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Comparison of atmospheric water vapor over Antarctica derived from CHAMP/GPS and AMSU-B data

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Abstract

The lack of traditional meteorological observations over Antarctica is a major challenge for the operational weather prediction as well as for the application of satellite data. It was shown that the US Global Positioning System can be used to observe the vertically integrated water vapor (IWV) with a high precision using ground-based GPS receivers, e.g. with standard deviations of about 1 kg/m^2 for differences between GPS and radiosondes. Limb sounding observations of the Earth's atmosphere by a GPS receiver on board the Low Earth Orbiter (LEO) CHAMP allow to obtain sufficiently accurate measurements of temperature or water vapor. They are now available for the validation of other spaceborne data. Here we present a comparison between CHAMP/GPS IWV and the IWV obtained from the NOAA-AMSU-B radiometers on board the Polar Operational Environmental Satellite (POES) NOAA-15 over Antarctica. CHAMP allows an adequate homogenity over the entire continent. Since the 14th of May 2001 the CHAMP radio occultation profiles are available. A comparison between the IWV derived from radiances of AMSU-B and from radio occultations of CHAMP over Antarctica shows a low mean difference (-0.08 kg/m^2) and also a low standard deviation (0.79 kg/m^2). Because both datasets are independent this shows that both datasets are valuable sources for the IWV over Antarctica and should be assimilated into numerical weather prediction (NWP) models within the near future.

1. Introduction

The lack of traditional meteorological observations over Antarctica is a major challenge for the operational weather prediction as well as for the application of satellite data. Water vapor is a key element in the climate of the Earth and in the hydrological cycle. Via its phase changes it drives atmospheric circulations. It is the most variable of the major components of the atmosphere.

With different networks of ground-based receivers it was shown that the US Global Positioning System (GPS) is an accurate technique to determine the integrated water vapor (IWV) within the atmosphere (Emardson et al., 2000; Ohtani and Naito, 2000; Cucurull et al., 2000; Johnsen and Rockel, 2001). A water vapor radiometer (WVR) operated by the Deutscher Wetterdienst (DWD) in Potsdam and radiosonde measurements in Lindenberg (Germany) were used for comparisons. The standard deviation was about 1 kg/m^2 for differences between radiosondes and GPS, and 0.75 kg/m^2 between WVR and GPS (Dick et al., 2001). Comparisons with the hydrostatic High resolution Regional weather forecast Model HRM of the DWD have e.g. shown standard deviations of IWV differences of HRM and GPS of about 2.5 kg/m^2 over Germany (Johnsen and Rockel, 2001). Similar results were found for mean IWV differences between the HRM model and data of the Advanced Microwave Sounding Unit A (AMSU-A; Johnsen and Kidder, 2002). For GPS IWV measurements between 0 and 6 kg/m^2 the standard deviation between GPS IWV and HRM IWV is about 1.30 kg/m^2.

The radio occultation technique has been applied for three decades to study planetary atmospheres of Mars (Fjeldbo and Eshleman, 1968), Venus (Fjeldbo and Kliore, 1971), Jupiter (Kliore et al., 1975; Hinson et al., 1997), Saturn (Lindal et al., 1985), Uranus (Lindal et al., 1987), and Neptune (Lindal, 1992).

Since the launch of the LEO Microlab-1 with the GPS/MET receiver on board in April 1995 some satellites are carrying GPS receivers: The US-German

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satellite CHAMP has obtained radio occultation profiles for around one year and about 215 profiles per day in 2002 (168 on average in 2001). Since the 10th of July 2001 SAC-C radio occultation data are also available. Different missions with one or more GPS receivers are launched or planned, e.g. the US-German GRACE mission (e.g. http://op.gfz-potsdam.de/grace/index_GRACE.html), the US-Taiwanese COSMIC mission (e.g. http://www.cosmic.ucar.edu) or the Atmosphere Climate Experiment (ACE) proposed to ESA.

Limb sounding observations of the Earth's atmosphere by a GPS receiver on board a Low Earth Orbiter (LEO) allow to obtain sufficiently accurate vertical profiles of temperature or water vapor. They are now available for the validation of other spaceborne data over the entire Antarctic continent with adequate homogenity.

Here we present a comparison between the IWV over Antarctica derived from CHAMP/GPS data and from data of the Advanced Microwave Sounding Unit AMSU-B on board the NOAA-15 satellite. Section 2 describes the CHAMP/GPS radio occultation data, Section 3 the AMSU-B data and Section 4 the comparison of both datasets over Antarctica.

2. CHAMP data

The GPS constellation currently consists of 29 satellites at around 26,500 km radius, orbiting in six different planes. Each GPS satellite transmits signals at two different frequencies in the L-band called L1 (at 1575.42 MHz) and L2 (at 1227.60 MHz).

The radio occultation technique relies on very precise measurements of the phase delays collected at these two frequencies with a GPS receiver in low-Earth orbit tracking a GPS satellite setting or rising behind the Earth's atmosphere. The atmosphere introduces an extra phase delay which can be converted to atmospheric bending and can be interpreted in terms of refraction at different heights. Under the assumption of local spherical symmetry of the atmosphere the refractivity profile can be obtained from the bending angle profile using an Abelian inversion.

To derive the water vapor from the CHAMP refractivity profiles an algorithm similar to that of Gorbunov and Sokolovskiy (1993) was applied: This iterative algorithm starts with the assumption of a dry atmosphere and calculates the density using the ionosphere free refractivities N together with an interpolated temperature profile T taken from ECMWF. The refractivities were derived by the University Corporation for Atmospheric Research (Hajj et al., 2002) using the Abelian inversion. The hydrostatic equation is applied to obtain the pressure profile $P(z)$ using the acceleration due to gravity g which is calculated according to

$$\begin{aligned} g(z,\phi) = {} & (1 - 0.0026373\cos\phi - 5.9\times10^{-6}\cos^2\phi) \\ & \times (1 - 3.14\times10^{-4}z)\times g_0 \end{aligned} \tag{1}$$

for the height z and the latitude ϕ of the occultation with $g_0 = 9.806\ \mathrm{kg/m^2}$. The refractivity N is related to atmospheric parameters via

$$\begin{aligned} N(z) = {} & \kappa_1\frac{P(z)}{T(z)} + \kappa_2\frac{P_w(z)}{T^2(z)} - \gamma\frac{n_e(z)}{f^2} + O\left(\frac{1}{f^3}\right) \\ & + a_w W_w(z) + a_i W_i(z). \end{aligned} \tag{2}$$

P is the pressure, T the temperature, P_w is the water vapor pressure, n_e the electron density ($\mathrm{m^{-3}}$), f (Hz) the operating frequency, W_w and W_i the liquid water and ice content, respectively. The last two terms are small compared to the others and will be neglected here. A ionospheric correction is applied according to Vorob'ev and Krasil'nikova (1994) which uses a linear combination for both separately derived refraction angles at the same impact parameter. We restrict our considerations to the troposphere, thus the third and fourth term are also neglected. Here the constant κ_1 is equal to 77.6 K/hPa, κ_2 is $3.73\times10^5\ \mathrm{K^2/hPa}$, a_w is $1.4\times10^3\ \mathrm{m^3/kg}$, a_i is 0.6×10^3 m/kg and γ is $40.3\times10^6\ \mathrm{m^3/Hz^2}$. From equation (2) the water vapor pressure profile $P_w(z)$ will be calculated and from

$$q(z) = \frac{0.622\times P_w(z)}{P(z) - 0.378\times P_w(z)} \tag{3}$$

the specific humidity profile $q(z)$. Starting with $q(z) = 0$ and $P_w(z) = 0$ these equations were iterated to obtain profiles of $P(z)$, $P_w(z)$ and $q(z)$. Less than four iterations are necessary. Finally a cubic spline of $q(z)$ is integrated from the surface up to the uppermost layer to obtain the IWV.

3. AMSU-B data

The Advanced Microwave Sounding Unit-B on board the NOAA Polar Operational Environmental Satellite NOAA-15 is a cross-track, line scanning instrument designed to measure scene radiances in the 5 channels at 89.0 ± 0.9, 150.0 ± 0.9, 183.31 ± 1.0, 183.31 ± 3.0 and 183.31 ± 7.0 GHz. Ninety contiguous scene resolution cells are sampled in a continuous fashion, each scan covering 50 degrees on each side of the subsatellite path. These scan patterns and geometric resolution translate to a 16.3 km diameter cell at nadir at a nominal altitude of 850 km.

To derive the IWV from AMSU-B data an algorithm of Miao et al. (2001) is used. The algorithm was originally developed for the water vapor sounder DMSP-SSM/T2 but due to the same frequencies available from AMSU-B it can also be applied to AMSU-B data. It uses the four highest frequencies at 150.0 and around

183.31 GHz (channels 17–20). A general form of the radiative transfer equation of Guissard and Sobieski (1994) is applied taking into account the effects of diffuse scattering from the ground surface and of the vertical nonuniformity of the atmosphere. In brief the algorithm calculates the water vapor, defining a new quantity

$$\eta_c = \frac{\Delta T_{ij} - b_{ij}}{\Delta T_{jk} - b_{jk}}, \tag{4}$$

using the following equation,

$$W \sec\theta = C_0 + C_1 \ln \eta_c \tag{5}$$

with $i, j, k \in 20, 19, 18$ for $0.0 \leqslant W \sec\theta \leqslant 1.5$ kg/m² and $i, j, k \in 20, 19, 17$ for $1.5 < W \sec\theta \leqslant 6.0$ kg/m². Here ΔT_{ij} is the brightness temperature difference between channels i and j of AMSU-B, W the IWV, θ is the angle of observation and C_0, C_1, b_{ij} and b_{jk} are constants. For further details see Miao (1998) or Miao et al. (2001).

4. Discussion

Altogether 1932 profiles of CHAMP/GPS were obtained between the 14th of May 2001 and the 31th of May 2002 over Antarctica and IWVs were calculated. Fig. 1 shows running 60-day mean values of these IWVs. It can be seen that the water vapor has a clear annual oscillation and is significantly larger in the austral summer compared to the austral winter. This is certainly related to the high air temperatures in summer. The annual mean value of the CHAMP/GPS IWVs over Antarctica (between day 134 of 2001 and day 134 of year 2002) is about 1.56 ± 1.57 kg/m². With an area of the Antarctic continent of about 11.9×10^6 km² the annual mean of the total amount of atmospheric water vapor over the entire continent is estimated to be about 1.9×10^{13} kg. Jacobs et al. (1992) obtained for the total accumulation through snow falling over the Antarctic ice sheet about 2.0×10^{15} kg/year. This shows, that the mean residence time of water vapor over Antarctica is only 3–4 days, which is significantly shorter than the global mean of 9–10 days (Howarth, 1983). Similar results were obtained by Miao et al. (2001) from data of the spaceborne microwave water vapor sounder SSM/T2 on board DMSP spacecraft F12 and F14 for the year of 1997.

Fig. 2 shows the mean tangent point positions of the radio occultation profiles taken over Antarctica between the 14th of May 2001 and the 27th of March 2002 which match AMSU-B data of NOAA-15. The mean horizontal distance between the measurement locations of both datasets is limited to 8 km. The time differences between the CHAMP/GPS radio occultation measurements and the NOAA-15 overpass are less than 30 min.

In Fig. 3 a comparison between the IWV derived from these CHAMP/GPS profiles and from AMSU-B is shown. The mean difference AMSU-B/IWV-CHAMP/GPS IWV between both datasets is with −0.08 kg/m² quite low and the standard deviation is about 0.79 kg/m².

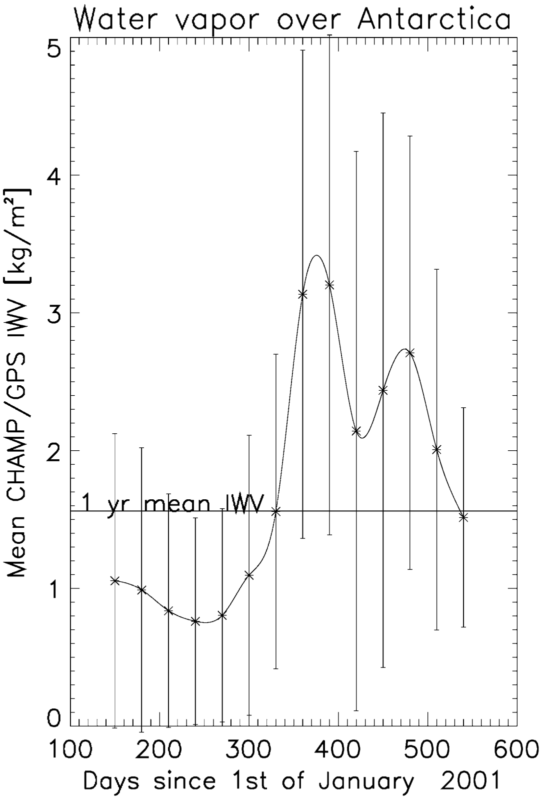

Fig. 1. Running 60-day mean values of the IWV over Antarctica derived from CHAMP/GPS water vapor data. The mean IWV over one year (between day 134 and day 499) is 1.56 ± 1.57 kg/m².

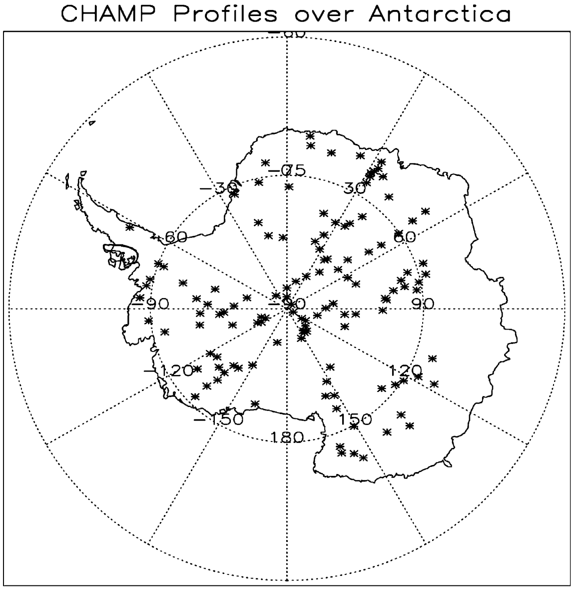

Fig. 2. CHAMP water vapor profiles over Antarctica between the 14th of May 2001 and the 27th of March 2002 matching the AMSU-B data.

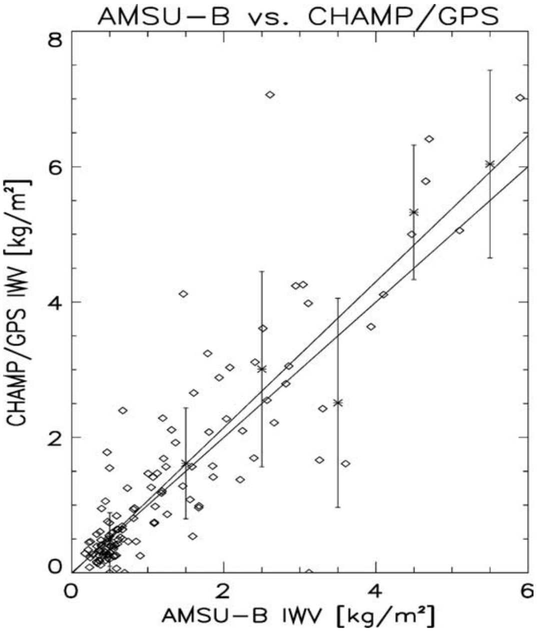

Fig. 3. Comparison between the IWV over Antarctica derived from AMSU-B using the algorithm of Miao et al. (2001) and from CHAMP/GPS at the positions shown in Fig. 1: The error bars show the IWV mean and standard deviation of all CHAMP/GPS radio occultations for all matches shown in a range ±0.5 kg/m^2 along the AMSU-B-IWV-axis. The 1:1 line as well as a linear fit are given.

A linear regression between the CHAMP/GPS IWV data (G) and the AMSU-B IWV data (A) gives

$$G = -0.01 + 1.08 \times A \qquad (6)$$

Due to the independence of both datasets this result shows that both algorithms allow to obtain the IWV with a low mean error over Antarctica. Therefore they should be assimilated into NWP models and the impact to NWP models should be quantified within the near future. A bias of CHAMP/GPS due to the multipath problem or due to noise contributions influencing the GPS phase tracking process (Gorbunov and Gurvich, 1998) seems to be small in case of low specific humidities like them obtained in Antarctica.

5. Conclusions

Since the 14th of May 2001 limb sounding observations from CHAMP observing the satellites of the US Global Positioning System (GPS) are available. Due to the sufficient accuracy of the specific humidities and of the IWVs derived from the phase delay measurements as well as the homogeneous coverage of Antarctica with radio occultations CHAMP/GPS is a valuable source for validating other spaceborne data over Antarctica.

In this study a comparison between the IWVs derived from CHAMP/GPS and from NOAA-15/AMSU-B is presented. Specific humidities and the IWVs were determined from CHAMP/GPS using an iterative algorithm of Gorbunov and Sokolovskiy (1993). To derive the IWV from the four channels 17–20 of AMSU-B an algorithm of Miao (1998) derived for the same frequencies of SSM/T2 is applied. The mean difference between both datasets is with -0.08 kg/m^2 quite low and the standard deviation about 0.79 kg/m^2. The annual mean IWV derived from the first year of CHAMP/GPS data over Antarctica is about 1.56 ± 1.57 kg/m^2. A similar result was obtained from Miao et al. (2001) from SSM/T2 data for the year 1997.

Because both datasets are shown to be independent and the mean difference is quite small, both datasets are valuable sources for the IWV over Antarctica and should therefore be assimilated into NWP models for Antarctica within the near future and the impact to NWP models should be quantified.

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