The wintertime South Pole tropospheric water vapor column: Comparisons of radiosonde and recent terahertz radiometry, use of the saturated column as a proxy measurement, and inference of decadal trends

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[1] We use a fifty-year record of wintertime radiosonde observations at the South Pole to estimate the precipitable water vapor column (PWV) over the entire period. Humidity data from older radiosondes is of limited reliability; however, we think an estimation of PWV is possible using temperature data because the wintertime lower troposphere is very close to saturated. From temperature data we derived PWV_{SAT} which is the PWV if the troposphere was saturated over the entire column. Comparisons to recent radiosonde humidity data indicate that $PWV \simeq 0.88 PWV_{SAT}$. Since 1998 a CMU/NRAO 860 GHz atmospheric radiometer has been operating at the South Pole producing zenith opacity data, τ_o. It is expected that $\tau_o \propto PWV$, and also $\tau_o \propto PWV_{SAT}$, since the lower atmospheric column is near to saturation. We compare trends in τ_o, PWV_{SAT}, and PWV. PWV and PWV_{SAT} showed little trend in the last fifty years, 1961 to 2010, except perhaps in the last two decades, when PWV_{SAT} was below average, followed by an increasing trend to above average. This increasing trend in the last decade was also observed in τ_o, except for the final two years when it appears that something changed in the instrument response. PWV_{SAT} is a useful metric for estimating PWV in the earlier years of wintertime South Pole radiosonde, and it is generally useful for evaluating the wintertime performance of radiosonde humidity and atmospheric opacity instrumentation.

1. Introduction

[2] The history of water vapor over the South Pole likely has significant influence on our understanding of Antarctic water vapor transport and precipitation [*Robin*, 1977; *Bromwich*, 1988; *Connolley and King*, 1993; *King and Turner*, 1997]. Because of its dry atmosphere, in recent decades the South Pole is of great interest to submillimeter astronomers and experimental cosmologists [*Carlstrom et al.*, 2011; *Stark et al.*, 2001; *Peterson et al.*, 2000; *Dragovan et al.*, 1990]. Trends in global warming may bring higher water vapor and more precipitation to the South Pole, and may affect the future astronomical site quality [*Holdaway*, 2004].

Increasing precipitation at the South Pole, and more generally on the Antarctic continent, influences the balance of global water retained in the polar ice cap [*King and Turner*, 1997]. Some recent research [*Boers and van Meijgaard*, 2009] suggests that trends in increasing water vapor in a cold, dry atmosphere may be very difficult to detect with even the best current radiosonde instrumentation and may take decades to show themselves. The South Pole lower troposphere, although cold, generally has quite high relative humidity. Therefore, detection of an increasing trend in water vapor abundance may be easier.

[3] Only two sites in the Antarctic interior have a long history of weather observations: South Pole and Vostok [*King and Turner*, 1997]. The Vostok upper air data stream apparently ceased in 1992 (see http://www.aari.aq/data/data.asp?lang=0&station=6) making the South Pole the only interior station with a really long upper air record. Year-round radiosonde observations at the Dome C site were performed from 2005 to 2009 [*Tomasi et al.*, 2011].

[4] Radiosonde humidity measurements are difficult to use for climatological studies because of varying instrument types [*Elliott and Gaffen*, 1991]. Humidity measurements taken in very cold and dry circumstances add to the difficulties

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[*Hudson et al.*, 2004]. Here we extend some earlier work [*Chamberlin*, 2001] that attempted to look at the history of the wintertime water vapor column over the South Pole by using the saturated water vapor column, PWV_{SAT}, as a proxy for the water vapor column. This proxy seems reasonable since the wintertime Antarctic plateau lower and middle troposphere is often in saturation, and sometimes even in supersaturation [*Schwerdtfeger*, 1984; *Bromwich*, 1988; *Gettelman et al.*, 2006]. The utility and validity of using PWV_{SAT} as a proxy for PWV was verified by comparison to millimeter-wave and submillimeter-wave ground-based radiometry measurements performed in support of South Pole radio astronomy and radio astronomy site survey [*Chamberlin*, 2001].

[5] An important feature of the South Pole atmosphere (and over East Antarctica in general) is the deep, low-level inversion layer [*King and Turner*, 1997]. At the South Pole, in wintertime, the surface is generally about 20°C cooler than the warmest part of the inversion layer, which is generally isothermal, relatively moist, and around 500 to 1500 m above the surface [*Schwerdtfeger*, 1984].

2. Radiosonde

2.1. Radiosonde in Very Cold Weather

[6] Year-round radiosonde observations at the South Pole have been attempted since before 1961 to the present, spanning more than 50 years. Many instrument types have been used over the years: see Table S1 in the auxiliary material.[1] In general it is difficult to use archived radiosonde records in climate studies of water vapor due to changing instruments types [*Elliott and Gaffen*, 1991]. Measurement of water vapor in very cold temperatures, such as below $-40°C$, by radiosonde has additional problems due to reduced detector responsivity, additional hysteresis, calibration, "thermal shock" (allowing inadequate time for sensor equilibration before launch), etc. [*Hudson et al.*, 2004; *World Meteorological Organization*, 1983].

[7] Concerns about accurate temperature measurement are less serious. The main problem with temperature measurement is the time constant of the detector, which is typically about 5 or 6 seconds. The balloon ascent rate is typically 3 to 6 m/s [*Hudson et al.*, 2004; *Mahesh et al.*, 1997], and this lag in detector response is of interest when the radiosonde is rising through the steep inversion layer above the South Pole surface. More generally, most radiosonde temperature measurements are accurate to $\pm0.2°C$ [*Elliott and Gaffen*, 1991].

[8] The record of long-term radiosonde temperature measurements is generally more credible than humidity; therefore, we suggested assuming the wintertime tropospheric water vapor column was entirely in saturation and used only the temperature profile to produce a proxy metric we called PWV_{SAT} [*Chamberlin*, 2001]. On average, this simplification might be nearly true since during winter much of the lower atmosphere cools to the ice/water-vapor coexistence curve: i.e., it is at saturation or perhaps even sometimes in supersaturation [*King and Turner*, 1997; *Gettelman et al.*, 2006]. For example, *Mahesh et al.* [1997] modeled the South Pole water vapor column by saturating it with respect to ice from the near-surface layer to above the inversion and then at 75 % of saturation to the tropopause. Later, a study of the performance and record [*Chamberlin*, 2001] of the A.I.R. Model 4A radiosonde from 1991 to 1996 indicated we could estimate the actual wintertime water vapor column as $\sim0.9 \times PWV_{SAT}$; for an example, see Figure 4.

[9] The value in using PWV_{SAT} as a proxy for wintertime South Pole water vapor column is that it might help us in interpreting the radiosonde record and in establishing if there are decade-scale trends. Also, we speculate that annual changes in PWV_{SAT} might also be an indicator for annual changes in precipitation because it is an integrated measure of the saturation vapor pressure (SVP), and there is evidently a link between the SVP and Antarctic precipitation rates [*Robin*, 1977].

2.2. Radiosonde Humidity Correction

[10] Methods have been proposed to correct extreme-cold-weather radiosonde humidity measurements, but they all depend on the exact instrument type and extensive field studies. We know of no corrections or detailed studies for instrument types used at the South Pole before 1991.

[11] In an earlier report [*Chamberlin*, 2001] we evaluated the performance of the A.I.R. Model 4A in measuring PWV. The A.I.R. Model 4A was used at the South Pole from 1991 to 1996. On average, and with no corrections, it compared well with 16 nearly concurrent measurements made with a NOAA radiosonde equipped with a frost point hygrometer: see Figure 1 which is reproduced from *Chamberlin* [2001].

[12] The cold weather performance of Vaisala instrument type RS-80 (used 2001 to 2003) was studied by *Hudson et al.* [2004]. That study also included the A.I.R. Models 4A and 5A. The study of the A.I.R Model 4A was based on a single sample instrument remaining from old stock at the South Pole. It did a "reasonable" job reporting the relative humidity, RH_w, down to at least $-40°C$ and with a time constant of about one half to one minute. (The average of two measurements at $-39°C$ showed a wet bias of about $8\%RH_w$.) A single measurement made at $-65°C$ showed a much longer time constant, over an hour, and an extreme dry bias. Time constants of the tested RS-80 varied from 30 seconds to 420 seconds, with a median of 140 seconds. The study of Hudson *et al.* confirmed the extreme dry bias of the A.I.R. Model 5A, which we reported earlier in *Chamberlin* [2001]. A possible limitation in all the studies is that instrument comparisons were made under relatively static conditions, and the greater ventilation that naturally occurs during the balloon ascent was not well simulated [*Hudson et al.*, 2004].

[13] *Miloshevich et al.* [2006] reported that VIZ (now Lockheed Martin Sippican, Inc., Marion, Massachusetts) hygristors (probably used by the A.I.R. Model 4A) perform poorly in low-temperature, low-humidity parts of the atmosphere. In comparison, even the uncorrected RS-90 and RS-92 series radiosondes performed relatively well when $RH_w > 20\%$ and could be accurately corrected for very dry conditions.

[14] Given the evident limitations of the VIZ hygristors, the earlier reported agreement in PWV between the NOAA frost point sonde measurements and the A.I.R. Model 4A was surprisingly good: see Figure 1. This good agreement might be attributable to the fact that the greatest contribution to PWV is from the lower troposphere, where the atmosphere

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2012JD017792.
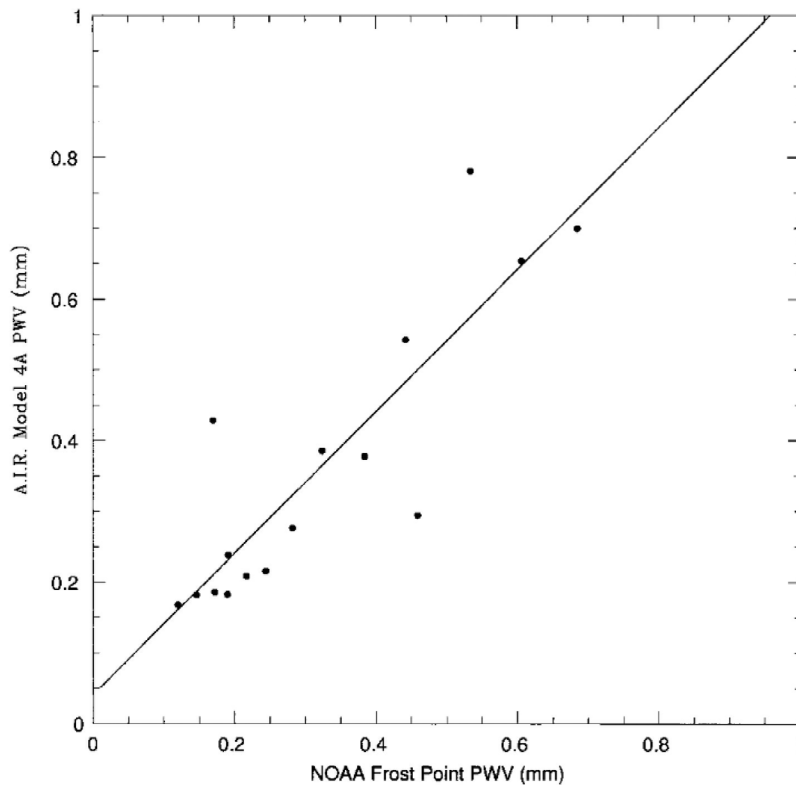
Figure 1. The *PWV* from the A.I.R. Model 4A radiosonde was compared with 16 nearly concurrent NOAA radiosonde flights instrumented with a frost point hygrometer. The line in the plot is a least-squares fit to the data. The slope was 1.00($\pm$0.15) and the intercept was 0.04($\pm$0.06) indicating the A.I.R. Model 4A may have had a slight wet bias in determining *PWV*. This figure is reproduced from *Chamberlin* [2001]. These data were obtained were obtained under South Pole winter and summer conditions in the years 1991 through 1994.

is relatively warm and moist, and that is the regime where VIZ hygristors can perform the best [*Miloshevich et al.*, 2006].

[15] In all the *PWV* results reported here, no corrections were applied to data acquired from the archives. To some extent, humidity errors caused by lag (i.e., slow response) are automatically compensated, since *PWV* is an integrated quantity [*Chamberlin*, 2001]. However, future refinements could include attempting to compensate for lag and other known Vaisala errors, which for the RS-90 and RS-92 generally are not large in moist conditions. Another area for possible correction is in the formula we used to calculate the water SVP: it is Bolton's equation appropriate for the A.I.R. radiosondes, whereas the formula needed for the Vaisala radiosonde is due to Hyland and Wexler [*Miloshevich et al.*, 2006; *Hyland and Wexler*, 1983]. At lower temperatures, such as at $-70°$C, Bolton's equation gives a SVP about 7% lower than the formula of Hyland and Wexler. Using the Hyland and Wexler formula on the data from Vaisala radiosondes would likely increase derived *PWV* by a few percent.

[16] Since only one old-stock A.I.R. Model 4A sample was studied under controlled conditions by *Hudson et al.* [2004], not enough is known about it to attempt much in the way of compensation. The dry bias of the A.I.R. Model 5A was so bad that probably no compensation scheme could help make it more realistic.

[17] In all cases, and for all years, in the derivation of PWV_{SAT} we used the SVP over ice determined from an integrated form of the Clausius-Clapeyron equation [*Rogers*, 1976] as described in *Chamberlin* [2001]. At $-70°$C this SVP was about 2% lower than the SVP determined by the formula of *Hyland and Wexler* [1983] and in *Murphy and Koop* [2005, equation 7].

2.3. Results From Radiosonde

[18] Figure 2 uses all of the radiosonde data available from 1961 to 2010 and gives the average PWV_{SAT} (small dots, and upper curve) versus day number starting from 1 January (here 1 January, 0000 GMT is defined "Day number 1.0", etc.). (All routine radiosonde data from 1978 to present are archived at ftp://amrc.ssec.wisc.edu/pub/southpole/radiosonde. For this study radiosonde records from 1991 to 2000 were obtained directly from the South Pole Meteorology office (met@spole.gov) via ftp on or before 2001. Records prior to 1991 were obtained from the NOAA Climate Monitoring and Diagnostics Laboratory ftp site (ftp.cmdl.noaa.gov/met/raobs/spo) in 1999. This ftp site has since been reorganized, and it is not clear if the old radiosonde records are still online there. Radiosonde records from 1957 to 1960 were never located by us. The current email for South Pole meteorological information is met@usap.gov.) The smoothing curve through the points is a five-day boxcar average. *PWV* is the lower
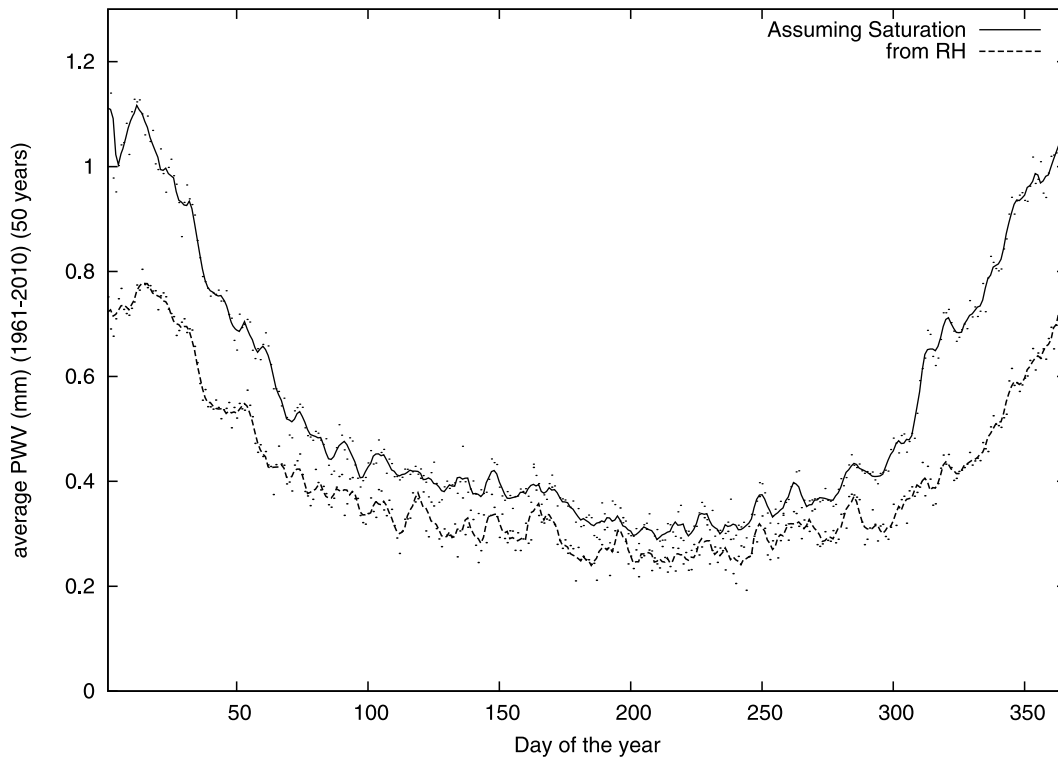
Figure 2. Fifty-year average of the South Pole tropospheric water vapor column versus day number derived from radiosondes by two methods. "Assuming Saturation" (PWV_{SAT}) is the water vapor column assuming the atmosphere is in saturation and it does not rely on humidity transducer measurement. "From RH" (PWV) is the water vapor column based upon radiosonde humidity transducer measurements. See text.

curve and heavier dots. The two curves draw near each other in wintertime, which for the purposes of this study we will define as between days 100 and 300. (Figure 2 updates *Chamberlin* [2001, Figures 1 and 2]. All the data were reduced as described in *Chamberlin* [2001].)

[19] Figure 3 shows the annual cumulative distributions for PWV_{SAT} and PWV for the years 1961 through 2010. For example, consider Figure 3 (top) ("PWV_{SAT} cumdist " versus Year). For the year 2010 these data show that 95% of the observed values of PWV_{SAT} were below 0.81 mm; 75% below 0.53 mm; 50 % (the median) below 0.42 mm; and, 25% below 0.30 mm. Figure 3 (middle) is the cumulative distribution of PWV with the lines and points representing the same percentile levels as Figure 3 (top). Figure 3 (bottom) is the yearly average of the daily ratio PWV/PWV_{SAT}. In the years 1997 to 2001 this ratio was anomalously low; these were the years when the A.I.R. Model 5A radiosonde was used. Over the years 1991 to 1996 the A.I.R Model 4A radiosonde was used, and this ratio was 0.91 ± 0.07. In the years 2005 through 2010 the Vaisala RS-92 was used and the ratio was 0.86 ± 0.08. The combined average of the ratio from the A.I.R Model 4A radiosonde and the Vaisala RS-92 is about 0.88.

[20] In Figure 4 we use 0.88 times the median PWV_{SAT} ($\widetilde{PWV}_{SAT}$) for estimating the median PWV. This estimate, PWV_{EST}, is the red line (solid points) in the plot. The orange line (one-half open points) is the median PWV measured by radiosonde, ($\widetilde{PWV}$). (These median values are the 50th percentile levels from Figure 3.) We show the deviation

between PWV_{EST} and $\widetilde{PWV}$ in Figure 4 (bottom), which is the normalized difference, $\left(\widetilde{PWV} - PWV_{EST}\right)/PWV_{EST}$. The agreement is very good from the years 1991 to 1996 when the A.I.R Model 4A was in use: $4 \pm 2\%$. For 2005 to 2010 when the Vaisala RS-92 was used the agreement was -7 ± 3 %. From 1997 to 2001 when the A.I.R. Model 5A was used the agreement was quite bad, about -55%. Since PWV from years before 1991 were never cross checked in any way against other instruments we might consider them unreliable.

[21] To see if there is an apparent trend, the annual PWV_{EST} was normalized by the fifty-year average, $\langle PWV_{EST}\rangle$: see Figure 5. We notice the trend is below the average years for 1991 to 2001, and mostly above the average for years 2002 to 2010. This trend may be real, or it might be attributable partly to instrument bias: years 1991 to 2001 the A.I.R. Model 4A and 5A were used; and years 2002 to 2010 the Vaisala RS-80, RS-90, and RS-92 were used. That said, the comparison of the these data to submillimeter opacity data presented in Figure 12 suggests that the generally increasing trend from 1998 through 2008 is real.

3. Comparison With Recent Ground-Based Radiometry

[22] Based on simple concepts such as the Beer-Lambert Law, we would expect a linear relationship between the zenith opacity coefficient, τ_o, and the number of absorbers in an optical path length of one airmass. Of course, the
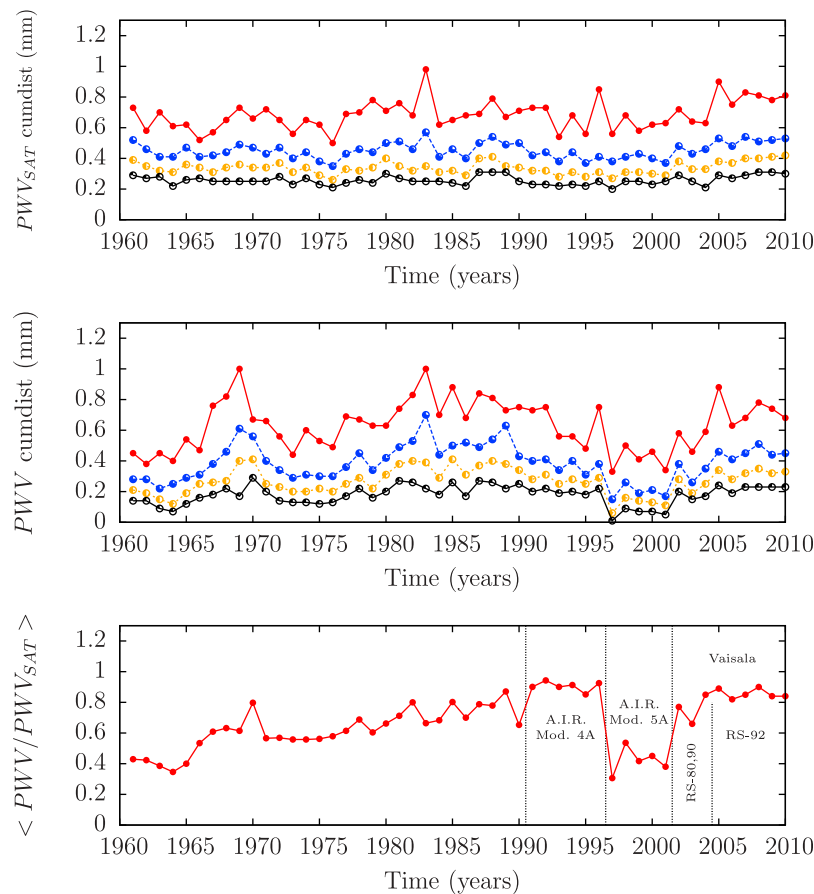
Figure 3. (top) The cumulative distribution of PWV_{SAT} versus year: the connected red, solid circle points represent the 95th percentile; blue, open corner on right points represent the 75th percentile; orange, half-open points represent the 50th percentile; black, closed corner on the left points represent the 25th percentile. (middle) Cumulative distribution of PWV with the same graphical presentation. (bottom) The yearly average of the daily ratio PWV/PWV_{SAT}.

absorbers (and emitters) we are concerned with are water vapor molecules, so we expect $\tau_o \propto PWV$. There is also a residual contribution to τ_o from non-water vapor molecules called "dry-air opacity".

[23] As mentioned in the abstract, a CMU/NRAO 860 GHz atmospheric radiometer was installed at the South Pole in 1998 and operated there continually to the present. The primary purpose of this instrument is to monitor the South Pole terahertz astronomy site quality. Its radiometric passband is centered on 860 GHz (λ = 350 μm) and is 100 GHz wide [*Peterson et al.*, 2003; S. J. E. Radford et al., unpublished manuscript, 2004]. The atmospheric transmission band centered on ∼860 GHz is of astronomical interest and it is bracketed by two very strong water vapor absorption/emission lines at 753 GHz and 989 GHz. Both of these lines are in the para spin state and their opacity has been shown to be approximately linearly dependent on RH_w at room temperature [*Xin et al.*, 2006; *Ge et al.*, 2009]. The water vapor opacity in the 860 GHz band is due mainly to the pressure-broadened wings of these and other nearby water lines. The τ_o data presented here—but not the raw atmospheric temperature versus air mass data from which it was derived—were communicated to us by S. Radford in August 2011.

[24] The operation of this radiometer bridged the transition of four different radiosonde types: the A.I.R. Model 5A; the Vaisala RS-80; the Vaisala RS-90; and, the Vaisala RS-92. Thus, in principle, the study of its results may help us sort out some of the issues with radiosonde consistency. However, as we shall show, there were evidently some problems with the year-to-year consistency of the radiometer, particularly in the years 2009, and 2010. In the Appendix we will discuss some ways the atmospheric brightness versus air-mass data can be modeled to derive τ_o and offer an explanation as to why the radiometer's response to atmospheric water vapor apparently changed in 2009 and 2010.

[25] The reported τ_o are from all-sky conditions. In the wintertime, clouds over the South Pole are thin, cirrus-like, ice clouds [*Ellison et al.*, 2006]. The wintertime cloud fraction is estimated at 35% [*Hines et al.*, 2004]. The ice water path (IWP) through these wintertime clouds is less than 5 g/m^2 55% of the time [*Mahesh et al.*, 2001]. 880 GHz radiometric measurements of cirrus clouds at lower latitudes show that an IWP of 5 g/m^2 increases the sky brightness temperature by about 2°K [*Evans et al.*, 1998] and we estimate it changes τ_o less than 0.015 which is very small compared to typical values reported here. So, for the purposes of this work, this small correction to τ_o is neglected. The very
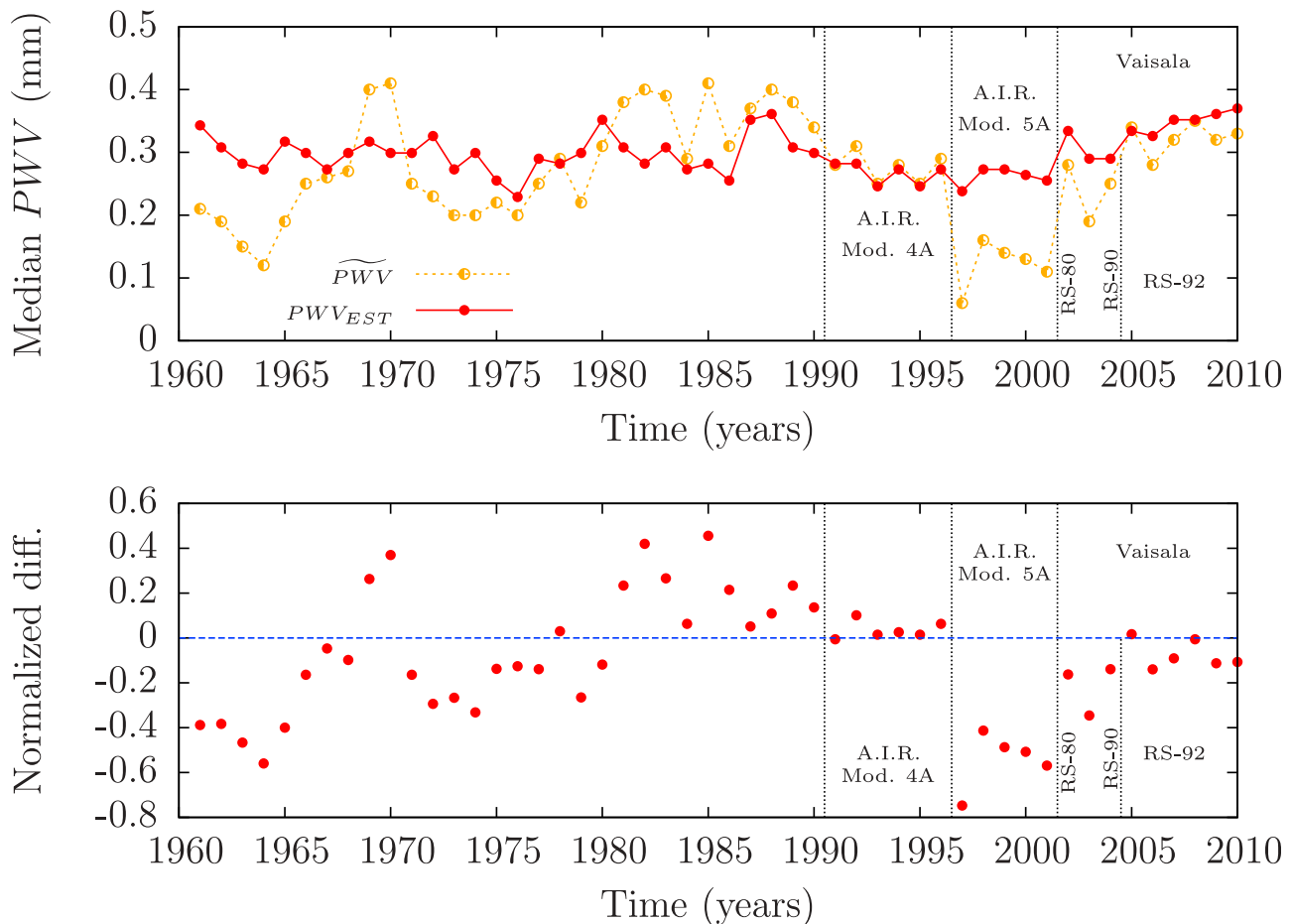
Figure 4. (top) We estimated the median PWV (PWV_{EST}, red line solid points) using $0.88*\widetilde{PWV}_{SAT}$ (see text). The median PWV from the previous plot is overlaid ($\widetilde{PWV}$, orange line, one half open points). (bottom) The quantity $\left(\widetilde{PWV} - PWV_{EST}\right)/PWV_{EST}$ ("normalized diff.") is plotted to give a normalized difference between the two methods of expressing PWV. The agreement is very good from the years 1991 to 1996 when the A.I.R Model 4A was in use: $4 \pm 2\%$. For 2005 to 2010 when the Vaisala RS-92 was used the agreement was $-7 \pm 3\%$.

low submillimeter extinction caused by suspended ice particles in cirrus clouds is predicted by modeling [*Liebe and Manabe*, 1989].

[26] Our simulations using the *am* [*Paine*, 2012] atmospheric model indicate that changes to τ_o caused by changes in stratospheric ozone, or changes in surface pressure are less 0.02 which for the purposes of this study can be considered negligible.

3.1. Zenith Opacity Versus *PWV*

[27] In this section we will compare CMU/NRAO radiometer τ_o to *PWV* from radiosonde. For some examples of earlier comparisons of South Pole submillimeter zenith opacity from other instruments to *PWV*, see *Chamberlin* [2001] and *Chamberlin et al.* [2002].

[28] Figure 6 (top) shows a short time series of the 860 GHz zenith opacity, τ_o, from the 2009 winter. Figure 6 (bottom) shows the *PWV* derived from concurrent RS-92 radiosonde flights.

[29] Figure 7 is the plot of the 860 GHz zenith opacity versus the RS-92 radiosonde derived *PWV*. The dashed line is a least-squares fit [*Bevington*, 1969] to the data, giving a

zero intercept of 0.47 ± 0.01 airmass^{-1}, a slope of 1.92 ± 0.03 airmass^{-1}/mm, and a correlation coefficient of 0.87 with 1031 points in the fit. Only opacity data from within one hour of the radiosonde launch time was accepted. Only winter days 100 to 300 were accepted. The fit obviously is significant, but to the eye there appears to be a slight positive bias in the intercept. The positive bias is likely due to a non-symmetric distribution of points around the best fit line: that is, we see more positive outliers above the line than below it.

[30] Like Figure 7, Figure 8 shows plots of the 860 GHz zenith opacity versus the A.I.R. Model 5A radiosonde derived *PWV*. The plots are broken down by year from 1998 through 2001. In August 2001 the Vaisala RS-80 went into operation. Thus, year 2001 contains data from both types of radiosondes.

[31] Figures 9 and 10 are similar plots of zenith opacity versus *PWV* for years 2002 to 2010 and for Vaisala radiosonde types RS-80, RS-90, and RS-92.

[32] Table S2 summarizes the results of the straight-line fits to the data in Figures 7–10. In all cases the correlation between τ_o and *PWV* is significant but obviously not as strong in the years 1999 and 2001 when the A.I.R. Model 5A was being used, probably because most of the acquired
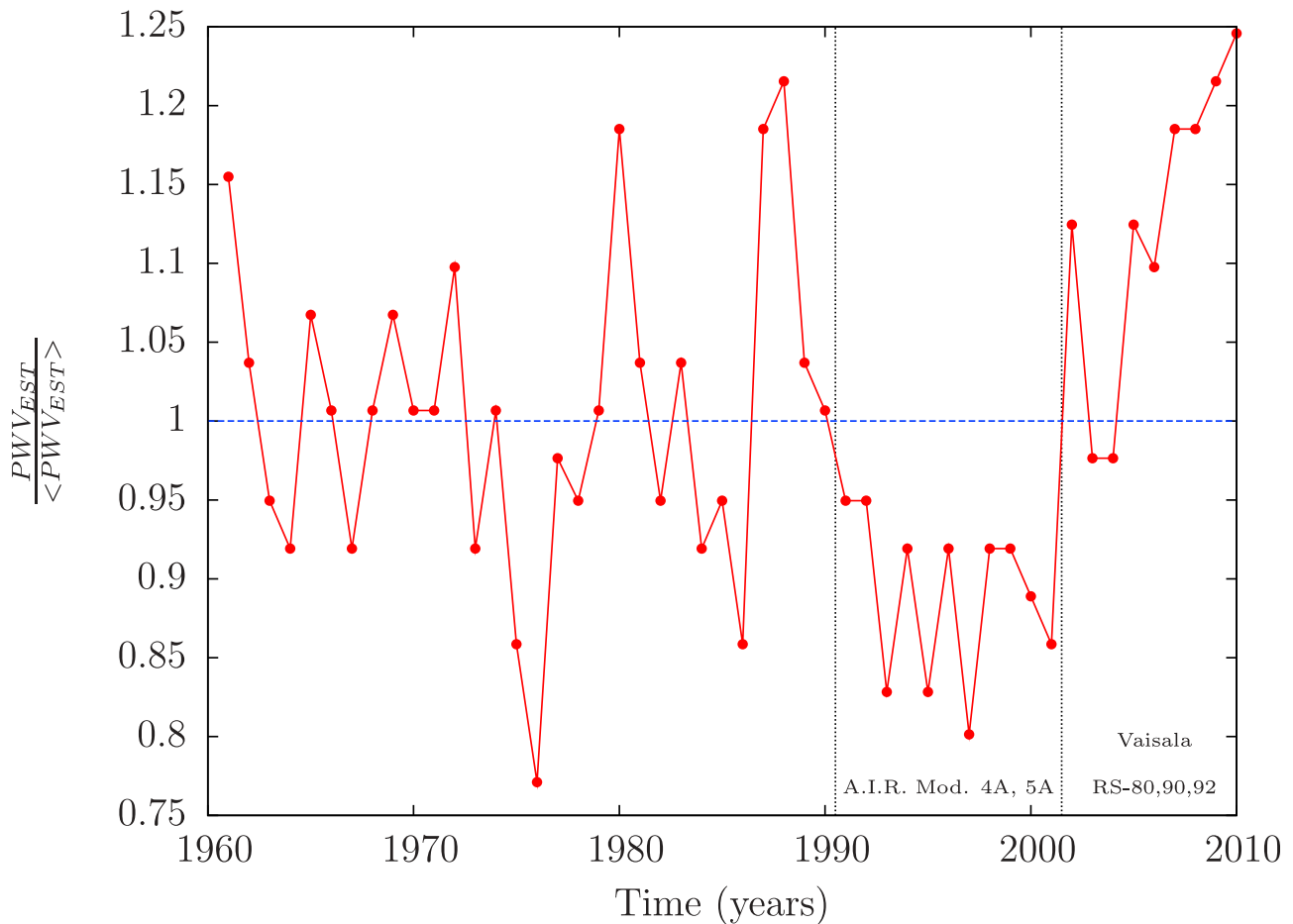
Figure 5. To help see if there is a trend, the annual PWV_{EST} is normalized by the fifty-year average, $\langle PWV_{EST} \rangle$. We notice the trend is below the average years 1991 to 2001 and mostly above the average years 2002 to 2010. This trend may be real, or it might be partly attributable to instrument bias: years 1991 to 2001 the A.I.R. Model 4A and 5A were used, and years 2002 to 2010 the Vaisala RS-80, RS-90, RS-92 were used. That said, the comparison of the this data to submillimeter opacity data presented in Figure 12 suggests that the generally increasing trend from 1998 through 2008 is real.

data points are clustered around the intercept, particularly in 2001. This clustering around the intercept might indicate that the radiosonde was not responsive to water vapor. The "Intercept" from the fits should give the "Dry-air opacity" and the "Slope" the dependence of τ_o on PWV. In principle, these results could be compared to atmospheric models. For example, the *am* model [*Paine*, 2012] predicts an Intercept of about 0.28 and a Slope of about 1.93. However, there is so much year-to-year variation in the Intercept and Slope that it is hard to make any comparisons with models. For example the Intercept in 2010 (0.29 ± 0.01) was only about one third of the value in 2005 (0.90 ± 0.01), even though the same type of radiosonde, RS-92, was used in both years. Averaging all years, 1998 to 2010, gives an Intercept of 0.72 ± 0.22 and a Slope of 2.00 ± 0.55.

[33] Referring again to Figure 10 and the correlation coefficients for those years in Table S2, we see that the straight-line fits for those years were appropriate and that derived intercept coefficients for those two years could not have been spurious. Therefore, it is valid to conclude that

something significant with the instrumentation changed in the years between 2005 and 2010.

3.2. A Comparison of Zenith Opacity and Water Vapor Annual Statistics

[34] Figure 11 compares of the cumulative distributions for τ_o, PWV, and PWV_{SAT} for the thirteen-year period 1998 through 2010. The definitions of the lines' percentile levels were given previously in the discussion about Figure 3. In all three panels the medians of the distributions are given by the orange line with the half open points. The A.I.R. Model 5A radiosonde was used from 1997 to 2001, and the PWV from those years is anomalously low: neither PWV_{SAT}, or τ_o indicate such a big change in water vapor column during the transition years 2001 to 2002. In the years 2009 and 2010 we note that τ_o seems anomalously low compared to the steady trends in PWV_{SAT} and PWV. The radiosonde types used are indicated in Figure 11 (bottom). It is interesting that apparently we can use PWV_{SAT} as a "sanity check" on other putatively more meaningful and sensitive measurements of total water vapor column.
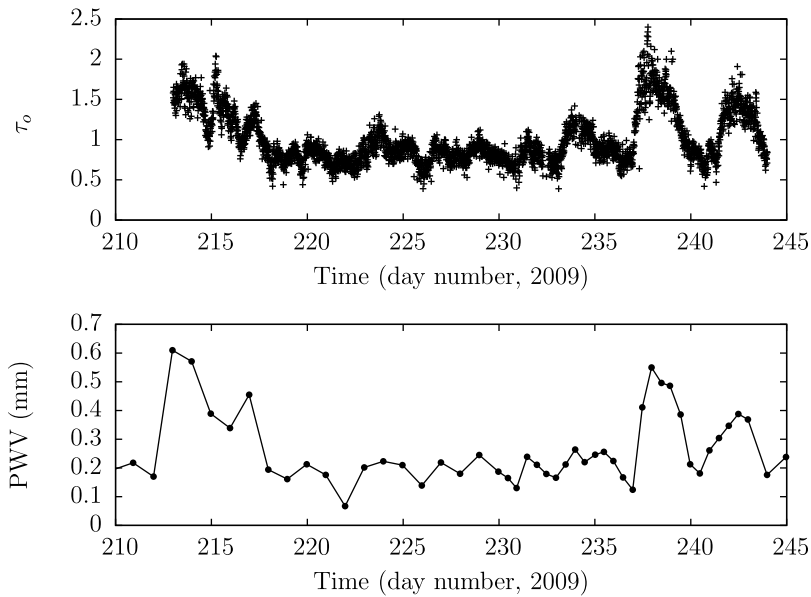
Figure 6. Time series from 2009 of τ_o: (top) the CMU/NRAO 860 GHz zenith opacity and (bottom) the *PWV* from the Vaisala RS-92 type radiosonde.

[35] In Figure 12 we compare the yearly median water vapor column estimated from PWV_{SAT} (i.e, PWV_{EST}) to the median value of τ_o, which we denote $\widetilde{\tau}_o$. To put PWV_{EST} and $\widetilde{\tau}_o$ on a similar scale, we normalized each variable by its average value over the entire history of its measurement period. The average values are denoted by $\langle PWV_{EST} \rangle$ and $\langle \widetilde{\tau}_o \rangle$. $PWV_{EST}/\langle PWV_{EST} \rangle$ and $\widetilde{\tau}_o/\langle \widetilde{\tau}_o \rangle$ seem to follow a similar trend until 2008, and then they diverge rapidly. Because both $\widetilde{\tau}_o$ and PWV_{EST} both roughly follow an increasing trend from 1998 to 2008, it seems likely there was an increasing trend in the water vapor column. The change in PWV_{EST} from 1998 to 2010 was 0.0093
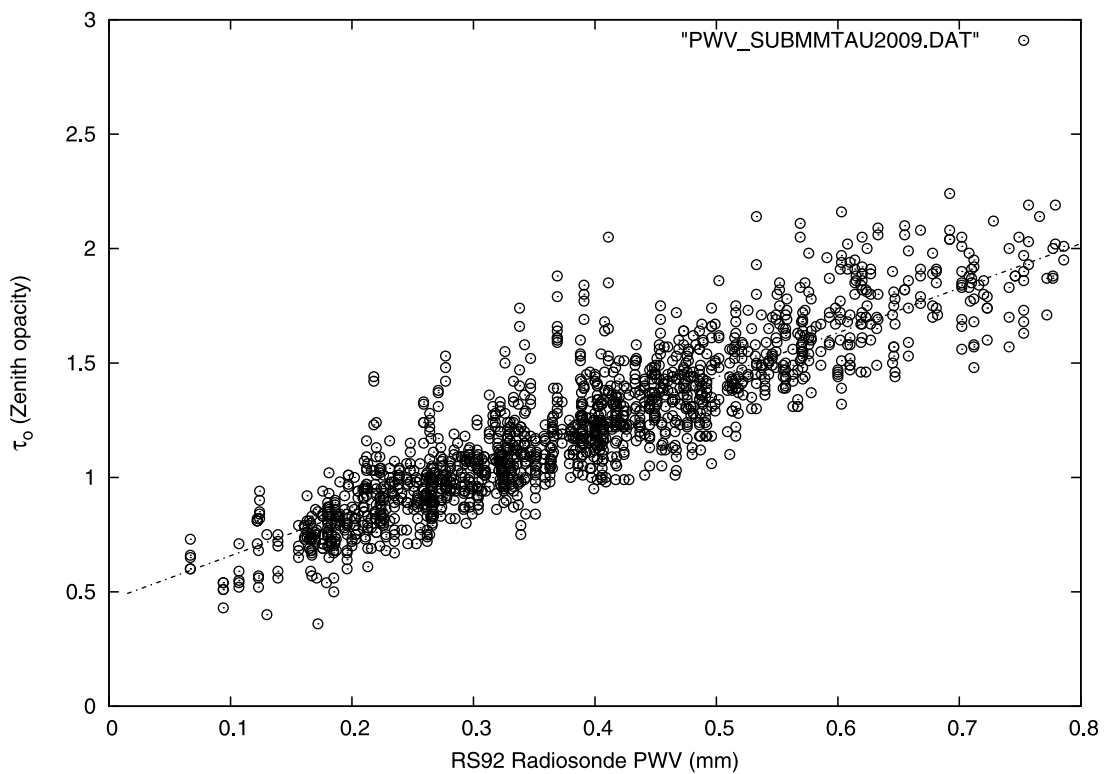

Figure 7. CMU/NRAO zenith opacity compared to *PWV* from the Vaisala RS-92 radiosonde for wintertime days in 2009. (This plot is also reproduced in Figure 10, bottom left.)
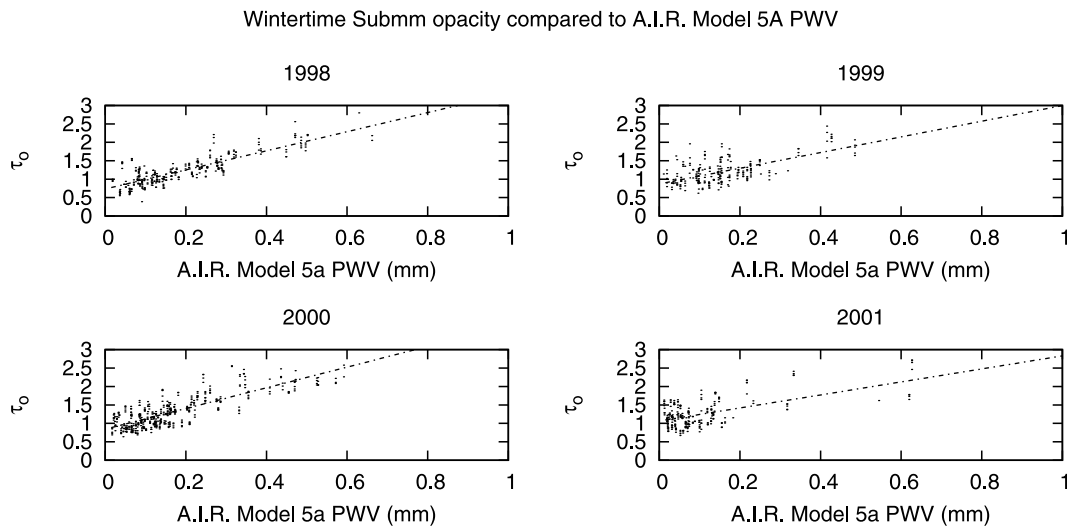
Figure 8. CMU/NRAO zenith opacity compared to *PWV* from the A.I.R. Model 5A radiosonde. Only wintertime days are included in the scatterplots.

(± 0.0014) mm/yr, see "PWV_{EST} trend line" in the plot. The linear correlation coefficient for this trend line is 0.895, and a t-test indicates that the probability of the null hypothesis explaining this data (i.e., no trend) is less than 0.01%.

[36] From 1961 to 1990 (Figure 5) a linear fit indicates the trend in PWV_{EST} was 0.0002($\pm$0.0006) mm/yr. Although a very small increasing trend in PWV_{EST} is indicated, it is not statistically significant, and the null hypothesis could explain it. From 1991 to 2001 PWV_{EST} was about 11($\pm$5)% below the 50-year average.

[37] In other words, the decadal changes in PWV_{EST} indicate there was a long period of basically no change in the lower troposphere, followed by an eleven-year cool period, and then followed by a fairly rapid warming trend that began around 2001. How much did the lower troposphere cool and how much did it warm? If we model the

contribution to *PWV* as entirely from the saturated inversion layer, isothermal at about $-36°$C [*Schwerdtfeger*, 1984], then we can use the change in SVP to estimate the change in temperature. Using the Clausius-Clapeyron equation to relate changes in SVP to changes in temperature we find: (1) from 1961 to 1990 the temperature change was about $\approx 0.17°$C ($\approx 0.0058°$C/yr); (2) from 1991 to 2001 the temperature was $\approx 1°$C below the 50 year average; and, (3) from the cool period to 2010 the temperature increased $\approx 2.2°$C ($\approx 0.22°$C/yr).

[38] If we average over the whole fifty-year period, our simple interpretation indicates a lower tropospheric warming trend of about 0.01°C/yr, but the statistical significance of the trend over the fifty-year period is low. *Turner et al.* [2006] report significant warming in the wintertime Antarctic troposphere at mid-levels: $\approx 0.06°$C/yr over 30 years.
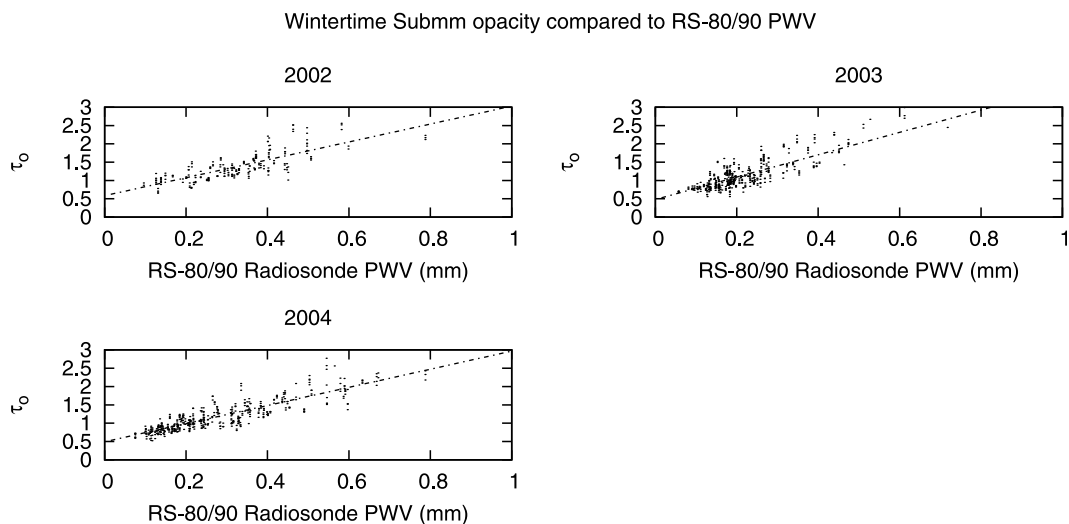

Figure 9. CMU/NRAO zenith opacity compared to *PWV* from the Vaisala RS-80, and RS-90 radiosondes, which were used during the comparison period. Only wintertime days are included in the scatterplots.
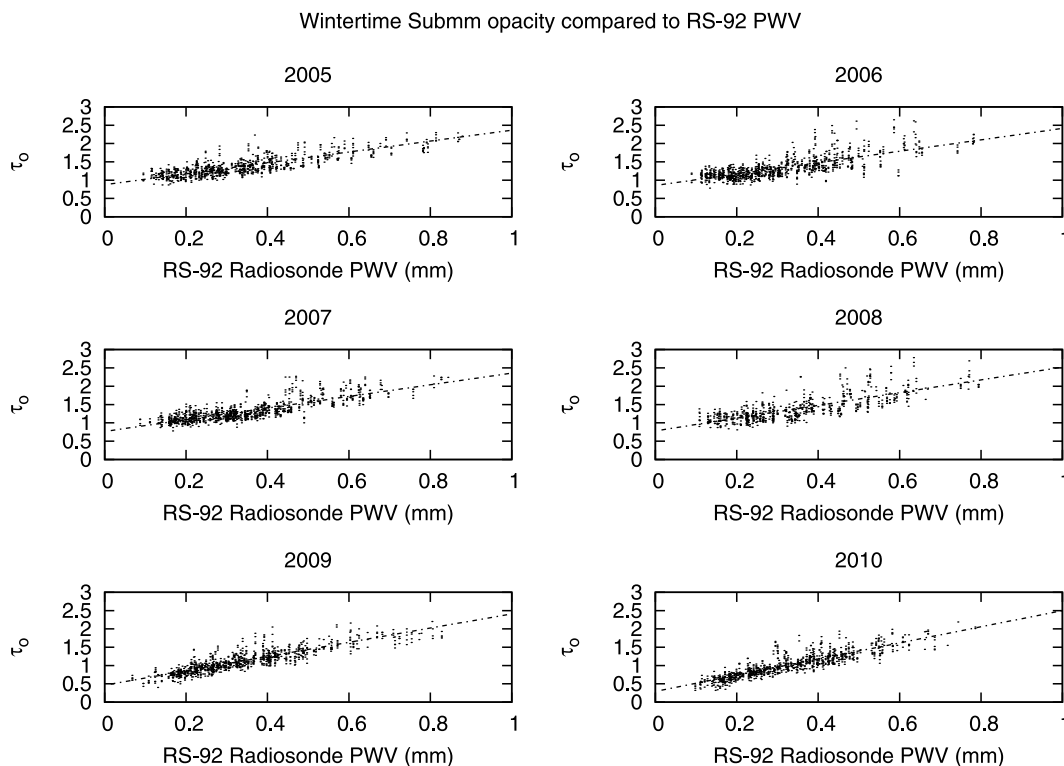
Wintertime Submm opacity compared to RS-92 PWV

Figure 10. CMU/NRAO zenith opacity compared to PWV from the Vaisala RS-92 radiosonde. Only wintertime days are included in the scatterplots. Linear regression was used to fit the data. Note that the zero intercept varies by a factor of up to three when different years are compared. For example in year 2010 the zero intercept is about 3X lower than in years 2005 and 2006.

Decadal trends in Antarctic continental surface temperature are smaller [*King and Turner*, 1997]: $-0.01°C/yr$ for the South Pole 1957 to 1991; $0.025°C/yr$ for Vostok Station 1958 to 1991; and, $0.02°C/yr$ for Byrd Station 1957 to 1969, and 1982 to 1987. Averaging reports from nine stations *Turner et al.* [2006] reported a wintertime warming trend of $0.015°C/yr$ from 1971 to 2003. All nine stations were near coastal areas, except for the South Pole.

[39] After 2008, and particulary in 2010, the generally lower values of τ_o (Figure 10), and the change in τ_o from trending with PWV and PWV_{SAT} (Figure 11) suggest that something significant changed in the CMU/NRAO radiometer performance. This point about the apparent change in the radiometer response is amplified in Figure 13, which compares the distributions of τ_o, PWV_{SAT}, and PWV for the years 2005 and 2010. There are two things to say about the actual water vapor column: (1) based on prior experience [e.g., *Chamberlin*, 2001] we do not expect the basic distribution to change much from year to year and this expectation is confirmed by looking at the distributions of PWV_{SAT} and PWV in Figures 13 (middle) and 13 (bottom), and (2) the PWV_{SAT} and PWV for 2005 and 2010 were obtained with the Vaisala RS-92 type of radiosonde, which has been well tested, found to perform consistently, and gives reliable results especially in conditions of higher RH [*Miloshevich et al.*, 2006]. Therefore, we think it is very reasonable to conclude that something significant changed with the CMU/NRAO radiometer in the years 2009 and

2010. One possible explanation might be that in many of the years prior to 2010 wintertime ice and/or snow built up on, or inside the instrument window; and, in the years 2009, 2010, for some reason this problem was not as acute: see the Appendix for more discussion.

4. Conclusion

[40] We have confirmed that the derived quantity PWV_{SAT} is useful for helping us discriminate when data from radiosonde humidity instrumentation, or radiometer instrumentation are giving inconsistent results. In addition, there is experimental evidence that on average wintertime $PWV \approx 0.88\ PWV_{SAT}$; so we may be able to use PWV_{SAT} to explore wintertime PWV trends from 1961 to the present in a consistent way without being too disturbed by changes in radiosonde models, or errors in humidity sensors. Using PWV_{EST} ($PWV_{EST} \equiv 0.88 \times \widetilde{PWV}_{SAT}$): we infer basically no change in PWV from 1961 to 1990; a slightly drier period in the 1990's; and then a strong increasing trend through 2010. An increasing trend in PWV from 1998 to 2008 appears to be supported by ground-based radiometer measurements at 860 GHz. After 2008, from comparison of the statistics of PWV and PWV_{SAT} to τ_o, we think there is evidence that the response of the CMU/NRAO radiometer to water vapor changed in a large way. The observation of a possible increase in the total moisture column from 1998 to 2010 needs to be cross-checked
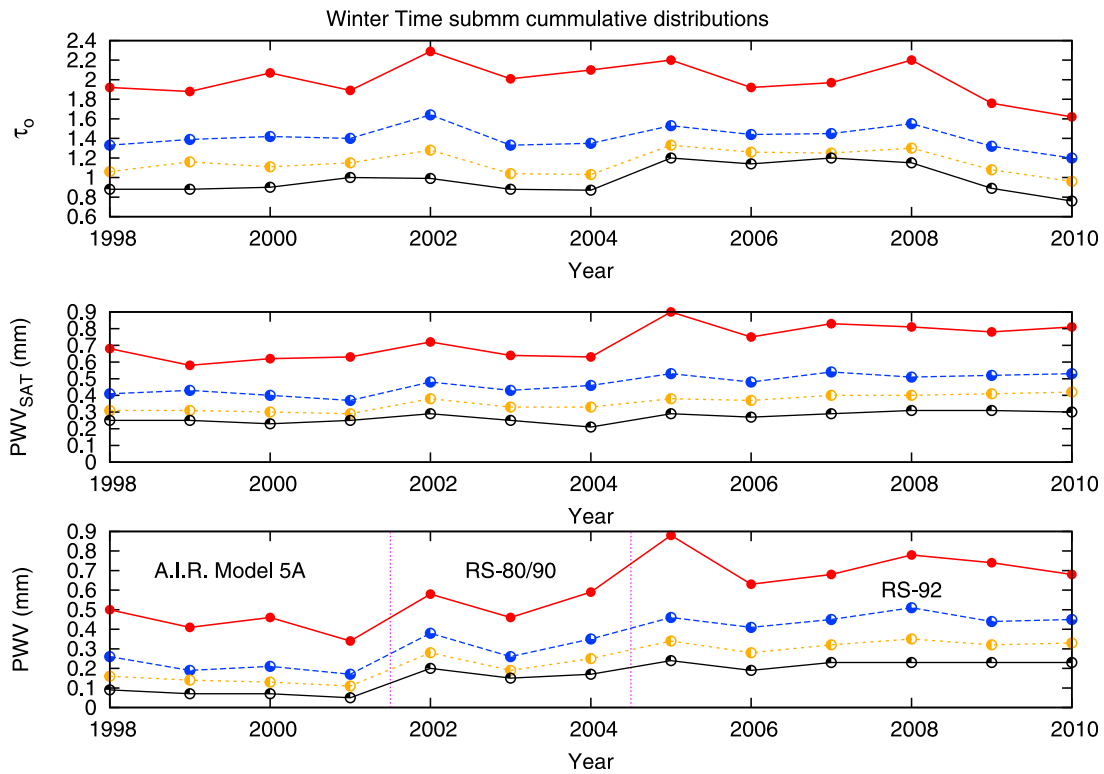
Figure 11. Comparison of cumulative distributions for the (top) 860 GHz zenith opacity (τ_o), (middle) PWV, and (bottom) PWV_{SAT} for the thirteen year period 1998 through 2010. The line and point percentile levels are defined in the caption of Figure 3. The A.I.R. Model 5A radiosonde was used from 1997 to 2001, and the PWV from those years is anomalously low; neither PWV_{SAT}, and, as shown here, τ_o indicate such a low water vapor column. In the years 2009 and 2010 we note that τ_o seems anomalously low when compared to the steady trends in PWV_{SAT} and PWV. The radiosonde types used are indicated in Figure 11 (bottom).
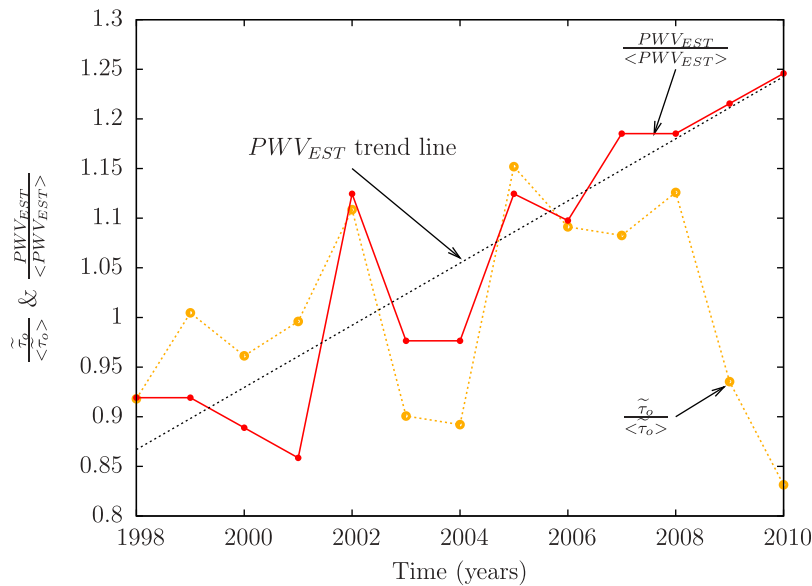

Figure 12. Comparison of $PWV_{EST}/\langle PWV_{EST}\rangle$ from Figure 5 and $\tilde{\tau}_o/\langle\tilde{\tau}_o\rangle$. $\tilde{\tau}_o$ is the median wintertime submillimeter zenith opacity, and $\langle\tilde{\tau}_o\rangle$ is the thirteen-year average from 1998 to 2010. We see that the trends are in rough agreement, until about 2008 when they start differing greatly. Given that the year 2010 gives an unusually low $\tilde{\tau}_o$, this plot suggests that something changed with the CMU/NRAO Radiometer performance in the years after 2008. From 1998–2010 the trend in PWV_{EST} is 0.009 mm/yr, as indicated by the straight line labeled "PWV_{EST} trend line".
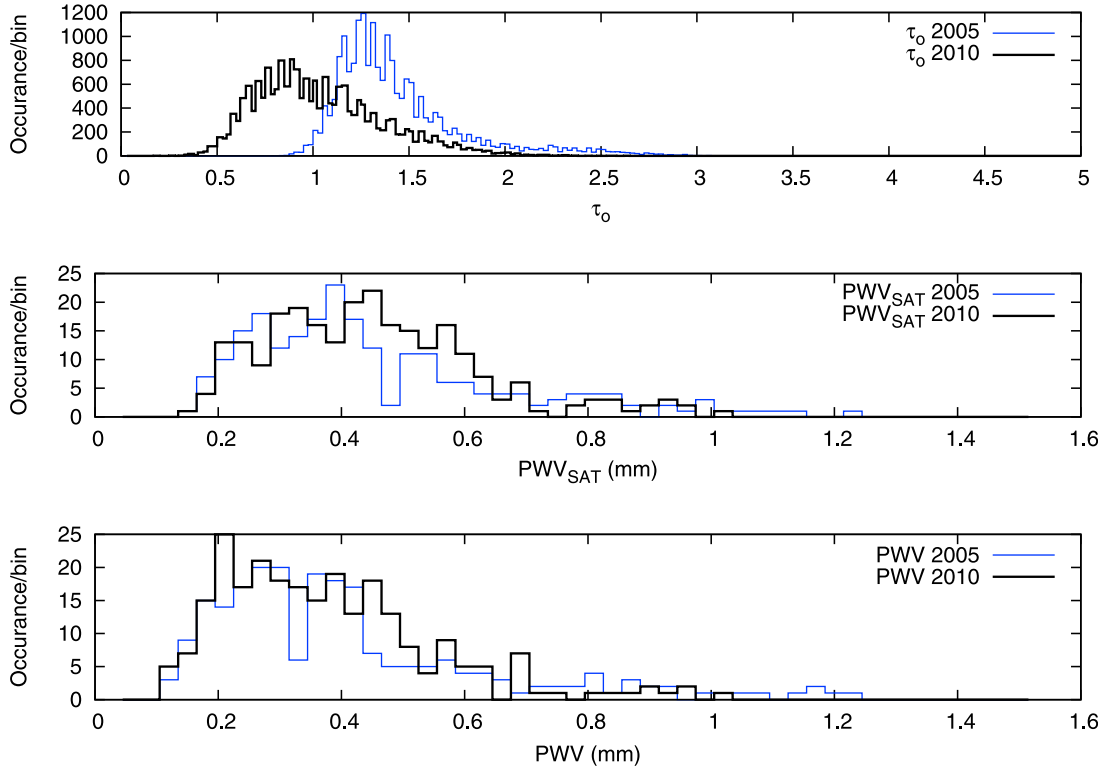
Figure 13. Comparison of 2005 and 2010 wintertime (top) τ_o, (middle) PWV_{SAT}, and (bottom) PWV occurrence distributions. In each plot the vertical axis is the number of occurrences per bin. In Figure 13 (top) the bin width is 0.025 zenith opacity units. In Figures 13 (middle) and 13 (bottom) the bin width is 0.03 mm and each "occurrence" is the average measurement per day if more than one radiosonde was launched. In each plot the light blue line represents data from 2005. The heavy black line represents data from 2010. As can be seen the PWV_{SAT} and PWV distributions from the two years are very similar. In contrast, there is a big shift in the τ_o distribution toward lower values in 2010. The comparison of these distributions reinforce our conclusion that the the CMU/NRAO radiometer response to water vapor was different in 2010.

with available satellite data such as those used in *Yang et al.* [2010] and *Miao et al.* [2001].

Appendix A

A1.   Reduction of Radiometer Data

[41] The method of reduction of data from ground-based millimeter and submillimeter radiometer instruments in Antarctica has been extensively studied at least since 1992. As noted [*Calisse*, 2004], artifacts in the derived data can be caused by not accounting for instrumental effects, such as window opacity (also called "radome" effect). When the dominant loss mechanism is due to window opacity [*Chamberlin*, 2004; *Calisse*, 2004] a good model to fit the radiometer data is

$$T_{sky}(A) = T_{window}(1 - \eta) + \eta T_{atm}\left(1 - e^{-\tau_o A}\right) \quad (A1)$$

where $T_{sky}(A)$ is the radiometer sky temperature as a function of airmass A; T_{window} is the window temperature; T_{atm} is the properly weighted atmospheric temperature (for more details on T_{atm}, see the Appendix in *Chamberlin* [2004]); τ_o is the sky zenith opacity; and η is the window transmission efficiency, with $\eta \equiv e^{-\tau_{window}}$, where T_{window} is the window opacity. Neglecting a small correction caused by the curvature of the earth, $A = 1/\cos(ZA)$, where ZA is the zenith angle of the radiometer measurement. If the window transmission was ideal, then $\eta \equiv 1$, but generally $\eta < 1$. In a laboratory setting, η for the CMU/NRAO radiometer was determined to be about 0.80 [*Peterson et al.*, 2003; Radford et al., unpublished manuscript, 2004].

[42] η is an instrumental constant that could be measured under controlled laboratory conditions as, was done for the results in *Chamberlin et al.* [2002], or it can be inferred from the zero intercept from data fitted to equation (A1), perhaps with the use of the methodology discussed in *Chamberlin* [2004] using only data from the best sky conditions. If derived from fitting, the most likely value of η could then be fixed in value and then all of the data should be fit again with the only remaining free parameters being τ_o and perhaps T_{atm}. One caveat is that if there is snow accumulation on the window, then the effective window opacity will increase. If this effect exists, it might be evident by examination of the raw CMU/NRAO 860 GHz sky dip data if they become available. (A similar instrument was operated in Antarctica at Dome C [*Calisse*, 2004], and it reported "increasingly
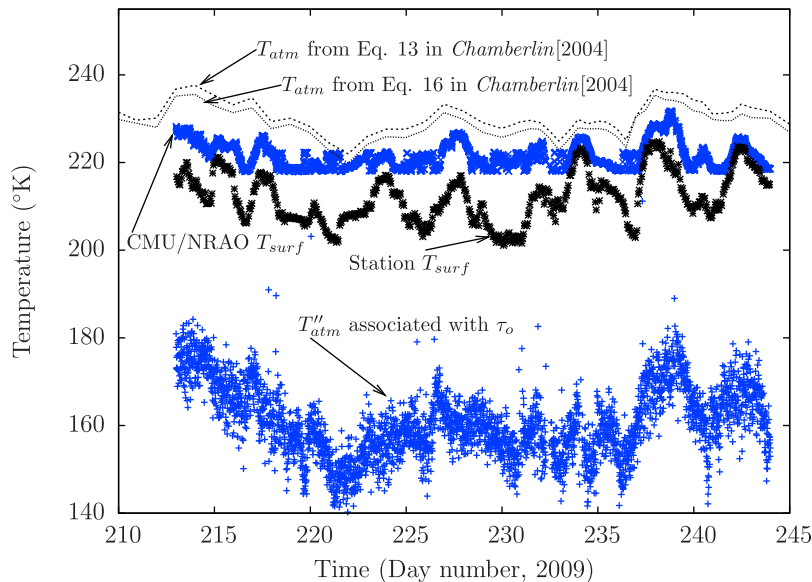
Figure A1. The atmospheric temperature from a few different methods and sources. T''_{atm} is the atmospheric temperature associated with τ_o. It is probably derived from equation (A2) corrected by the method prescribed in *Calisse* [2004]. The surface temperature recorded by the South Pole meteorological office is labeled "Station T_{surf}". The surface temperature recorded by CMU/NRAO radiometer is labeled "CMU/NRAO T_{surf}". The top two plots are T_{atm} derived by use of radiosonde data and integrating the atmospheric column: (1) with use of temperature and water vapor pressure weighting (T_{atm} from *Chamberlin* [2004, equation 16]) and (2), with use of submillimeter opacity radiometric weighting (T_{atm} from *Chamberlin* [2004, equation 13]) appropriate for a relatively high-opacity passband in the atmosphere around 492 GHz. Both of these different methods of deriving T_{atm} give values very close to each other and substantially greater than the surface temperature, which is expected because of the strong inversion layer that forms over the South Pole in the wintertime.

pessimistic" values of τ_o that were later traced to ice build-up inside the instrument window due to improper sealing.)

[43] In contrast to the model and procedures just described, consider the model [*Peterson et al.*, 2003; Radford et al., unpublished manuscript, 2004],

$$T_{sky}(A) = T'_{atm}\big(1 - \exp(-\tau'_o A)\big), \qquad (A2)$$

where τ'_o is the 860 GHz zenith opacity from the CMU/NRAO atmospheric radiometer. This model is deficient in that it does not account for the instrument window opacity [*Calisse*, 2004]. It has been proven analytically [*Calisse*, 2004] that fitting $T_{sky}(A)$ data to equation (A2) always results in $\tau'_o > \tau_o$ when $\eta < 1$. Our understanding is that the τ_o data presented in this paper were reduced according to equation (A2) and that the window opacity was subsequently accounted for by use of the corrective methods suggested in *Calisse* [2004] [*Peterson et al.*, 2003; S. Radford, private communication, 2011].

A2. Atmospheric Temperature

[44] Figure A1 is the atmospheric temperature derived from a few methods. We see that the T''_{atm} associated with τ_o gives a result significantly less than the surface temperature, "Station T_{surf}". This result seems unphysical since due to the deep inversion layer at the surface the wintertime T_{atm} is always greater than the surface temperature.

[45] Illustrating this expectation that $T''_{atm} > T_{surf}$, T_{atm} derived from concurrent radiosonde measurements are also shown [*Chamberlin*, 2004, equations 13 and 16].

[46] It is possible $T''_{atm} \approx \eta T_{atm}$, which would account for some of the discrepancy (S. Radford, private communication, 2011). The ratio T''_{atm}/T_{atm} from 1998 to 2010 is shown in Figure A2. Within the statistical variation shown by the error bars, the ratio does not change over the years: $\overline{T''_{atm}/T_{atm}} = 0.736 \pm 0.007$. This lack of variation may be a consequence of an implicit assumption that η was constant when the
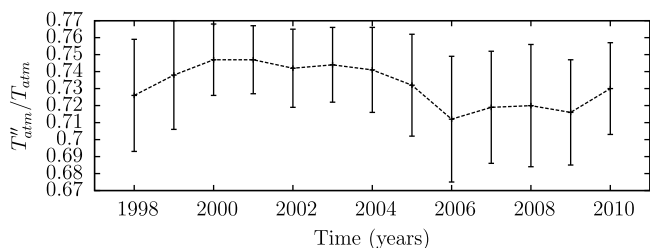

Figure A2. It can be seen that the T''_{atm}/T_{atm} does not change much over the years but that might be a consequence of an assumption that the window opacity was constant when the method of *Calisse* [2004] was employed to correct the result of the initial fit to equation (A2). Averaging all years, $\overline{T''_{atm}/T_{atm}} = 0.736 \pm 0.007$, and the expressed uncertainty is the standard deviation of the mean.
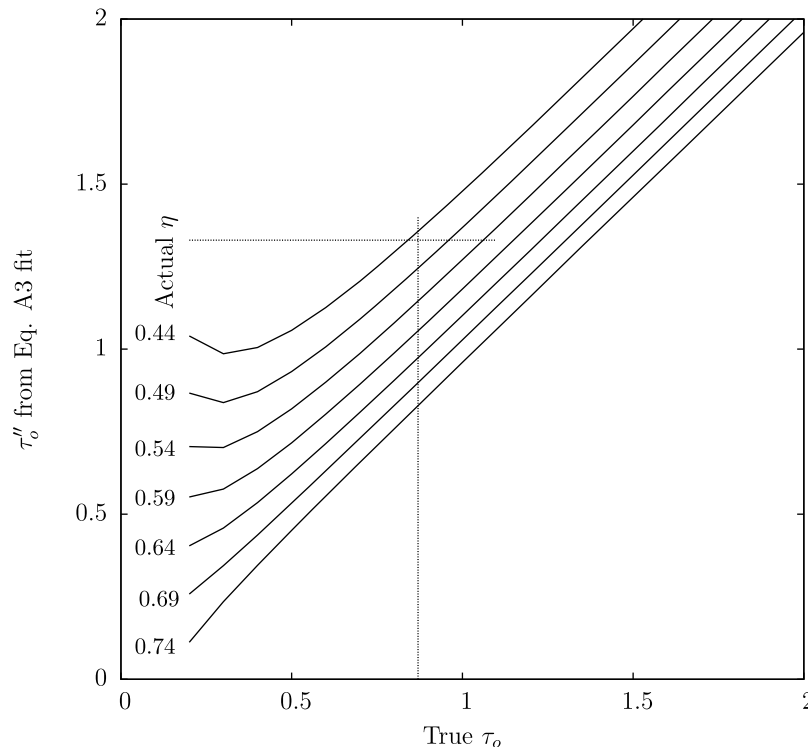
Figure A3. This figure displays the relation between the true τ_o and τ_o'' as a function of the actual window transmission coefficient ("Actual η") based on comparisons between equations (A1) and (A3). The solid lines in the graph are the loci of constant "Actual η".

corrective method of *Calisse* [2004] was applied to the results of fitting $T_{sky}(A)$ data to equation (A2).

[47] From Figure A1 we see a problem with the CMU/NRAO instrument's measurement of the ambient temperature, "CMU/NRAO T_{surf}", saturating at approximately 218°K (-55°C). We know neither the exact placement and use of this temperature transducer, or whether this saturation problem affected the instrument's calibrated measurement of the sky brightness temperature.

A3. Opacity Corrections if the Window Transmission Was Less Than Modeled

[48] Based on the previous section that examined T_{atm}''/T_{atm}, we deduced that the window transmission coefficient, η, was modeled as a constant equal to about 0.74. Therefore, the effective fitting equation was probably like

$$T_{sky}(A) = T_{window}(1 - 0.74) + 0.74T_{atm}\left(1 - e^{-\tau_o''A}\right), \qquad (A3)$$

which is equation (A1) with $\eta \equiv 0.74$. If, in fact the window transmission was less than 0.74, for example due to snow and ice accumulation on or inside the window, then the τ_o'' resulting from the fit to equation (A3) would be higher than the true τ_o. Figure A3 displays the relation between the true τ_o and τ_o'' as a function of the actual window transmission coefficient. Each of the curves in the plot is labeled on the left end with the actual η. For example, if the actual η was 0.54, and the true τ_o was 0.5, then a fit to equation (A3) would give $\tau_o'' = 0.82$.

[49] Figure A3 was generated by first using equation (A1) to simulate true $T(A)$ data, and then least-squares fitting the simulated data to equation (A3). For the simulated data we fixed $T_{window} = T_{atm} = 236$°K, which is the approximate physical temperature of the inversion layer that contains the bulk of the water vapor. (This method is similar to the one described in *Calisse* [2004].)

[50] We might use Figure A3 to get a rough idea of what the actual window transmission was as follows. If in 2010 the radiometer window was ice free, then from the data in Figures 11 and 13 the true median τ_o ($\widetilde{\tau}_o$) was 0.96. Following the trend of PWV_{EST} in Figure 12, the true $\widetilde{\tau}_o$ in 2005 was about 0.87 (vertical line in Figure A3). The 2005 data gave $\widetilde{\tau}_o = 1.33$ (horizontal line in Figure A3). The intersection of those lines indicate that in 2005 the actual window transmission efficiency, η, was about 0.45.

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