircraft data provide the crucial link for validating UT/LS satellite observations. More flights are needed in the tropical UT/LS region, especially in and around clouds for better understanding of satellite cloud observations. Different conditions and different seasons, such as over the tropical Western Pacific, and during boreal summer, are necessary.

[19] Aqua satellite observations can be used to both understand variability as well as to help validate global model cloud and transport processes. There is now the immediate capacity to develop climatologies of upper tropospheric humidity, UT/LS temperature, and UT/LS ozone. There is the near term potential for being able to merge AIRS humidity, temperature and ozone data and MODIS cloud and aerosol data with data from instruments on the NASA Aura satellite, to develop a comprehensive picture of the UT/LS from 10 km all the way into the stratosphere. Aura instruments gain sensitivity where AIRS loses sensitivity.

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