GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L19701, doi:10.1029/2006GL028547, 2007

Atmospheric total precipitable water from AIRS and ECMWF during Antarctic summer

Hengchun Ye,[1] Eric J. Fetzer,[2] David H. Bromwich,[3] Evan F. Fishbein,[2] Edward T. Olsen,[2] Stephanie L. Granger,[2] Sung-Yung Lee,[2] Luke Chen,[2] and Bjorn H. Lambrigtsen[2]

Received 31 October 2006; revised 17 July 2007; accepted 4 September 2007; published 5 October 2007.

[1] This study compares the atmospheric total precipitable water (PWV) obtained by Atmospheric Infrared Sounder (AIRS) with radiosondes and the European Centre for Medium-range Weather Forecasts (ECMWF) operational analysis products during December 2003 and January 2004. We find that PWV from AIRS Level 3 (daily gridded) data is about 9% drier while ECMWF is 14% moister than sondes at the two grid points closest to the Dome C radiosonde site on the Antarctic Plateau at 3233 m elevation. The largest ECMWF moist biases occur on warmer days at Dome C. When AIRS Level 3 data are compared with ECMWF over the entire Antarctic continent, AIRS and ECMWF PWV have similar variability (correlation coefficients are predominantly 0.8 or higher), but with AIRS drier over most of the Antarctic by a consistent offset of about 0.1–0.2 mm. Because of this constant difference, the largest percentage differences are found over the highland areas of about 2500 meters and above, where absolute water vapor amounts are smallest.
Citation: Ye, H., E. J. Fetzer, D. H. Bromwich, E. F. Fishbein, E. T. Olsen, S. L. Granger, S.-Y. Lee, L. Chen, and B. H. Lambrigtsen (2007), Atmospheric total precipitable water from AIRS and ECMWF during Antarctic summer, *Geophys. Res. Lett.*, *34*, L19701, doi:10.1029/2006GL028547.

1. Introduction

[2] Antarctica has the poorest spatial and temporal coverage by weather stations of any continent due to its remoteness and extreme environment. Most inland surface weather observations have been obtained since 1980 by a sparse and intermittent network of automatic weather stations [*King and Turner*, 1997]. Most research on Antarctica thus relies heavily on computer model outputs or satellite observations. However, models are of uncertain quality in reproducing the true atmospheric and surface conditions in the pre-satellite era [*Bromwich and Fogt*, 2004; *Turner et al.*, 2006]. This testifies to the critical importance of satellite information to Antarctic climate study.

[3] The atmospheric total precipitable water vapor (PWV) and associated humidity profiles are very important in Antarctic precipitation and sublimation/vapor deposition processes, and consequently for the ice sheet surface mass balance, and for potential sea level changes. However, little water vapor information has been collected over ice-covered surfaces [*King and Turner*, 1997]. The Atmospheric Infrared Sounder (AIRS), a combined infrared and microwave profiler, is the first satellite sensor to obtain high-vertical-resolution profiles of the atmospheric moisture content. The AIRS water vapor products have been studied mostly for middle and low latitude regions from the surface through middle troposphere [*Tian et al.*, 2006; *Fu et al.*, 2006] and upper troposphere [*Gettelman et al.*, 2004]. A recent study by *Gettelman et al.* [2006] compared AIRS- and radiosonde-derived relative humidity profiles over Dome C on the Antarctic Plateau. In this study, we compare the PWV of AIRS with those of radiosonde observations, and with ECMWF operational analysis products over the Antarctic continent.

2. Data and Methods

[4] The AIRS instrument suite is carried on the Aqua spacecraft and has been collecting high-resolution atmospheric temperature and moisture profiles, along with trace gas, cloud and surface properties, since September 2002 [*Chahine et al.*, 2006]. The AIRS instrument is a near-nadir cross-track sounding hyperspectral infrared spectrometer and operates in concert with the Advanced Microwave Sounding Unit (AMSU) and the Humidity Sounder for Brazil (HSB) [*Lambrigtsen*, 2003; *Susskind et al.*, 2003]. Two AIRS data sets have been released. This study uses AIRS Version 4.0 data [*Fetzer et al.*, 2005] available at http://daac.gsfc.nasa.gov/data/datapool/AIRS/index.html.

[5] The AIRS products consist of three types, designated Level 1 through Level 3. Level 1 data are calibrated radiances. These radiances are the inputs to a set of retrieval algorithms [*Susskind et al.*, 2003] that estimate geophysical quantities such as temperature, water vapor and minor gases. These geophysical estimates are designated Level 2. The Level 3 data consist of Level 2 data averaged to a 1° latitude by 1° longitude grid with twice daily coverage [*Granger et al.*, 2004]. The twice daily estimates include averages of ascending (north-moving) daytime orbits and descending nighttime orbits. We further average the ascending and descending Level 3 quantities to derive a daily mean. The daily Level 3 fields over Antarctica are based on many Level 2 samples of the highest quality retrievals (Qual_Temp_Profile_Bot = 1) because of dense orbital coverage at high latitudes.

[6] Radiosonde records are available from the summertime campaigns during January 2003, December 2003 and January 2004 at Dome C, Antarctica as part of an AIRS

[1]Department of Geography and Urban Analysis, California State University, Los Angeles, California, USA.
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[3]Polar Meteorology Group, Byrd Polar Research Center, Ohio State University, Columbus, Ohio, USA.

0094-8276/07/2006GL028547$05.00

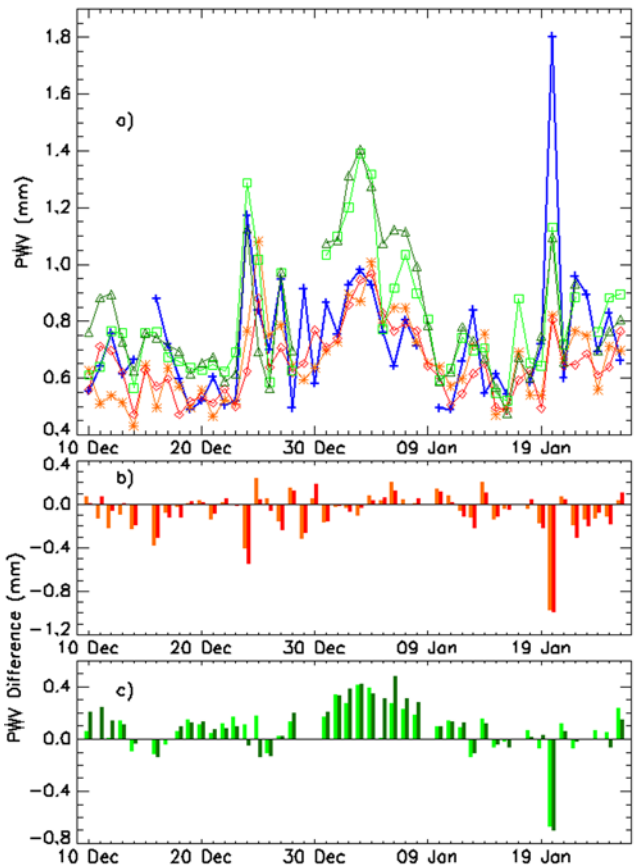

Figure 1. Time series of (a) PWV (mm) radiosonde (blue) at Dome C, AIRS (grid 1- red, grid 2-orange), and ECWMF (grid 1-dark green, grid 2-light green), (b) departures (mm) of AIRS from Dome C radiosonde, and (c) departures (mm) of ECMWF from Dome C radiosonde.

validation project and were provided by Von Walden from the University of Idaho. These data were used in the studies by *Walden et al.* [2006] and *Gettelman et al.* [2006]. Dome C is located at 75°06′S, 123°21′E at an elevation of 3233 meters. In this study we describe comparisons with the December 2003 and January 2004 sondes since only 16 sondes were launched during January 2003 – a relatively small seasonal sample using an earlier generation of sonde humidity sensors.

[7] Three different sonde humidity sensor types were used during 10 December 2003 to 26 January 2004. All were manufactured by Vaisala: RS-90 (47 total launches), RS80-A (25 launches), and RS80-H (6 launches) [*Gettelman et al.*, 2006]. For the Vaisala radiosondes, temperatures are accurate to 0.1–0.2 K and relative humidity values are accurate to 30%. As described by *Gettelman et al.* [2006], corrections have been applied to the Dome C radiosonde data for three known error sources: temperature dependence error [*Miloshevich et al.*, 2001], time lag error [*Miloshevich et al.*, 2004], and another empirical calibration correction for RS80-H and RS90 described by *Miloshevich et al.* [2006]. After these corrections, the data may still contain possible dry biases of 6–8% for daytime RS90 [*Miloshevich et al.*, 2006], and 3–4% for daytime RS80-H [*Turner et al.*, 2003].

[8] The total number of successful launches during our study period is 78, with most days having one or two launches to match the ascending and descending orbits when the satellite was nearest the zenith [*Walden et al.*, 2006]. There were 3 days with no observations: 15 December 2003 and 9 and 17 January 2004. Also, among the 18 days with only one launch, 5 have morning observations only and 13 have afternoon observations only. The sonde PWV values used in this study are derived from the humidity and temperature profile by vertically integrating specific humidity from the surface to the top of the atmosphere. The *Hyland and Wexler* [1983] formulation is used to calculate the saturation mixing ratio over ice. Two radiosonde PWV time series are constructed and used: Time Series One is the daily average of all available measurements for each corresponding day regardless of the number of observations (48 days); Time Series Two is the daily average based on only two observations: one in the morning (whichever is closest to 7 AM), and one in the afternoon (whichever is closest to 2 PM). If any one observation is missing, that day is considered as having a missing value. So there are a total of 28 days in Time Series Two. These two time series are used for matching grid points of AIRS Level 3 and ECMWF data. Because there is significant diurnal variation in the PWV (higher in the afternoon than in the morning), Time Series Two better represents the true daily mean values while Time Series One contains more sample days.

[9] The PWV from ECMWF is the daily average of analyses at 0Z, 6Z, 12Z, and 18Z. The ECMWF grids of 0.25° latitude by 0.25° longitude are averaged into 1° by 1° bins to match the AIRS grid points. We have missing ECMWF data for 29 and 30 December 2003 and 23 January 2004 in our data archive, so these three days are excluded from the comparisons. Towards the end of 2003, ECMWF started to assimilate AIRS radiance observations globally [*McNally et al.*, 2006]. However, over the Antarctic landmass AIRS usage is restricted to temperature sensitive channels in the upper troposphere and lower stratosphere and no humidity sensitive AIRS channels are used. Thus, the only influence AIRS observations can have upon the ECMWF humidity analysis over Antarctica is via transport from the Southern Ocean where AIRS humidity channels are assimilated.

[10] We first compare PWV from radiosondes with PWV from AIRS and ECMWF at the Dome C location at the two nearby grid points during the study time period: grid one centered at 74.5°S, 123.5°E and grid two centered at 75.5°S, 123.5°E. Then, the PWV of AIRS and ECMWF are compared for the entire Antarctic continent to reveal any temporal and geographical patterns of differences. The mean percentage difference is calculated as the difference between the two data sets divided by the time mean of either radiosonde or ECMWF. Correlation analyses are applied between the corresponding grids of AIRS and ECMWF where no more than 4 days were missing in AIRS during the study period.

3. Results

[11] Daily Time Series One of the radiosonde PWV, the two grid points of AIRS observations, and those of ECMWF are shown in Figure 1a. The AIRS PWV was a little lower during December and late January, while it is more consistent with the radiosonde values during the

middle section of the time period. The ECMWF PWV is higher during most days, except for the last 10 or so days when ECMWF values are closer to those of the radiosonde than they are to AIRS. The radiosonde has one extremely high PWV value on January 20, 2004 when a single observation at 7:48AM was made, apparently related to unusually moist air in the troposphere and accompanied by dense cloud cover. It was the time when AIRS retrieval (within 100 km and 30 minutes) failed due to cloudy conditions.

[12] The difference becomes clearer when departures from the radiosonde data are plotted for AIRS and ECMWF separately (Figures 1b and 1c). The PWV of the two AIRS grid points fluctuates randomly along zero with larger negative departures than positive departures in general. ECMWF has predominantly positive values for both grid points with larger positive than negative departures in general, except for January 20. For ECMWF PWV negative departures, all but January 20 is less than one standard deviation of radiosonde PWV of 0.23 mm. This suggests that AIRS is slightly drier on average while ECMWF is often moister than the radiosonde at Dome C during the study period. The average departures for the two AIRS grid points are −0.071 mm (−9.6%) and −0.082 mm (−11.1%) respectively. The mean departures for the two ECMWF grid points are 0.073 mm (9.9%) and 0.096 mm (13.1%). The mean absolute departures for the two grid points are 19.4% and 18.6% for AIRS and 19.9% and 23.3% for ECMWF. When Time Series Two of the radiosonde (two observations per day) is used to compare with AIRS and ECMWF, the average departures for AIRS drops to −0.052 mm (−7.1%) and −0.076 mm (−11.1%) while the average departures for ECMWF increased to 0.079 mm (11.7%) and 0.110 mm (16.4%). The absolute departures for AIRS decreased to 16.4% and 17.0% for the two grids and also decreased to 11.7% and 16.4% for ECMWF grids. Taking the average of these two grids, AIRS is about 0.063 mm (9.1%) drier and ECMWF is about 0.095 mm (14.1%) wetter than the radiosonde.

[13] The departure of ECMWF from sonde PWV is positively correlated with sonde-measured daily surface air temperature at both grid points, with high statistical significance. The largest moist biases in ECMWF in Figure 1 occurred on warmer days at Dome C. All departures larger than 0.2 mm are on days with a surface air temperature at 245.5 K and above, and all departures larger than 0.3 mm are on days with surface air temperature at 249 K and above.

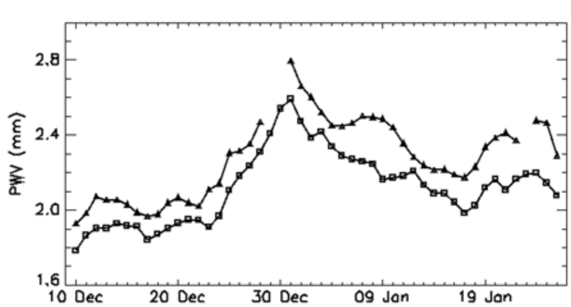

Figure 2. Time series of daily mean PWV over Antarctica (square: AIRS; triangle: ECMWF).

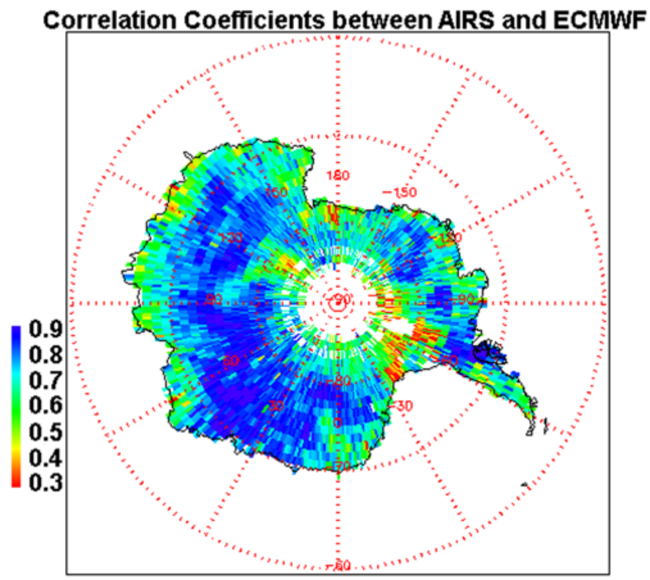

Figure 3. The geographical patterns of correlation coefficients between AIRS and ECMWF during the study period.

[14] The mean differences between AIRS and ECMWF PWV over all of Antarctica during the study period show predominantly negative values over the Antarctic (−1.5 mm to +0.6 mm with average value of −0.14 mm), with large negative values over East Antarctica but some small positive areas in low-lying areas on the coast. PWV frequency distributions from AIRS and ECMWF are very similar, but with ECMWF having slightly more occurrences on the lower end of the PWV values (see auxiliary material).[1] Because East Antarctica has high elevations and is much drier, the largest percentage differences are found over this highland area where PWV is less than 1 mm. The magnitude of differences increases with increasing height, with the largest negative percentage differences located at elevations higher than 2500 m and reaching −30% at around 4000 m and above. The largest negative values are concentrated at grid points where PWV is less than 1 mm (see auxiliary material).

[15] Figure 2 shows that the daily area weighted average PWV over the entire Antarctic continent from ECMWF is consistently higher than the corresponding quantity for AIRS on all days (for ECMWF, only grids with AIRS data are used). The average PWV over Antarctica for the study period is 2.12 mm based on AIRS and 2.28 mm based on ECMWF. The mean difference is −0.15 mm or 6.7% (7.2% if divided by the mean values of AIRS). The two time series in Figure 2 are highly correlated (correlation coefficient of 0.95, significant at higher than the 99% confidence level). The ECMWF time series shows a slightly larger range than AIRS suggesting ECMWF might be responding too vigorously to synoptic moisture. The geographical pattern of correlation between AIRS and ECMWF indicates highly correlated PWV across the middle of the Antarctic continent, but weaker correlation over some costal regions. The

[1]Auxiliary materials are available in the HTML. doi:10.1029/2006GL028547.

correlation coefficients range from near 0.001 (one grid point) to 0.98, and the majority are 0.8 or above (Figure 3).

4. Conclusion and Discussion

[16] This study compares PWV observations over Antarctica from AIRS, radiosondes and ECMWF analyses for the time period from 10 December 2003 to 26 January 2004. Results suggest that AIRS Level 3 data on average are about 9.1% drier while ECMWF PWV is around 14.1% moister than radiosondes near the Dome C site. The largest moist biases of ECMWF are found on warmer days during the two month radiosonde study period.

[17] Geographically, the largest percent discrepancy between AIRS and ECMWF is found over high elevations of 2500 meters and above where PWV is very small (limit of 31.5% drier for AIRS at an elevation around 4000 m). Over some lowland areas near water, AIRS is moister than ECMWF (limit of 23.6%). In general, there are small percentage differences between AIRS and ECMWF over places lower than 2500 m. Also, the daily variability is very similar between AIRS and ECMWF across Antarctica.

[18] The similar daily variability between AIRS and ECMWF further supports the inference by *Monaghan et al.* [2006] that the ECMWF operational analysis is able to provide reliable precipitation variations. Wetter ECMWF fields over the high-latitude Southern Hemisphere were pointed out by *Kursinski and Hajj* [2001]. They compared PWV of ECMWF and Global Positioning System occultation data and found ECMWF was wetter by up to 1 mm in some southern high latitude zones. Based on Dome C radiosondes, the systematic wet bias of ECMWF compared to AIRS over higher elevations is likely from a combination of a slightly drier ($\sim$0.06 mm) contribution from AIRS and a wetter ($\sim$0.1 mm) contribution from ECMWF.

[19] There are several potential sources of the slight dry bias between AIRS and sondes (as discussed earlier, the sondes may themselves have a 3–6% dry bias.) The Gettelman et al. study of the relative humidity profile over Dome C suggested AIRS had about 20% higher relative humidity in the Antarctic middle troposphere (around 400 mb), possibly due to dry biases of radiosondes or colder air temperature in AIRS [*Divakarla et al.*, 2006]. Gettelman et al. also show a slightly drier bias of AIRS relative humidity near the surface (below 650 mb) compared to sondes. Since most water vapor is concentrated in the lower atmosphere, the vertically integrated AIRS PWV will be more affected by this lower layer dryness. The bias may also be partly caused by cloud-induced sampling effects [*Fetzer et al.*, 2006]. This could explain some of the discrepancy in the continent-averaged time series in Figure 2, which can be expected to be dominated by wetter, potentially cloudy coastal areas. Most AIRS retrieval information is obtained from infrared observations, so the retrieval process may be affected by clouds. Algorithm yields (the percentage of converged retrievals using both infrared and microwave observations) decreases to zero as cloud fraction approaches 70% [*Fetzer et al.*, 2006]. Cloud fraction is defined here as the product of cloud emissivity and areal coverage [*Susskind et al.*, 2003]. The retrieval accuracy of all AIRS products, including PWV, is independent of cloud fraction [*Susskind et al.*, 2006; *Fetzer et al.*, 2006], so clouds do not bias AIRS retrievals. Clouds may prevent sampling of certain scenes, creating sampling biases in AIRS PWV [*Fetzer*, 2006]. In this study we find no differences in the magnitude or the sign of the biases at the two grid points near the radiosonde site. This suggests a constant bias in either sondes or AIRS, but no significant cloud-induced AIRS sampling biases. This study again finds that cloud-induced sampling is unlikely to explain all the AIRS-sonde differences in Figure 1c. Differences in saturation vapor pressure formulations are not a plausible explanation the AIRS-sonde bias since it has is no discernable temperature dependence. In conclusion, the AIRS dry bias is most likely due to an intrinsic dryness in the retrieval, though cloud induced sampling may be contributing slightly.

[20] Because the ECMWF-sonde wet bias is temperature dependent, it could indicate model shortcomings. One is a difference in the model and sonde saturation formulation. Another is precipitation processes. *Monaghan et al.* [2006] found that the ECMWF model underestimates annual precipitation over a large part of the Antarctic interior, and does not capture frequently observed clear sky precipitation (diamond dust). *Schwerdtfeger* [1984] quotes statistics from Vostok station (elevation 3488 m) that observations of ice needle precipitation are reported on average 19 days per month during December and January. This corresponds primarily to clear sky precipitation. Although precipitation is driven by convergence, not the size of the reservoir (the PWV), results show here point to the possibility of shortcomings in ECMWF precipitation prediction. Inefficient ECMWF model precipitation may lead to larger amounts of water vapor at the higher elevations typical of the Antarctic continent, especially under warmer conditions.

[21] Given that radiosondes may still be too dry in the upper troposphere, the magnitude of dryness of AIRS and the wetness of ECMWF cannot be determined with certainty. However, further investigation is needed of the nearly constant absolute difference of roughly 0.15 mm between AIRS and ECMWF, leading to large percentage differences over high elevation. Also, the influence on surface air temperature on ECMWF's PWV calculation needs careful examination. Despite uncertainty in both the exact value and cause of these offsets, the high correlation between AIRS and ECMWF PWV throughout Antarctica shown in Figure 3 is remarkable, and suggests that both data sources are appropriate for climatic variability and regional process studies.

[22] **Acknowledgments.** This research is supported by NASA Summer Faculty Fellowship and NOAA Climate Change and Data Protection Program to HYE; NSF grant OPP-0337948 to DHB; NASA Energy and Water Study Project to EJF; and the AIRS project to all JPL authors. The authors would like to express their gratitude to A. P. McNally for his valuable knowledge and input on the ECMWF model and to V. Walden for the radiosonde data. Finally, the authors thank the two anonymous reviewers for their time and valuable comments and contribution 1364 of Byrd Polar Research Center.

References

Bromwich, D. H., and R. L. Fogt (2004), Strong trends in the skill of the ERA-40 and NCEP-NCAR reanalyses in the high and middle latitudes of the Southern Hemisphere, 1958–2001, *J. Clim.*, *17*, 4603–4619.

Chahine, M. T., et al. (2006), The Atmospheric Infrared Sounder (AIRS): Improving weather forecasting and providing new insights into climate, *Bull. Am. Meteorol. Soc.*, *87*, 911–926, doi:10.1175/BAMS-87-7-911.

Divakarla, M. G., C. D. Barnet, M. D. Goldberg, L. M. McMillin, E. Maddy, W. Wolf, L. Zhou, and X. Liu (2006), Validation of Atmospheric Infrared Sounder temperature and water vapor retrievals with matched radiosonde measurements and forecasts, *J. Geophys. Res.*, *111*, D09S15, doi:10.1029/2005JD006116.

Fetzer, E. J. (2006), Preface to special section: Validation of Atmospheric Infrared Sounder Observations, *J. Geophys. Res.*, *111*, D09S01, doi:10.1029/2005JD007020.

Fetzer, E. J., et al. (2005), Validation of AIRS/AMSU/HSB core products for data release version 4.0, *JPL D031448,* 79 pp., Jet Propul. Lab., Pasadena, Calif.

Fetzer, E. J., B. H. Lambrigtsen, A. Eldering, H. H. Aumann, and M. T. Chahine (2006), Biases in total precipitable water vapor climatologies from Atmospheric Infrared Sounder and Advanced Microwave Scanning Radiometer, *J. Geophys. Res.*, *111*, D09S16, doi:10.1029/2005JD006598.

Fu, X., B. Wang, and L. Tao (2006), Satellite data reveal the 3-D moisture structure of Tropical Intraseasonal Oscillation and its coupling with underlying ocean, *Geophys. Res. Lett.*, *33*, L03705, doi:10.1029/2005GL025074.

Gettelman, A., et al. (2004), Validation of satellite data in the upper troposphere and lower stratosphere with in-situ aircraft instruments, *Geophys. Res. Lett.*, *31*, L22107, doi:10.1029/2004GL020730.

Gettelman, A., V. P. Walden, L. M. Miloshevich, W. L. Roth, and B. Halter (2006), Relative humidity over Antarctica from radiosondes, satellites, and a general circulation model, *J. Geophys. Res.*, *111*, D09S13, doi:10.1029/2005JD006636.

Granger, S. L., et al. (2004), Development of level 3 (gridded) products for the Atmospheric Infrared Sounder (AIRS), in *IGARSS '04*, vol. 4, pp. 2506–2509, Inst. of Electr. and Electr. Eng., New York.

Hyland, R. W., and A. Wexler (1983), Formulations for the thermodynamic properties of the saturated phases of H_2O from 173.15K to 473.15K, *ASHRAE Trans.*, *89*, 500–519.

King, J. C., and J. Turner (1997), *Antarctic Meteorology and Climatology*, 409 pp., Cambridge Univ. Press, Cambridge, U. K.

Kursinski, E. R., and G. A. Hajj (2001), A comparison of water vapor derived from GPS occultations and global weather analysis, *J. Geophys. Res.*, *106*, 1113–1138.

Lambrigtsen, B. H. (2003), Calibration of the AIRS microwave instruments, *IEEE Trans. Geosci. Remote Sens.*, *41*, 369–378.

McNally, A. P., P. D. Watts, J. A. Smith, R. Engelen, G. A. Kelly, J. N. Thépaut, and M. Matricardi (2006), The assimilation of AIRS radiance data at ECMWF, *Q. J. R. Meteorol. Soc*, *132*, 935–957.

Miloshevich, L. M., H. Vömel, A. Paukkunen, A. J. Heymsfield, and S. J. Oltmans (2001), Characterization and correction of relative humidity measurements from Vaisala RS80-A radiosondes at cold temperatures, *J. Atmos. Oceanic Technol.*, *18*, 135–156.

Miloshevich, L. M., A. Paukkunen, H. Vömel, and S. Oltmans (2004), Development and validation of time-lag correction for Vaisala radiosonde humidity measurements, *J. Atmos. Oceanic Technol.*, *21*, 1305–1327.

Miloshevich, L. M., H. Vömel, D. N. Whiteman, B. M. Lesht, F. J. Schmidlin, and F. Russo (2006), Absolute accuracy of water vapor measurements from six operational radiosonde types launched during AWEX-G and implication for AIRS validation, *J. Geophys. Res.*, *111*, D09S10, doi:10.1029/2005JD006083.

Monaghan, A. J., et al. (2006), Insignificant change in Antarctic snowfall since the International Geophysical Year, *Science*, *313*, 827–831.

Schwerdtfeger, W. (1984), *Weather and Climate of the Antarctic*, 261 pp., Elsevier, New York.

Susskind, J., C. D. Barnet, and J. M. Blaisdell (2003), Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds, *IEEE Trans. Geosci. Remote Sens.*, *41*, 390–409.

Susskind, J., et al. (2006), Accuracy of geophysical parameters derived from Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit as a function of fractional cloud cover, *J. Geophys. Res.*, *111*, D09S17, doi:10.1029/2005JD006272.

Tian, B., D. E. Waliser, E. J. Fetzer, B. H. Lambrigtsen, Y. L. Yung, and B. Wang (2006), Vertical moist thermodynamic structure and spatial-temporal evolution of the Madden-Julian Oscillation in Atmospheric Infrared Sounder observations, *J. Atmos. Sci.*, *63*, 2462–2485.

Turner, D. D., B. M. Lesht, S. A. Clough, J. C. Liljegren, H. E. Revercomb, and D. C. Tobin (2003), Dry bias and variability in Vaisala RS80-H radiosondes: The ARM experience, *J. Atmos. Oceanic Technol.*, *20*, 117–132.

Turner, J., W. M. Connolley, T. A. Lachian-Cope, and G. J. Marshall (2006), The performance of the Hadley Centre Climate Model (HADCM3) in high southern latitudes, *Int. J. Climatol.*, *26*, 91–112.

Walden, V., W. Roth, R. S. Stone, and B. Halter (2006), Radiometric validation of the Atmospheric Infrared Sounder (AIRS) over the Antarctic Plateau, *J. Geophys. Res.*, *111*, D09S03, doi:10.1029/2005JD006357.

D. H. Bromwich, Polar Meteorology Group, Byrd Polar Research Center, Ohio State University, 1090 Carmack Road, Columbus, OH 43210–1308, USA.

L. Chen, E. J. Fetzer, E. F. Fishbein, S. L. Granger, S.-Y. Lee, B. H. Lambrigtsen, and E. T. Olsen, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

H. Ye, Department of Geography and Urban Analysis, California State University, Los Angeles, 5151 State University Drive, Los Angeles, CA 90032, USA. (hengchun.ye@calstatela.edu)