

Relative humidity over Antarctica from radiosondes, satellites, and a general circulation model

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[1] Radiosonde measurements are used to validate measurements of relative humidity (RH) over Antarctica from the Atmospheric Infrared Sounder (AIRS) satellite instrument. Radiosonde observations are corrected for most known biases but still have a solar heating dry bias of up to 8% relative to other instruments. AIRS reproduces the observations of temperature and relative humidity with good fidelity. There is a $\sim 20\%$ moist bias to the data in the upper troposphere relative to radiosonde measurements, but it is within the standard deviation of the measurements. Probability distribution functions of RH from radiosondes and AIRS are similar, suggesting that variability over Antarctica is well reproduced by the satellite. AIRS data are also compared to simulations from the Community Atmosphere Model version 3 (CAM3) and are found to be significantly moister than the model, although the model does not allow supersaturation with respect to ice or liquid water. A climatology from AIRS indicates that it has a repeatable annual cycle over Antarctica. Supersaturation with respect to ice is very common over the continent, particularly in winter, where it might occur almost half the time in the troposphere. This may affect the quantity and isotopic composition of ice over Antarctica.

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1. Introduction

[2] Antarctica plays an important role in Earth's climate system. It is the coldest and driest place on Earth and differs greatly from the warmer Arctic. It is a region where large amounts of heat are lost to space, which helps drive Earth's general circulation. In addition, the Antarctic ice sheet contains important historical records of climate within ice cores going back hundreds of thousands of years. Interpreting these records and relating them to present and future climate requires an understanding of ice deposition to the ice sheet, and, therefore, the humidity over the continent.

[3] In situ measurements of atmospheric conditions over Antarctica are difficult and expensive to obtain, so scientists tend to rely heavily on retrievals from satellite-based instruments. To ensure high accuracy, satellite retrievals should be compared with in situ data. Observing stations in Antarctica that measure ground-based meteorological data are located mostly around the coast. There are only a few stations on the high plateau (above 2500 m), including South Pole Station (90°S), Vostok (78°S, 106°E), Dome C (75°S, 123°E), and Dome Fuji (77°S, 40°E). South Pole Station has been launching radiosondes for decades, but the other high-altitude stations have relatively short records of sonde data. Radio-

sonde observations from Antarctica have a tendency to have problems associated with launching procedures [Mahesh *et al.*, 1997; Hudson *et al.*, 2004]. In addition, radiosonde sensors (especially pressure and relative humidity) have long response times at low temperatures [Hudson *et al.*, 2004; Miloshevich *et al.*, 2004, 2006]. The radiosonde observations at South Pole also suffer from changes in instrumentation over time, which greatly affects the usefulness of the data for studying long-term trends. Automatic weather stations (AWS) provide ground-based measurements, but are also dedicated primarily to lower elevations and coastal areas.

[4] In this work we present the results of a summer-time campaign of radiosonde measurements at Dome C, Antarctica, and we use them to validate measurements of relative humidity (RH) over Antarctica from the Atmospheric Infrared Sounder (AIRS) on the NASA Aqua satellite. RH is used because it is the fundamental measure for radiosondes, and most relevant for ice formation. The AIRS data are then used to examine the variability of water vapor over the Antarctic continent and to assess the performance of a general circulation model (GCM) at representing water vapor variability over Antarctica. The radiosonde and satellite data are described in section 2. Corrections for the radiosondes are described in section 3. The methodology for comparing these data is detailed in section 4. Comparisons between the radiosondes and satellite are shown in section 5. We also compare the variability seen in AIRS with simulations from a state of the art climate model in section 5. Section 6 examines the variability of humidity over the continent on various time

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and space scales. Discussion and conclusions are in section 7.

2. Data Description

2.1. Radiosonde Data

[5] Vaisala radiosondes were launched at Dome C, Antarctica (location indicated on the maps in Figures 8 and 10) during the austral summers of 2002/2003 and 2003/2004 as part of an AIRS validation project. The radiosondes measure profiles of temperature and relative humidity, in addition to wind speed and direction, as a function of pressure. One of the primary goals of this project was to measure spectral infrared radiances at the surface [Walden *et al.*, 2005] for validation of AIRS radiances [Walden *et al.*, 2006]. The radiosondes were used to characterize the atmosphere so that top-of-the-atmosphere radiances could be calculated from the ground-based radiance measurements. The radiosonde data also provide a means to directly validate retrievals of temperature and humidity made from the AIRS infrared radiances.

[6] Seventy-eight radiosondes were launched at Dome C in December 2003 and January 2004 in collaboration with the astrophysics groups at the University of New South Wales and the University of Nice [Aristidi *et al.*, 2005]. All of the sondes were manufactured by Vaisala, but were of three different types: RS-90 (47), RS80-A (25), and RS80-H (6), with different humidity sensors.

2.2. AIRS Data

[7] Relative humidity data are derived from the AIRS instrument on the NASA Aqua satellite as discussed by Gettelman *et al.* [2006a]. AIRS is a cross-track scanning, high-spectral resolution infrared sounder (3.7–15.4 micrometers) with ~2300 independent channels enabling retrieval of an entire profile of temperature and water vapor in the presence of up to 70% cloud cover [Aumann *et al.*, 2003]. We use AIRS level 2 data retrievals (version 3.0) [Fetzer *et al.*, 2003] with an effective vertical resolution of 1–3 km [Susskind *et al.*, 2003]. Horizontal resolution of the retrieval is approximately ~45 km, and there are on the order of 300,000 AIRS profiles per day. AIRS is in a sun synchronous orbit, with equatorial crossings at ~1330 and ~0130 local time. AIRS overpasses are more frequent and at different local times near the poles.

[8] We use retrieved profiles of water vapor (specific humidity) and temperature to derive relative humidity for each profile. Retrievals provide the column water vapor mixing ratio between two pressure levels, and temperature on the level edges. We construct relative humidity by dividing the column water vapor by a saturated vapor column mixing ratio $RH = \bar{q}/\bar{q}_s \times 100\%$. The saturated vapor mixing ratio in a column between two pressure levels (\bar{q}_s) is estimated by numerically integrating the saturation vapor pressure assuming temperature in the layer is linear between the two edges. We have conducted a detailed sensitivity test of the method of calculating relative humidity, and the results are not highly sensitive to the method chosen.

2.3. GCM

[9] We have also compared radiosonde and AIRS data to a simulation of the NCAR Community Atmosphere Model,

version 3 (CAM3), described by Collins *et al.* [2006]. A detailed analysis of global RH from CAM3 is described by Gettelman *et al.* [2006a]. The CAM3 simulation is at 1×1.25 degree horizontal resolution and 26 levels in the vertical. The sea surface temperatures (SSTs) in the simulation cover the time period 2001–2004. We analyze the 2003 calendar year, and compare it to AIRS observations over Dome C. Most importantly, the model does not permit supersaturation over ice to occur, but limits relative humidity to 100% over ice. The assumption is made that very high supersaturations are not seen over the 100 km horizontal and ~2 km vertical grid spacings of the model. For these comparisons, relative humidity from the satellite data and radiosondes is recalculated the same way the model calculates relative humidity, which is using the formulation of Goff and Gratch [1946] over water for temperatures above 0°C (273°K) and over ice for temperatures below –20°C (253°K), with linear weighting between these two temperatures. Temperatures at Dome C are generally below 253°K.

3. Radiosonde Corrections

[10] For the Vaisala radiosondes, Vaisala reports that the temperatures are accurate to 0.1–0.2°K and that the relative humidity values with respect to water (RHw) are accurate to ±3%. The RHw values are probably more uncertain when used in Antarctica because of the long response times (minutes) of radiosonde humidity sensors at low temperatures. However, Hudson *et al.* [2004] have recently shown that Vaisala RS80 radiosondes can measure temperature, pressure, and humidity accurately in Antarctica if the sensors are properly equilibrated to ambient conditions before launch. All of the sondes launched during this time period were stored and prepared at ambient, outside temperature to avoid errors induced by thermally shocking the sensors [Hudson *et al.*, 2004].

[11] Corrections were applied to the Dome C radiosonde data for three known sources of RH measurement error; temperature dependence, time lag and calibration correction errors. Although the three Vaisala radiosonde types used in this study (RS80-A, RS80-H, and RS90) are subject to the same general sources of measurement error, the magnitude of the error varies substantially between the sensor types. The calibration of RS80 radiosondes is inaccurate at low temperatures and leads to a dry bias in the measurements. A correction for this “temperature dependence” (TD) error was developed for both RS80-A measurements [Miloshevich *et al.*, 2001] and RS80-H measurements [Wang *et al.*, 2002]. The magnitude of the TD correction for RS80-H measurements, given as a percentage of the measured RH, is 1% at –30°C, 3% at –40°C, 7% at –50°C, and 12% at –60°C, whereas the TD correction for RS80-A measurements is considerably larger: 5% at –30°C, 15% at –40°C, 35% at –50°C, and 75% at –60°C.

[12] A correction was also applied for the “time lag” (TL) error that results from slow sensor response to changes in the ambient humidity. Sensor time lag error “smooths” the true RH profile by an amount that depends on temperature and on the local humidity gradient. A time lag correction algorithm was developed by Miloshevich *et al.* [2004] on the basis of laboratory measurements of the sensor time constant as a function of temperature. The

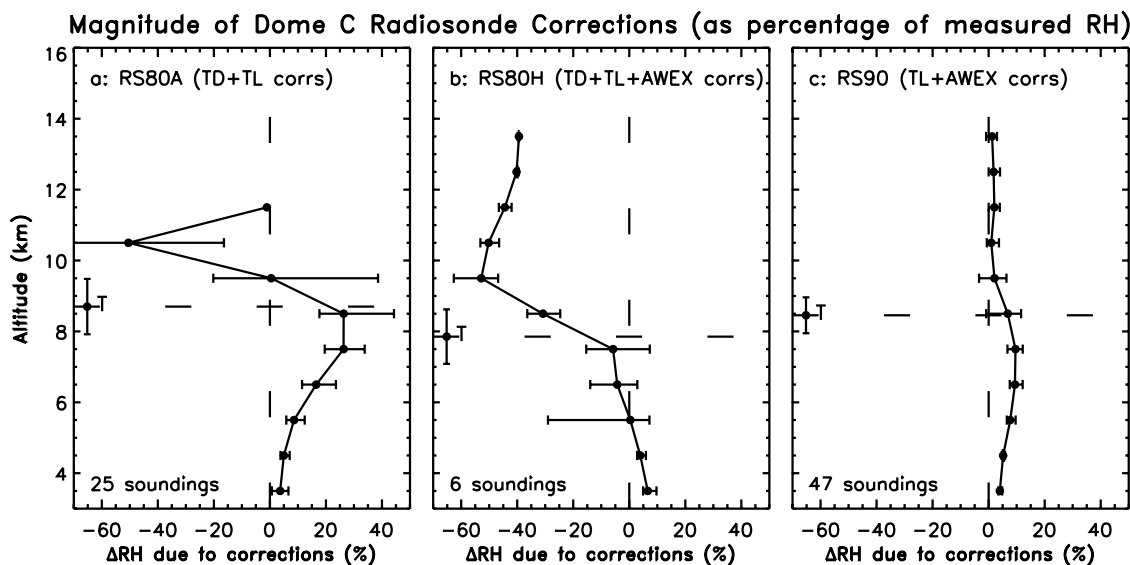


Figure 1. Mean (dots) and variability (bars) of the percent change in the measured RH from the indicated correction as a function of altitude. Error bars indicate the 68th percentile above and below the mean. The horizontal dashed line is the mean tropopause altitude, and the vertical bar is its standard deviation.

sensor time constant (i.e., the time required to respond to 63% of an instantaneous change in RH) at -60°C is 60 s for RS80-A sensors (~ 300 m of ascent), 170 s for RS80-H sensors (~ 850 m of ascent), and 46 s for RS90 sensors (~ 230 m of ascent).

[13] Finally, an empirical calibration correction for RS80-H and RS90 measurements was developed from a data set of simultaneous nighttime measurements by radiosondes and the reference-quality University of Colorado Cryogenic Frostpoint Hygrometer (CU CFH), acquired during the AIRS Water Vapor Experiment (AWEX) in fall 2003 at the DOE/ARM Southern Great Plains (SGP) site. The “AWEX empirical calibration correction” [Miloshevich *et al.*, 2006] is a temperature and RH-dependent correction that results in zero mean bias relative to the CFH, whose absolute accuracy was shown to be in the range 3–5% over the -30 to -60°C temperature range of the Dome C soundings. This correction addresses inaccuracy in the Vaisala calibration model, and it is applied after the TD and TL error has been removed.

[14] The magnitude of the RH corrections that were applied to the Dome C radiosonde data is shown in Figure 1, expressed as altitude profiles of the mean percentage correction and its variability between soundings. Variability (error bars) in Figure 1 indicate the 68th percentile above and below the mean, which is analogous to the standard deviation (σ) but more appropriate for an asymmetric distribution. By definition, 16% of soundings receive a correction beyond each end of the error bars. Note that all three corrections are not needed for all radiosonde types. The absolute accuracy of the corrected data are discussed in detail by Miloshevich *et al.* [2006]. On average, the RS80-A measurements were moistened by 4% near the surface to 27% in the upper troposphere (UT); the RS80-H measurements were moistened by 7% near the surface and dried by -5% in the UT; and the RS90 measurements were moist-

ened by 4% near the surface to 9% in the UT. There can be considerable variability between individual soundings of the same sensor type, because of the dependence of the corrections on RH, T, and $d\text{RH}/dt$ (humidity gradient). As a general rule, even the corrected radiosonde data are not sufficiently accurate to use at altitudes more than a few km above the tropopause, above the level where the RH has dropped to very low stratospheric values at low pressures. Because of these low RH values near the sensor response threshold, the large RS80-H correction in the stratosphere (-40% in Figure 1) is not particularly meaningful since it is only 1% RH (the resolution of the data). Neither the corrected or uncorrected data are a meaningful measure of humidity in the lower stratosphere.

[15] Detailed assessments of the mean accuracy and its variability for both standard and corrected RS80-H and RS90 measurements were derived from the AWEX data set, on the basis of comparison to simultaneous measurements from both the CFH [Miloshevich *et al.*, 2006] and the NASA Scanning Raman lidar [Whiteman *et al.*, 2006]. The mean accuracy is the most relevant parameter when analysis of a data set as a whole is considered, and the mean accuracy was shown to vary as a function of RH and temperature. Over the temperature range of the Dome C soundings, the mean percentage accuracy of standard RS90 measurements (relative to the CFH reference standard) is -4% if $\text{RH} > 60\%$, -8% at $\text{RH} = 30\%$, and about -12% when $\text{RH} < 20\%$, where negative indicates a dry bias. When the corrections are applied, the mean accuracy of the RS90 measurements relative to the CFH is $<1\%$ for $\text{RH} > 10\%$. The absolute accuracy of the CFH measurements was determined from instrumental considerations to be 4–6% in the troposphere [Miloshevich *et al.*, 2006]. Measurements from any individual sensor are less accurate, and are given by the standard deviation of differences from the CFH shown in Table 3 of Miloshevich *et al.* [2006]. Standard

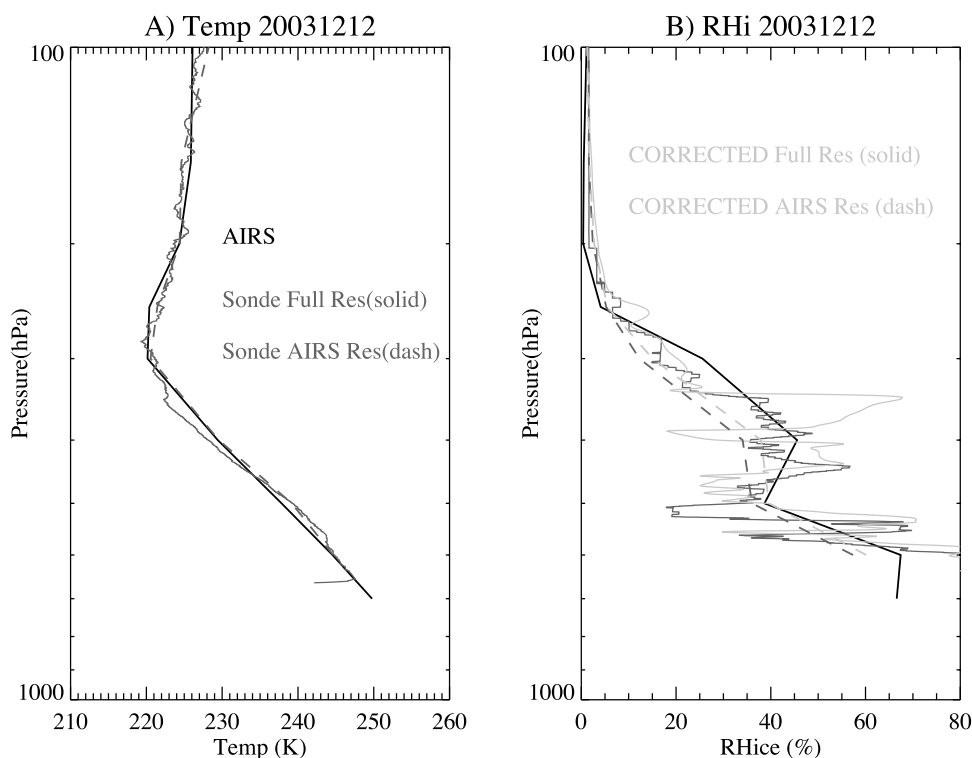


Figure 2. Sample profiles of (a) temperature and (b) relative humidity over ice. Raw sonde data are the thin gray line. Dashed gray line is sonde data binned to the AIRS vertical resolution. The AIRS data at this location and time are shown in black. In Figure 2b, corrected relative humidity is shown as light gray thin line, and the corrected relative humidity averaged to AIRS resolution is shown as light gray dashed line.

RS80-H measurements exhibit a dry bias under moist conditions and a moist bias under dry conditions, by about -10% for $RH > 40\%$, to $+10\%$ at $RH = 15\%$, and $>15\%$ for $RH < 10\%$. The mean percentage accuracy of the corrected RS80-H measurements is better than -4% for $RH > 20\%$, and about -12% for drier conditions.

[16] The above mean accuracy values correspond to nighttime measurements, whereas daytime measurements (including the Dome C soundings) have additional uncertainty caused by solar heating of the RH sensor, which leads to a dry bias in the measurements. By comparison to measurements of precipitable water vapor (PWV) by a microwave radiometer that has little or no diurnal variability in its accuracy, Turner *et al.* [2003] found a dry bias of 3–4% for daytime RS80-H measurements, and Miloshevich *et al.* [2006] found a dry bias of 6–8% for daytime RS90 measurements. These dry biases will be present even in the corrected Dome C data. Note that the values for the solar radiation error are in terms of PWV and therefore represent the lower troposphere, whereas the dry bias is likely larger in the UT.

[17] A typical radiosonde flight from Dome C consists of data from when the sonde was both ascending and descending. The data used in this study are from the ascent only. A small fraction of the raw data were rejected because of temporary loss of transmission between the sonde and its ground station. The thin gray lines in Figure 2 show sample profiles of temperature (Figure 2a) and RH_{ice} (Figure 2b) from 12 December 2003. The temperature profile exhibits a near-surface temperature inversion, which is prevalent when

the sun dips low in the sky at “night.” The tropopause is visible at about 300 hPa. The corresponding profile of relative humidity shows large variations of 20% to 80% in the troposphere (likely due to atmospheric variability and vertical wind shear), without a discernible near-surface humidity inversion. The relative humidity drops off rapidly toward the tropopause and remains low into the stratosphere (above 300 hPa).

[18] Figure 3 shows the mean profiles of temperature and humidity, and their variability, for the entire field season. Figure 3a shows the mean temperature profile and the profiles of plus and minus one standard deviation from that mean. The standard deviation of temperature is about ± 2.5 to 3°K in the tropopause and decreases to about $\pm 1^\circ\text{K}$ in the lower stratosphere. The standard deviation of relative humidity (Figure 3b) is larger with tropospheric variability of $\pm 20\%$. The variability in the stratosphere is much less, ± 1 to 2%

4. Methodology

[19] Here we compare Dome C radiosonde profiles with AIRS retrievals. AIRS data are binned to the locations of the soundings using a collocation criteria of ± 50 km in space, ± 1 hour in time. Consistent with AIRS quality control, we require that the retrieval process successfully complete an infrared retrieval algorithm (denoted by the retrieval type = 0). In general two to five AIRS profiles meet this criteria for each radiosonde launch. All profiles meeting these location, time and quality criteria are aver-

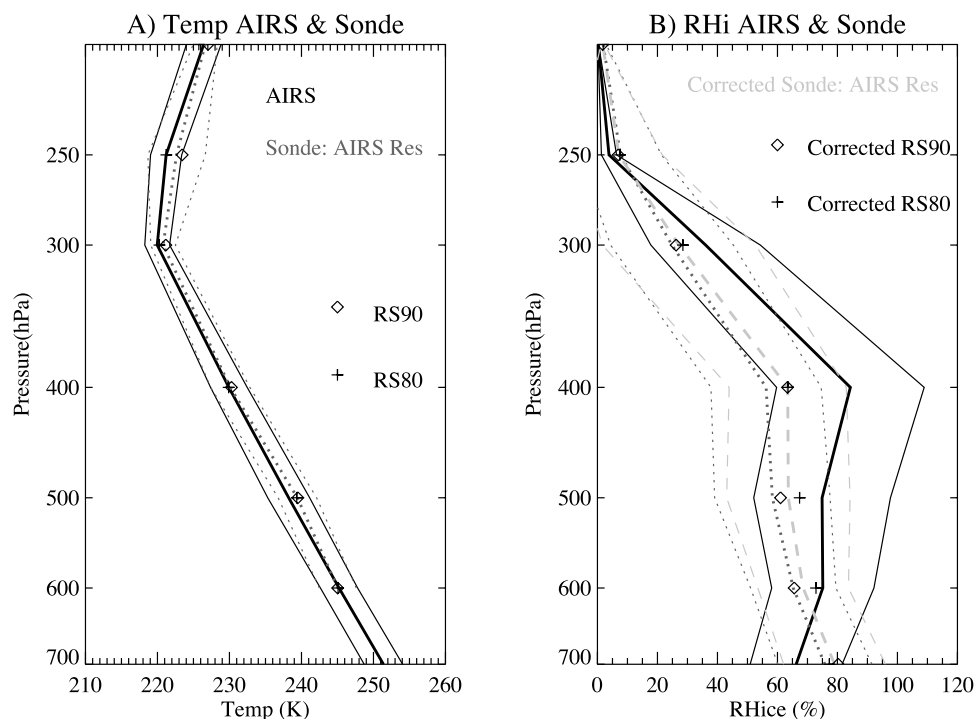


Figure 3. Mean (thick lines) and 1σ (thin lines) of all 73 soundings (or the subset of these for which AIRS data exist). (a) Temperature and (b) RH over ice. Gray dotted line indicates radiosonde data averaged to AIRS vertical resolution. Black solid line indicates binned AIRS data. In Figure 3b, corrected radiosonde relative humidity averaged to AIRS vertical resolution is shown as light gray dashed lines. Corrected data sorted by sounding type are shown for RS90 radiosondes (diamonds) and RS80 radiosondes (crosses).

aged together. For direct comparisons, radiosonde data are degraded to AIRS vertical resolution by taking an average of the data between two AIRS pressure levels for RH (which is a layer quantity in the AIRS data) and ± 250 m for temperature (a level quantity).

[20] The references to “RH” in this study reflect differences in the calculations. RH refers in general to relative humidity, or the merged GCM relative humidity over water and ice, while RHw refers to relative humidity with respect to liquid water, and RH_i with respect to ice.

[21] The saturation vapor pressure is calculated using two different methods in this work to ensure compatibility with correlative data and models. Since radiosonde RHw is calculated using the formulation of *Hyland and Wexler* [1983], we adjust this to RH_i using the formulation of *Hyland and Wexler* [1983] over ice. For comparisons with the CAM3 GCM, we recalculate AIRS RH using the same formulation of RH as used in the model, described above in section 2. Differences in the saturation vapor pressure relative to other measures are within 1–2% [*Murphy and Koop*, 2005].

[22] Following the AIRS convention, pressures here refer to the bottom of the layer (50 hPa thick from 100–300 hPa and 100 hPa thick at higher pressures).

5. Results

5.1. AIRS-Radiosonde Comparisons

[23] Figure 2 shows a sample profile for temperature and humidity. AIRS is able to accurately retrieve temperature in

this profile (Figure 2a), into the stratosphere. The tropopause lies near 300 hPa in this sounding, typical for the experiment period. The AIRS data are also able to better capture the tropopause than a simple degraded average of the radiosonde data, as the data are actually retrieved on a finer grid (100 levels) for temperature. For relative humidity (Figure 2b), AIRS is able to reproduce the major features of this radiosonde profile, but not the detailed vertical variability at vertical scales less than 1 km. AIRS is able to capture the midtroposphere inversion in the data.

[24] Figure 3 presents the average of all the soundings and collocated satellite data. Since we do not know the spatial variability of temperature or relative humidity from the radiosonde data, we approximate it with the temporal variability from the 73 soundings, and show $\pm 1\sigma$ from the mean (thin lines in Figure 3). This we interpret as the potential “horizontal variability” of the atmosphere within the AIRS horizontal averaging kernel around Dome C (± 50 km). Though it is likely an upper limit on horizontal variability, it is the only measure of horizontal variability available.

[25] Temperature (Figure 3a) is quite good throughout this entire range. AIRS corresponds to the radiosonde data within this deviation in Figure 3a. The tropopause again is at ~ 300 hPa, and is slightly colder in AIRS, but as with the individual profile, this is likely due to the simple bulk degrading of the radiosonde temperature around the tropopause for comparisons.

[26] Relative humidity has a very large scatter (1σ is 30% in the upper troposphere, which is 1/2 the value) for both

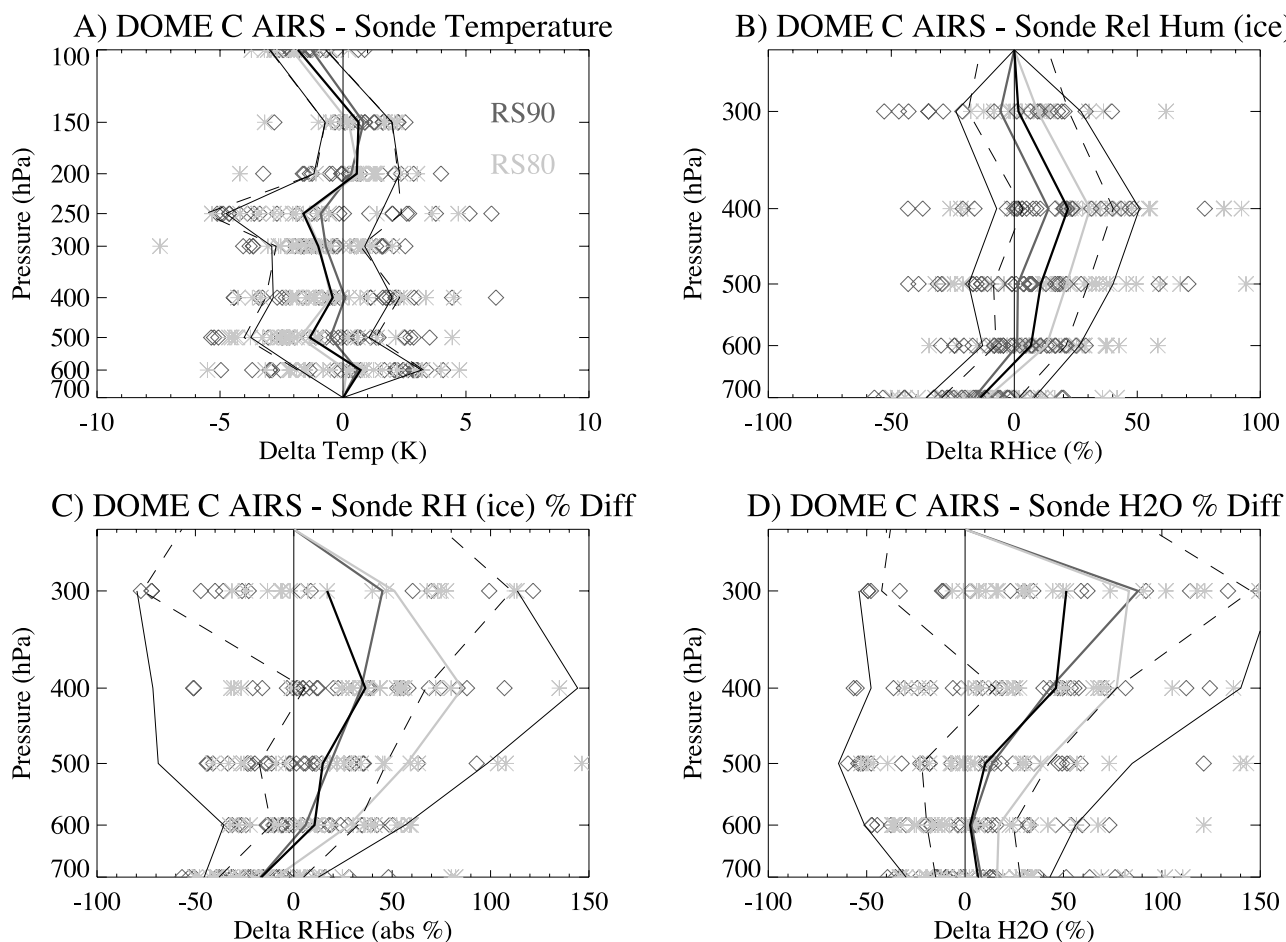


Figure 4. Scatterplots of each difference pair by level. RS90 Sondes are indicated by dark gray (diamonds), and RS80 are indicated by light gray (asterisk). (a) Temperature difference ($T_{AIRS} - T_{Sonde}$), (b) RH difference over ice in RH units ($RH_{AIRS} - RH_{Sonde}$), (c) absolute differences ($(RH_{AIRS} - RH_{Sonde})/RH_{Sonde}$), and (d) water vapor (H_2O) percent differences ($(H_2O_{AIRS} - H_2O_{Sonde})/H_2O_{Sonde}$). Thick line is the mean difference for all launches (black) as well as just RS90 (gray) and RS80 (light gray). Thin lines are $\pm 1\sigma$ of the difference (from the mean difference) for all soundings. Dashed lines are $\pm 1\sigma$ from the sounding data in Figure 3 at each level. Height range is different on each plot. Radiosonde RH and H_2O data are corrected.

the sounding data and AIRS (Figure 3b), indicating that there is high variability, and it may be difficult to accurately represent a single point sounding with the large horizontal average of AIRS (100 km here). The mean of the AIRS RH data is within 1 standard deviation of the radiosonde, though there appears to be a moist bias of up to 20% RH (40% absolute) in the upper troposphere, peaking at 400 hPa. AIRS data in the stratosphere (above 300 hPa) are too dry, which might be expected because the satellite cannot see stratospheric levels of humidity below 10 parts per million of water vapor.

[27] We have also examined differences between the RS90 radiosondes and RS80 radiosondes. There is little discernible difference for temperature (Figure 3a). There are however distinct differences between the mean of the corrected soundings using RS90 radiosondes (Figure 3b, diamonds) and those using corrected RS80 radiosondes (Figure 3b, crosses). Corrected RS80 radiosondes appear to be up to 10% RH (15% absolute) moister in the middle troposphere than corrected RS90 radiosondes, but within 1 standard deviation of the total spread of data. We highlight

that the “H” Humicap sensor, calibration accuracy and susceptibility to both solar heating and cloud influences is different between the RS90-H and RS80-H, so this difference is not unexpected. Thus there is some solar dry bias, but no indication of sensor icing in clouds. Part of the differences could also be due to random sampling error since there are fewer RS80H than RS90H soundings.

[28] Figure 4 shows scatterplots of the temperature, relative humidity and specific humidity differences as a function of altitude for all 73 soundings with AIRS data meeting the colocation and quality criteria. Individual differences are sorted by sonde type (RS90, dark gray diamonds; RS80, light gray asterisk). Thick lines in Figure 4 are the mean difference, thin lines are ± 1 standard deviation (σ) of the difference. Dashed lines are the mean difference (thick black line) $\pm 1\sigma$ of the sounding data at each level (Figure 3, thin lines). Where the mean difference is less than the standard deviation of the sounding data, this indicates that differences are less than the temporal variability in the radiosondes, which we use as a surrogate

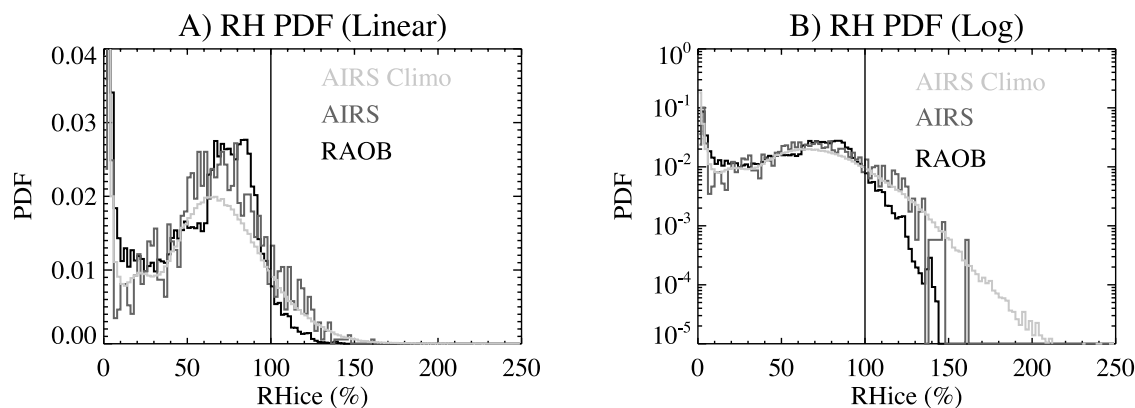


Figure 5. Probability distribution functions (PDFs) for Radiosonde data (RAOB, black), AIRS data within 50 km and ± 1 hour of the soundings (AIRS, dark gray) and AIRS climatology over Dome C (AIRS Climo, light gray). Shown are 700–200 hPa data. Same data for (a) linear and (b) logarithmic vertical axes.

for the potential horizontal variability within the AIRS averaging kernel.

[29] The mean temperature difference (Figure 4a) between AIRS and the soundings is $\sim 1^\circ\text{K}$ or less at all levels. This is well within one standard deviation of the AIRS data. Differences maximize in the lower stratosphere, where AIRS is $\sim 1^\circ\text{K}$ colder than the sounding at 250 hPa. AIRS is $\sim 0.5^\circ\text{K}$ warmer than the radiosondes near the surface (600 hPa) and above the tropopause (200 hPa). There is little difference between sounding types, except the RS90 soundings have less bias in the middle troposphere (up to 400 hPa). The biases up through the troposphere and up to 150 hPa are less than the standard deviation between the soundings at all levels.

[30] For RH (Figure 4b), the mean AIRS RH_i is slightly higher than radiosondes except at the surface. There is less difference with respect to the RS90 sondes, which have a superior humidity sensor. AIRS appears to be slightly (10% RH_i) drier than the RS90 data at 700 hPa, and moister than the soundings by 10–20% RH at 400 hPa. The differences are within the range of variability of RH_i in the soundings (thin dashed line in Figure 4b). This difference is also in the same sense implied by the temperature biases in Figure 4a (colder temperatures imply higher RH_i for the same water vapor, and vice versa), although where RH_i differences are largest at 400 hPa (Figure 4b), there is little temperature difference (Figure 4a), especially from the RS90 soundings (see Figure 4d below).

[31] It is instructive to look at the absolute difference between the radiosonde data and AIRS data, illustrated in Figure 4c as $(\text{RH}_{i,\text{sonde}} - \text{RH}_{i,\text{AIRS}})/\text{RH}_{i,\text{sonde}} \times 100$. The units are also percent, but this is the fractional (absolute) deviation, not the RH_i deviation. Again, the RS90 humidity data are superior. Differences are small in the lower troposphere where humidity is high (refer to Figure 3b) and are largest at 400 hPa which represents the column between 400–300 hPa (as described in section 2). This is the region just below the tropopause where the gradient is large (Figure 3b). AIRS data in the mean are $\sim 30\%$ (absolute) higher than the RS90 radiosondes, but still within the scatter seen in the soundings at this level (dashed lines in Figure 4c).

[32] Figure 4d illustrates specific humidity from AIRS and radiosondes. Radiosondes fundamentally measure RH,

so water vapor (H_2O) is calculated using the saturation vapor pressure at the reported temperature. This introduces the possibility of a bias in the radiosonde temperature data, but eliminates any possible biases in AIRS temperature data seen in Figure 4a. In Figure 4d, H_2O in AIRS is generally larger than the radiosondes, consistent with the possibility of a radiosonde dry bias (but of larger magnitude). Water vapor compares quite well near the surface up to 500 hPa, with differences of 10% or less, but is large (up to 50%) as water vapor concentrations are low near the tropopause (300–400 hPa). This contributes to the positive RH bias seen in Figures 4b and 4c. In summary, there is an upper tropospheric moist bias in the AIRS retrievals relative to the corrected radiosonde profiles, maximizing in the column just below the tropopause, which appears to be due to a combination of AIRS having higher water vapor and lower temperatures (recall that the radiosondes themselves have a solar dry bias, a point we will return to later).

[33] Another way to look at the overall fidelity is to compare the raw probability distribution functions of the full resolution sounding data, and the unaveraged AIRS profiles, along with an AIRS climatology over Dome C. Figure 5a illustrates this comparison for data from 700–200 hPa, which includes part of the lower stratosphere. The lower stratosphere shows up as a peak in the distribution for humidities below 10%. On the whole, the distribution of RH_i from the radiosondes is reproduced by AIRS. Both AIRS and radiosonde data show a peak in the PDF between about 50–80% RH_i. Interestingly, the AIRS data are drier. This is likely due to the effects at 600 hPa and 300 hPa (Figure 4b). There are slightly fewer values of RH in the 10–20% range observed by AIRS. Both the radiosondes and AIRS indicate some supersaturation with respect to ice (4% of the radiosonde data, 10% of the AIRS climatology and 11% of the AIRS data). The AIRS climatology is not significantly different from the sampled data, indicating that the 73 sounding correspondences from AIRS are probably sufficient to sample the PDF of humidity around Dome C station.

5.2. Climate Model Comparisons

[34] We have also compared radiosonde and AIRS data to a simulation of the NCAR Community Atmosphere

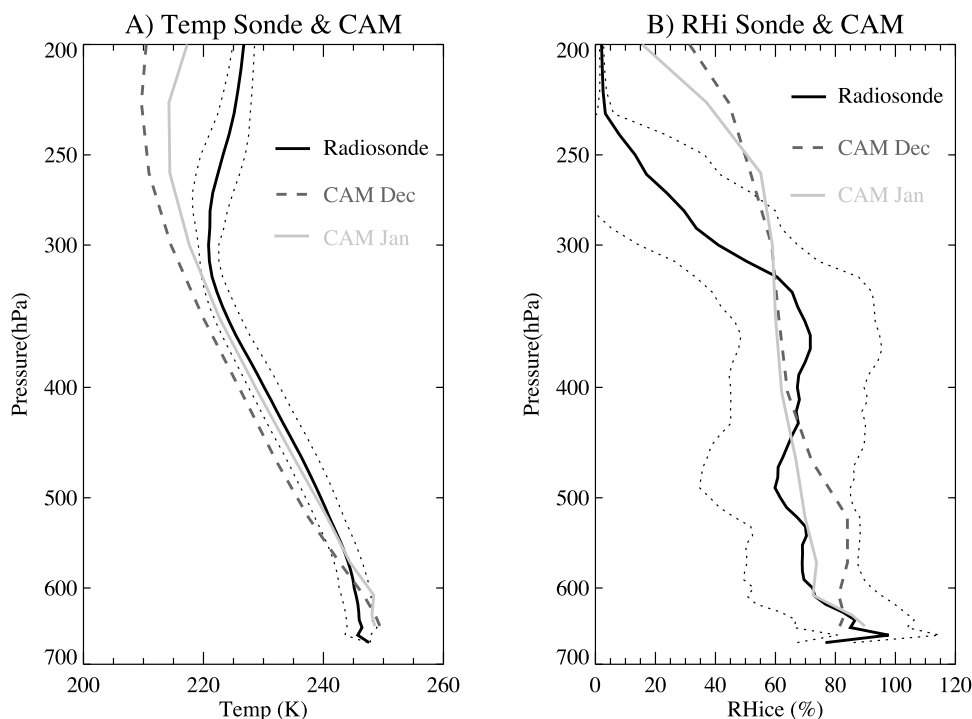


Figure 6. (a) Temperature and (b) relative humidity (over ice) profiles from radiosondes and CAM. Thick black line is the mean campaign radiosonde profile, and thin black dotted line is the standard deviation. Also shown are CAM monthly means, Dome C station (73°S, 123.75°E), for December (dark gray dashed) and January (light gray solid).

Model, version 3 (CAM3). Figure 6 illustrates a comparison between the mean sounding temperature (Figure 6a) and relative humidity (Figure 6b) and monthly means from the climate model. Sounding data are averaged every 10 hPa in the vertical from all soundings. As noted above, relative humidity has been recalculated from the soundings to match the model formulation of relative humidity, so the mean curve is different than Figure 3b. Near the surface (650–500 hPa) the model and observed temperatures are quite close. Monthly mean model temperatures are about 1–5°K colder than the radiosondes in the upper troposphere. This might be because the model does not really resolve the stratosphere well, and puts the tropopause at 250 hPa, higher than in the observations. It may also be due to internal model variability not constrained by the boundary conditions. We do not expect perfect agreement even in the monthly mean, since synoptic variability in the model need not match the observations for a particular time period. For example, a different structure of the Antarctic stratospheric polar vortex in the model will significantly affect upper tropospheric temperatures. For RH (Figure 6b), the model RH is within the range of variability of the observations. There is little vertical variation in the troposphere in CAM3, so the model is 5–10% dry in the upper troposphere (350 hPa), and 5–10% moist in the lower troposphere (550 hPa). Differences are well within the temporal variability observed from radiosondes. We expect the model to be drier in the upper troposphere because no supersaturation is permitted. We expect the radiosondes to be drier in the lower troposphere because

of solar radiation biases of perhaps 3–8%, even for corrected profiles.

[35] Figure 7 presents the annual cycle of AIRS (Figure 7a) and CAM3 (Figure 7b) humidity over the latitude band around Dome C station (66–76S), and a monthly zonal mean comparison between CAM and AIRS (Figures 7c and 7d). Note that the December–January summer period when the soundings are launched is actually the lowest mean humidity observed in the lower and middle troposphere from AIRS (Figure 7a). Agreement between CAM3 and AIRS is good for the period of the radiosonde campaign during December–January. During the rest of the annual cycle, CAM3 data are drier than AIRS data (Figure 7c). AIRS has an annual cycle in RH, with a lower-tropospheric max in March to May and an upper tropospheric maximum from July to October (Figure 7a). The annual cycle in CAM3 is smaller. The model is 8–12% (RH units, Figure 7c) drier than AIRS data with largest differences from April to September (fall and winter). The absolute difference is ~15% (Figure 7d) since relative humidity is about 80%. This dry bias is likely due to the lack of supersaturation with respect to ice in the simulation, whereas supersaturation occurs often in the AIRS data. Differences at upper levels (300 hPa and lower pressures) are likely due to the different altitude of the tropopause in the model simulation.

6. Antarctic Climatology

[36] The advantage of AIRS data is the tremendous spatial coverage and sampling, even if there is some bias

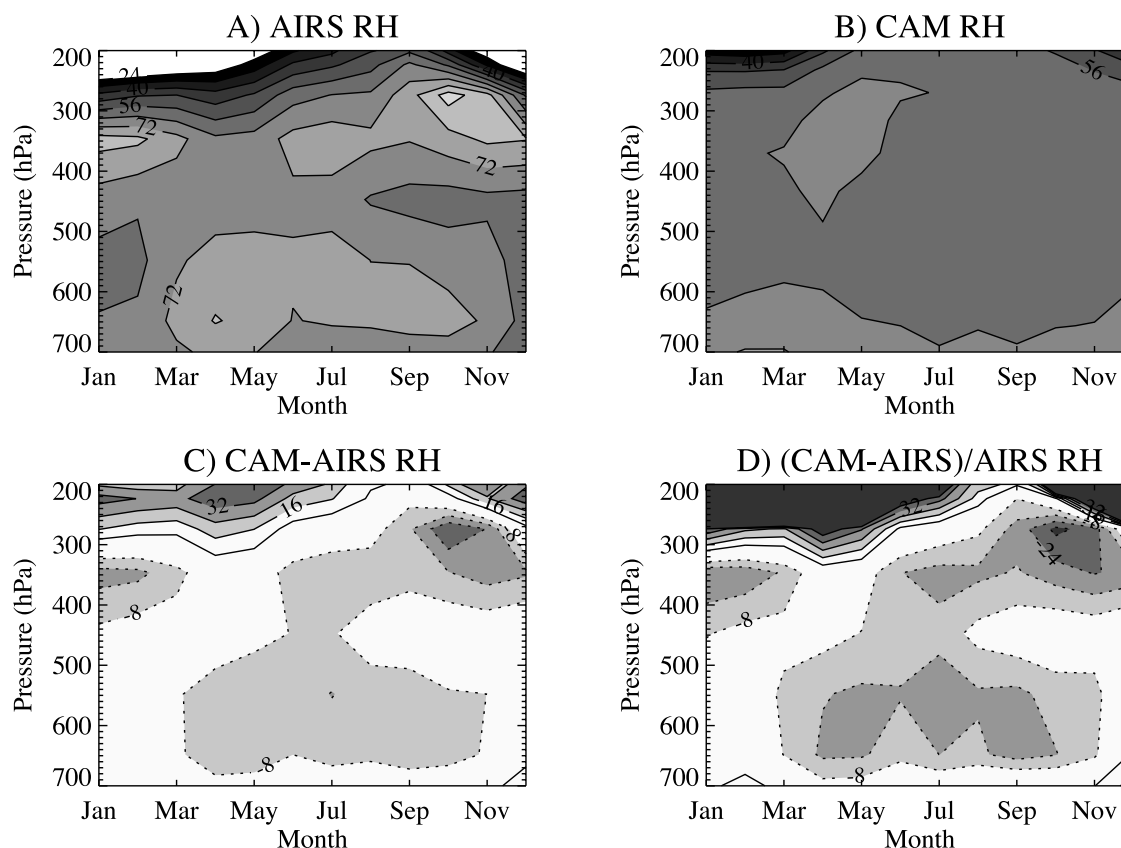


Figure 7. (a) Monthly zonal mean AIRS RH from 76°S – 66°S and 700–200 hPa, (b) same quantity simulated by CAM3, (c) difference plot (CAM-AIRS), and (d) absolute difference (CAM-AIRS)/AIRS. Contour interval is 8% RH in all three panels.

in the RH retrieval. The basic climatology of RH over Antarctica from AIRS at 500 hPa is presented by season in Figure 8. While traditionally Antarctic seasons are defined with a six month winter from April to September, and a two month spring, summer and fall [Warren, 1996], we choose standard three month seasons for illustration. The location of Dome C station (73°S , 123°E) is indicated by a black cross inside a white diamond. In Figure 8, RH is calculated as the “merged RH” over water and ice, using vapor pressure formulations of Goff and Gratch [1946] identically to the climate model. Practically, all of the data are with respect to ice ($T < 253^{\circ}\text{K}$) over Antarctica. Consistent with Figure 7, the summer season (December to February, Figure 8a) has the lowest RH, and the winter season (June to August, Figure 8c) the highest RH. Monthly mean RH varies from about 65%–90% at 500 hPa over Dome C. Over the Antarctic ocean in the middle troposphere RH is near 50%. Over the highest regions of the Antarctic continent, there are significant supersaturated regions where $\text{RH}_i > 100\%$, indicated by the heavy black line in Figure 8.

[37] Figure 9 illustrates monthly and interannual variability for Dome C and for the South Pole for the available period of AIRS data. Note that RH is quite high in the troposphere, consistent with the zonal mean in Figure 7a. Figure 9 indicates that the annual cycle repeats. Outside of December and January observed by radiosondes, there is significant supersaturation present in the data at both levels examined. Highest humidities in each year at 300 hPa

(Figures 7b and 7d) are found in November (spring) over both South Pole and Dome C, likely related to changes in the tropopause. At 500 hPa (Figures 7a and 7c), humidity is highest in June or July (winter), likely related to cold tropospheric temperatures.

[38] Supersaturation is also illustrated over Dome C station in Figure 5. Figure 5b on a log scale highlights the regions of supersaturation ($\text{RH}_i > 100\%$). In Figure 5, 11.0% of the AIRS observations coincident with the radiosondes were supersaturated, 9.6% of the AIRS climatology over Dome C station showed supersaturation, and 4.3% of the radiosonde observations were supersaturated with respect to ice. By a priori construction (noted above), 0.0% of the climate model points are supersaturated with respect to ice (not shown). AIRS sees almost twice as much supersaturation as radiosondes during this campaign. This may be a consequence of the AIRS moist “bias” in the middle troposphere or a radiosonde dry bias. What is not known is whether this is a consistent difference, or whether it might vary over the annual cycle. Supersaturation from AIRS globally is discussed in more detail by Gettelman *et al.* [2006b].

[39] The frequency of supersaturation in AIRS data over Antarctica is illustrated in Figure 10 by season. In fall and winter (Figures 10b and 10c), supersaturation occurs a majority of the time over the Antarctic ice cap at 500 hPa. It occurs rarely at this altitude over the Southern Ocean. There are also large gradients, with the Dome C site (73°S ,

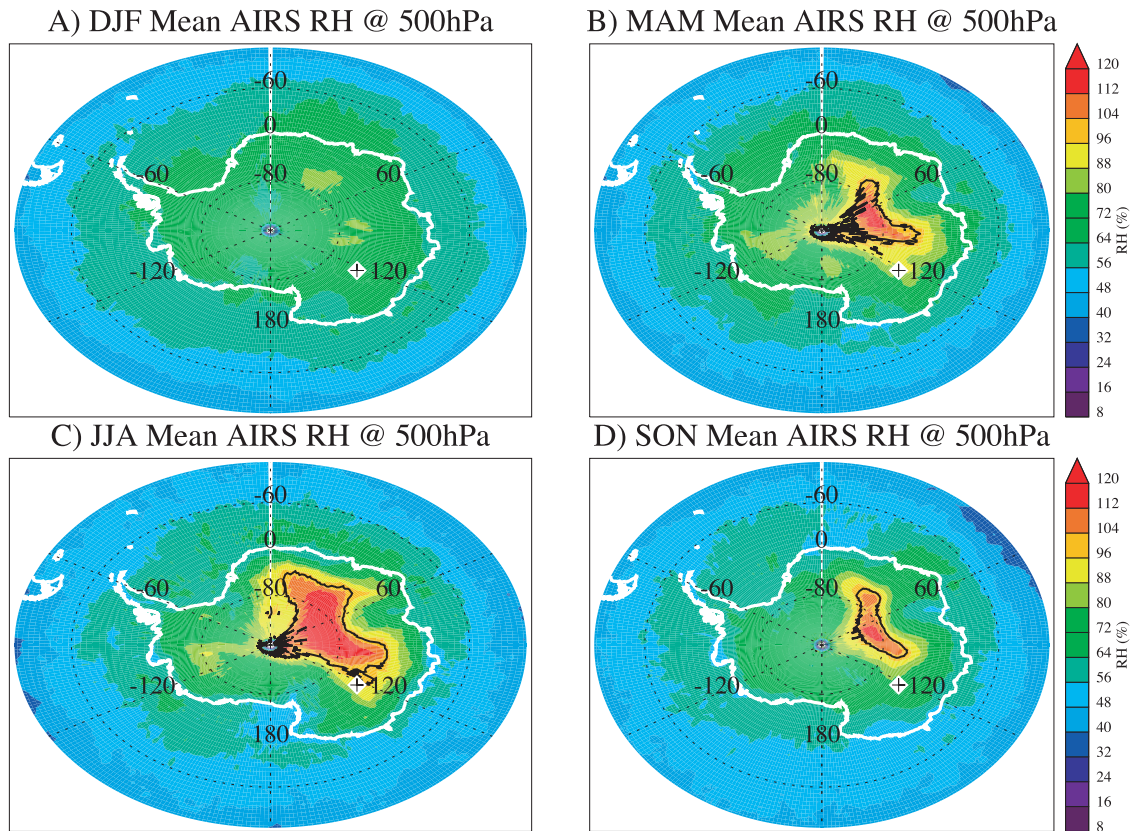


Figure 8. Seasonal mean AIRS RH over Antarctica for (a) December to February, (b) March to May, (c) June to August, and (d) September to November. Dome C location (75°S , 123°E) is indicated by white diamond with black cross in it. Thick line denotes monthly mean RH $> 100\%$.

123°E) at the edge of the region of highest frequency of supersaturation. Supersaturation is most common from April to June (early winter), and least from October to December (early summer). The distribution of supersaturation mirrors that of mean RH (Figure 8), except that in spring (September to December) there appears to be less supersaturation than expected (Figure 10c) given the high mean relative humidity (Figure 8c) and the relationship between the highest mean RH and frequency of supersaturation in fall (Figures 8b and 10b) and winter (Figures 8c and 10c). The reason for this discrepancy is unknown.

7. Discussion/Conclusions

[40] Relative humidity from AIRS satellite data and a climate model have been compared to radiosondes launched over Dome C Antarctica (73°S , 123°E) during summer (December to January). Overall the satellite data for temperature are of very high fidelity, with mean differences less than 1°K (AIRS colder than the radiosonde). Humidity is biased high relative to radiosonde observations, by as much as 20% RH_i at 400 hPa, or nearly 30% absolute. This is due to slightly (1°K) colder temperatures and higher specific humidity in AIRS. The differences in specific humidity may be due to representation of the tropopause gradient and lower stratospheric humidity. Even the corrected radiosondes are up to 6–8% dry in the lower troposphere, and perhaps more at higher altitudes, because of biases in radiosonde humidity sensors caused by solar radiation.

Some of the difference between radiosondes and AIRS is thus attributable to biases in the radiosonde measurements. It would help further validation efforts if radiosonde measurements were also collected in darkness.

[41] The RH bias is in the same sense as the temperature bias. For typical temperature conditions at 400 hPa (230°K), a temperature difference of -1°K increases the vapor pressure by 12%, hence increasing RH by 12% (absolute). Specific humidity differences contribute linearly to the RH differences.

[42] Some of the discrepancy between AIRS and radiosondes is also likely because of the AIRS vertical averaging kernel of 1–2 km in the presence of strong vertical gradients in RH (which may also be why RH and temperature biases are not the same near the tropopause at 300 hPa). These biases should be considered, but are small considering the extreme conditions sampled, and the temporal variability in the soundings ($1\text{--}3^{\circ}\text{K}$ for temperature, $\sim 20\%$ for RH). All of the differences between AIRS and radiosondes are within the one standard deviation temporal variability of the sounding data.

[43] Biases in AIRS RH are thus due to small biases in temperature and slightly larger biases in specific humidity, and horizontal and vertical averaging. We recognize that the radiosondes themselves are biased dry, so on balance AIRS is probably “slightly” moist in the upper troposphere, and shows little absolute bias in the lower troposphere (where humidity is higher). The differences between the radio-

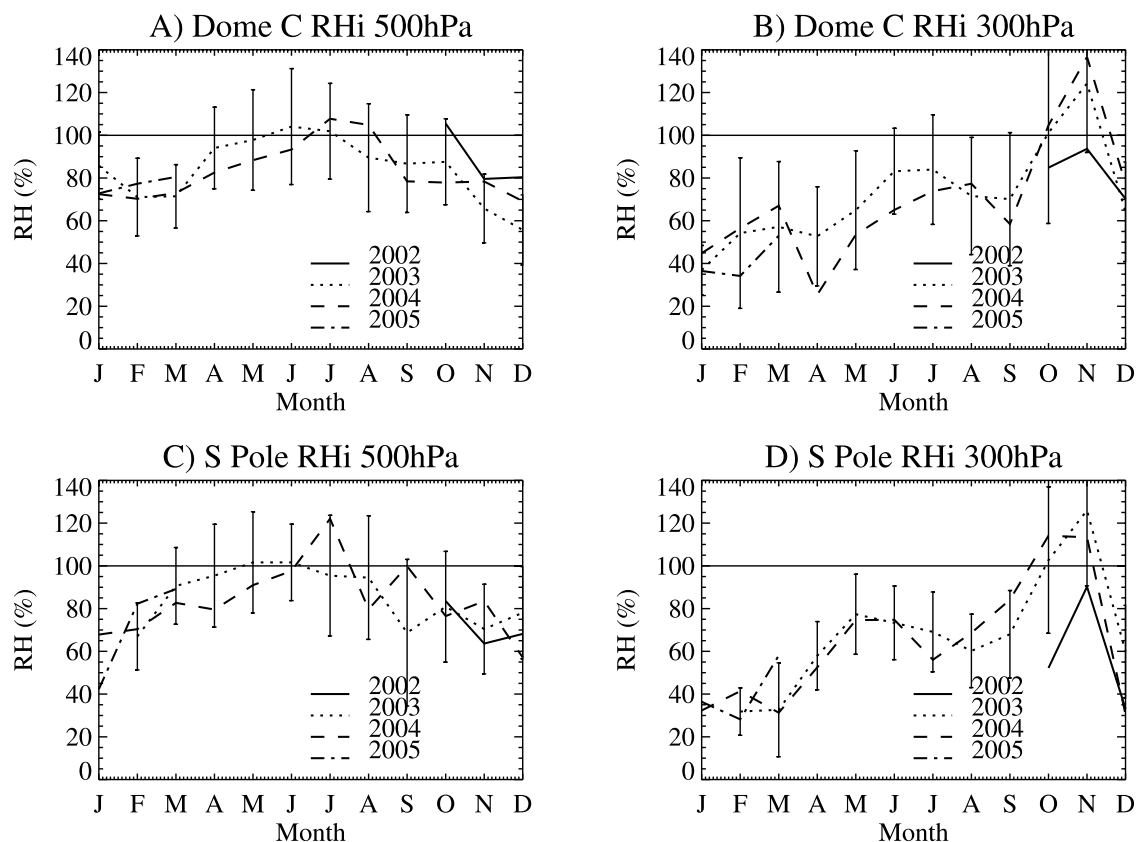


Figure 9. Monthly mean AIRS relative humidity (thick lines) for 2002–2005 (solid line, 2002; dotted line, 2003; dashed line, 2004; and dot-dashed line, 2005) and daily standard deviation for each month for 2003 (error bars). (a) Dome C 500 hPa, (b) Dome C 300 hPa, (c) South Pole 500 hPa, and (d) South Pole 300 hPa.

sondes and AIRS data are consistent with the known uncertainties with the radiosonde data. Overall the variability in RH, represented by the PDF of the radiosonde observations (Figure 5) is well reproduced by AIRS data. Largest disagreement between AIRS and radiosondes typically occur when temperatures differ significantly, which also causes issues in the water vapor retrieval, since temperatures are input to the water vapor retrieval.

[44] CAM3, a climate model with high horizontal resolution, compares favorably to the mean temperature and RH observed at Dome C by radiosondes, throughout most of the troposphere (Figure 6). The climate model, with coarse vertical resolution, does not resolve well the region around and above the tropopause (300 hPa and above). The model also compares favorably to AIRS data, with again $\sim 10\%$ (15% absolute) positive bias in AIRS relative to the climate model output. Differences in the annual cycle between AIRS and CAM3 outside of the December to January campaign period of the radiosonde observations are large.

[45] Major uncertainties remain in whether differences between AIRS and radiosondes can be extrapolated to the entire annual cycle from data over just December and January. This is a critical issue, because AIRS humidity provides one method of estimating the humidity fluxes over the continent, which are critical for understanding the ice sheet mass balance.

[46] A climatology of AIRS data over Antarctica indicates very high relative humidity over ice (Figure 8), and

frequent supersaturation over ice (Figure 10). These high values are not unexpected from satellites, and have been observed before [Spichtinger *et al.*, 2003; Gettelman *et al.*, 2006b]. Geophysically, homogeneous nucleation of ice particles occurs at relative humidities over ice of $\sim 160\%$. Heterogeneous freezing occurs at lower supersaturations (110–120%). So we expect some supersaturation in ice conditions.

[47] There is significant uncertainty however in quantifying these statistics, especially given the differences in the frequency of supersaturation noted between colocated AIRS and radiosonde data during the campaign. These differences make it difficult to use these high supersaturations for quantitatively understanding ice nucleation processes. Nonetheless, it is clear from the radiosondes that some supersaturation is observed, even in summer when RH is low. Even if we extrapolate that the frequency of supersaturation is half of what AIRS observes, it indicates that supersaturation over ice is a frequent (if not dominant) condition in the Antarctic troposphere, particularly during the fall and winter (from March to August) over the high-altitude region of the polar ice cap.

[48] These results have important implications for understanding the past and future of the Antarctic ice sheet. Supersaturation is important for understanding conditions for condensation and deposition of ice over the ice sheet. The potential for snow formation is important for understanding the mass balance of the ice sheet, and whether ice

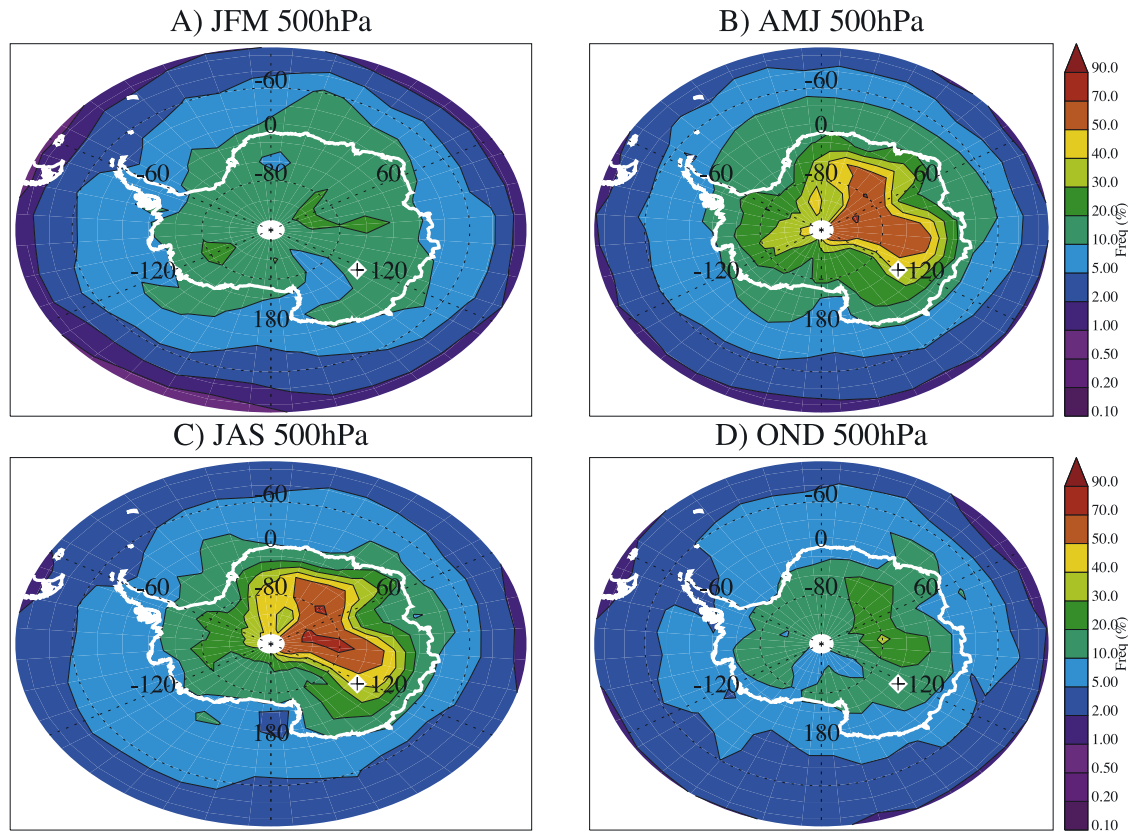


Figure 10. Seasonal cycle of the frequency of supersaturation at the South Pole observed by AIRS at 500 hPa. (a) January to March, (b) April to June, (c) July to September, and (d) October to December. Dome C location (75°S , 123°E) is indicated by white diamond with black cross in it.

is deposited by frontal systems, or in situ accumulation. In addition, supersaturation affects the isotopic fractionation of water upon condensation [Jouzel and Merlivat, 1984], and thus supersaturation may also affect interpretations of ice cores which are based on isotopic ratios to obtain proxy temperature records.

[49] In summary, AIRS data compare well to observations, with a slight ($<1^{\circ}\text{K}$) cold temperature bias and a 20% positive bias relative to radiosonde RH in the upper troposphere due to this temperature bias and due to a positive specific humidity bias. There is little bias in the lower troposphere over Antarctica. Some of the AIRS “bias” is attributable to known problems with daytime radiosonde observations, and some is probably due to problems with the AIRS sensor at low humidities, combined with sharp vertical gradients around the tropopause. AIRS data are able to capture the variability seen in the observations. Considering the difficulty of retrieving in extreme conditions and the large temporal and vertical variability, this agreement is impressive. There is a tendency to overestimate the frequency of supersaturation. A high-resolution climate model also is able to reproduce radiosonde observations throughout the troposphere with differences in the annual cycle. Understanding the annual cycle is critical, and further validation during the Antarctic winter, though difficult, would be valuable. These data provide a valuable starting point for understanding humidity over Antarctica and the mass balance of the Antarctic ice sheet. With the caveats

noted here, AIRS data have the potential to improve our understanding of these processes.

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