An Assessment of the Quality of GPS/MET Radio Limb Soundings During February 1997

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Abstract. Spaceborne GPS radio occultation sounding of the Earth's atmosphere is regarded as a highly accurate measurement technique for the remote sounding of stratospheric temperature and tropospheric humidity profiles.

In this study, we describe the validation of GPS/MET data during the a/s off period in February 1997. The meridional structure of deviations between GPS/MET temperatures and several meteorological analyses of the stratosphere show a complex structure, reflecting some shortcomings of the analyses. However, radio occultation measurements exhibit a significant warm bias at low temperatures relevant for Polar Stratospheric Cloud formation at and above the 30 hPa level.

Global humidity fields at the 500-1000 hPa level obtained from GPS/MET soundings during the same period are also compared with analysis data. While GPS/MET soundings highlight known deficiencies in the analyses' tropical moisture budget, large relative errors of more than 50% in specific humidity are caused by uncertainties in ancillary temperatures used in the retrieval of humidity in mid and high latitudes.

1 Introduction

Remote sensing of the Earth's temperature and humidity using radio signals from the satellite network of the Global Positioning System (GPS) received by a GPS receiver onboard a satellite in low earth orbit is a new and promising application of GPS. While radio occultations have been used for the remote sensing of planetary atmospheres (e.g., Fjeldbo and Eshleman, 1968), the US experiment GPS/MET, operating between March 1995 and May 1997, was the first experiment conducting radio limb soundings in the Earth's atmosphere (e.g., Melbourne et al., 1994; Kurzinski et al., 1996; Ware et al., 1996). GPS/MET has been highly successful and delivered several thousand stratospheric and upper tropospheric temperature and tropospheric humidity profiles (Rocken et al., 1997; Steiner et al., this issue).

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In theory, radio occultation measurements allow for accuracies of better than 1 K from the upper troposphere up to 40 km altitude (Melbourne et al., 1994; Kurzinski et al., 1997). Several studies have confirmed this view, e.g., Kurzinski et al. (1996); Ware et al. (1996) and Steiner et al. (1999).

The most comprehensive validation effort so far has been undertaken by Rocken et al. (1997), who validated several hundred temperature profiles and also looked into a small number of water vapor profiles.

Results from these studies indicate that radio occultation measurements of temperatures do indeed have mean errors of less than 0.5 K and root mean square (RMS) errors of less than 1.5 K between 8 and 25 km altitude. An important argument made in these studies is that the meteorological analyses' quality is diminished over data sparse regions like the southern hemisphere. A poorer agreement between GPS/MET and analyses found on the southern hemisphere than on the northern hemisphere has therefore been attributed to weaknesses in the meteorological analyses.

All of these studies, however, are based on GPS/MET data from spring, summer or autumn 1995. During this time of the year, the dynamical activity in the northern hemisphere stratosphere is low; day-to-day and interannual variability of temperatures does not exceed a few K. During northern hemispheric winter, stratospheric dynamics can be grossly disturbed, and sudden warmings may yield local temperature changes of several 10 K within few days. In periods with low dynamic activity extremely low temperatures often occur. Thus, the range of temperatures occurring in the wintertime stratosphere is significantly larger than on the summer hemisphere; and deviations from a long term climatological mean state of the atmosphere occur more frequently, and have larger amplitudes. It is therefore not clear if larger deviations between GPS/MET and meteorological analyses in the winter hemisphere (as found in the validation studies mentioned above) are really due to the sparseness of observational data; they might also be caused by a larger overall variability which is not completely captured by the GPS/MET measurements or the analyses, or even by systematic errors.
Especially the ability to measure very low temperatures is important, as their occurrence determines the Polar Stratospheric Cloud (PSC) formation potential of the stratosphere (e.g., Pawson et al., 1995), which influences the amount of chemically induced ozone depletion in the stratosphere. Radio occultation measurements, if able to measure such low temperatures accurately, could contribute significantly to the quality of operational analyses during winter, as these tend to have a warm bias at such temperatures and thereby underestimate the stratosphere's PSC formation potential systematically (Knudsen, 1996; Pawson et al., 1999).

Apart from the A/S off periods in 1995, a large number of GPS/MET profiles is also available for an A/S off period in February 1997. This winter was characterized by a very cold polar vortex from February into late April (Coy et al., 1997). Due to the high ozone depletion because of high PSC activity, record low ozone values were observed during late winter (e.g., Newman et al., 1997). Thus, our study deals with the validation of GPS/MET temperature data during February 1997. In addition, the global moisture distribution in the mid–lower stratosphere is compared with analysis data during the same period. We introduce the data sets used in this study in Sect. 2. Section 3 deals with the validation of stratospheric temperatures, while Sect. 4 focuses on the water vapor comparison. We summarize our results in Sect. 5.

2 Data sets

We have used level 3 profiles of temperature and partial water vapor pressure from the GPS/MET experiment as available from UCAR for the A/S off period during February 1997. This data set contains 1790 profiles taken between February 2, 1997 and February 16, 1997. Each profile is sampled at a nominal vertical resolution of 200 m from the troposphere up to 60 km. The retrieval of GPS/MET data performed by UCAR contained the following steps (see Rocken et al., 1997, for details): First, excess doppler shifts and bending angles were calculated from GPS phase measurements using precise orbit information and Bouger’s formula (i.e., assuming local spherical symmetry). Ionospheric effects have been corrected for by applying a linear combination of bending angles. As this cannot completely remove ionospheric residuals, the resulting bending angle profile still suffers from uncertainties above (typically) 50 km altitude. This was handled by a “statistical optimization” of the bending angle profile using climatological bending angles, where weighting factors were determined empirically from the bending angle noise between 60 and 80 km altitude; vertical correlations of possible errors in the climatological bending angle profile were neglected. Rocken et al. argue that climatology does not significantly influence the measurements below an altitude of approximately 40 km. An Abel transform (again assuming local spherical symmetry) was further used to calculate atmospheric refractivity as function of geometrical altitude. Eventually, stratospheric temperatures were derived from refractivity assuming the ideal gas law in hydrostatic equilibrium. In the troposphere, temperature profiles interpolated from ECMWF meteorological analyses were used to calculate partial water vapor pressure from refractivity. For GPS/MET, an iterative approach was used, which we will refer to as “standard” water vapor retrieval. The water vapor profile obtained by this algorithm solves the relation between refractivity, temperature and moisture under hydrostatic equilibrium exactly; therefore, errors in refractivity or external temperature are directly mapped onto humidity.

In this study, we have used global moisture and stratospheric temperature fields from 6–hourly operational analyses of the European Center for Medium Range Weather Forecast (ECMWF) and the reanalysis data from the National Centers for Environmental Prediction (NCEP; Kalnay et al., 1996). Daily temperature analyses of the northern hemisphere from the Stratospheric Research Group at the Free University Berlin (FUB; Naujokat and Labitzke, 1993) and global temperature analyses from the Stratospheric Data Assimilation System of the UK Met. Office (UKMO; Swinbank and O’Neill, 1994) complemented the stratospheric data sets. Since NCEP and ECMWF analyses have their upper boundary at about 30 km altitude, 10 hPa (27–30 km) meteorological fields from these analyses may suffer from upper boundary problems. UKMO stratospheric analyses end at about 60 km, and are therefore not influenced by an upper boundary at 10 hPa. The FUB analyses of the northern hemispheric 50 (18–22 km), 30 (22–26 km) and 10 hPa levels are based on radiosonde observations; one feature of this data set is that
3 Stratospheric temperatures

Northern hemispheric error statistics at the 30 hPa level between GPS/MET temperature soundings and the analyses are summarized in Tab. 1. Mean and RMS deviations have been calculated for all profiles northward of 30°N. The table reveals that GPS/MET measurements are essentially unbiased against the FUB analysis at this level, but colder by nearly 1.5 K when compared against both the ECMWF and the NCEP analyses; for UKMO, the cold bias against the analyses is below 1 K. RMS deviations between GPS/MET and all of the meteorological analyses are in the order of 2.3 to 2.6 K. This is significantly larger than the RMS error of less than 1.5 K previously given in the literature for this altitude.

Tab. 1 also shows the mean and RMS deviation between FUB and the other analyses, calculated from the differences at the occultations’ locations. Mean deviations between FUB and the other analyses are consistent with those found for GPS/MET, showing that the analyses of UKMO, ECMWF and NCEP are by 0.8 to 1.3 K warmer than FUB. RMS differences between FUB and the other analyses are in the order of 2.1 to 2.3 K (as well as crosswise RMS deviations between the other analyses), indicating that this is the order of uncertainty of the analyses during February 1997. Given the known tendency of the analyses to be slightly warmer than reality in cold winters and the good agreement between GPS/MET and FUB, we might conclude that – at the 30 hPa level and averaged over the mid and high latitudes of the northern hemisphere – GPS/MET does indeed provide unbiased temperatures, and that RMS errors are within the range of uncertainty of the analyses.

More insight into the structure of mean deviations between GPS/MET and the analyses can be gained by looking into their meridional distribution shown in Fig. 1 for, e.g., NCEP data, calculated in 10° wide latitude bins. As tropospheric water vapor was neglected in the GPS/MET temperature retrievals, we have restricted the plots to the atmosphere above the 400 hPa level.

Near the tropical tropopause (around 100 hPa), GPS/MET soundings are colder than the analyses by up to 3 K. Another, similar cold bias of the radio occultations is apparent at the 300 hPa level in high latitudes of the southern hemisphere, accompanied by a warm bias above. These temperature deviations can be attributed to the sharper resolution of the tropopause by radio occultation measurements, and have been noted by several authors (e.g., Rocken et al., 1997).

In the tropical stratosphere, GPS/MET data exhibit a warm anomaly centered at the 30 hPa level above the equator. This anomaly is also present in comparisons with ECMWF and UKMO data (not shown), although the detailed structure varies between data sets. This tropical temperature bias is consistent with known deficiencies in the analyses’ representation of the tropical Quasi-Biennial Oscillation (QBO) in the analyses (e.g., Pawson and Fiorino, 1998), and is likely to be related to the temperature anomaly associated with the downward propagating westerly shear zone (e.g., Baldwin et al., 2000) of the tropical QBO during February 1997.

Northward of 30°N and up to (and including) the 50 hPa level, the agreement between GPS/MET and NCEP data (as well as with ECMWF and UKMO; not shown) is indeed better then 1 K, supporting the findings of earlier validation studies. At 30 hPa and above, negative mean deviations of more than 1 K dominate the mid-latitude stratosphere (and, due to the large number of GPS/MET profiles in this latitude range, also the hemispheric mean deviation given in Tab. 1).

In polar regions of the northern hemisphere, however, a warm bias of GPS/MET temperatures against NCEP (as well as the other analyses; not shown) is apparently present. High latitudes during February 1997 were characterized by unusually low temperatures throughout the stratosphere (Coy et al., 1997), allowing for PSC formation. We have therefore compared GPS/MET with FUB data for temperatures below the PSC formation temperature. An often used proxy for this is the condensation temperature for Nitric Acid Tri-hydrate (NAT) for 5 ppmv water vapor and a high latitude profile of nitric acid, $T_{\text{MAE}} = -80.3^\circ$C (at 30 hPa; e.g., Knud-
sen, 1996). According to FUB, 15 GPS/MET profiles sampled air masses with temperatures below $T_{M}$ at this level. They exhibit a warm bias of 2.3 K against the FUB analysis. The other analyses have a warm bias of 1.8, 2.0 and 2.6 K (for UKMO, ECMWF and NCEP, respectively) against FUB. These numbers are consistent with the warm bias against radiosonde observations given by Manney et al. (1996) for UKMO and Knudsen (1996) for ECMWF and UKMO at temperatures low enough for PSC formation. Thus, at temperatures relevant for ozone depletion, GPS/MET exhibits a warm bias which is comparable to that of the operational analyses.

According to Fig. 1, the warm bias of GPS/MET in polar latitudes is increasing with altitude. Even larger systematic deviations between GPS/MET and FUB data can therefore be found at higher levels: Figure 2 shows a scatterplot of GPS/MET vs. FUB temperatures at 10 hPa for February 11, 1997, when the lowest temperatures occurred. Here, GPS/MET temperatures have a warm bias for all temperatures below -60°C.

GPS/MET's warm bias at low temperatures also dominates the meridional distribution of RMS deviations between GPS/MET and UKMO analyses, shown in Fig. 3. While the differences between GPS/MET and the analyses around the tropopause as well as in the tropical stratosphere are clearly visible in the RMS deviations, largest uncertainties appear in high latitudes of the northern hemisphere at and above the 30 hPa level, with RMS errors of more than 3 K. Comparing GPS/MET with UKMO data in the upper stratosphere and mesosphere (not shown) reveals that this structure is a downward extension of even larger RMS deviations above. It is interesting to note that the same pattern – large RMS deviations in high latitudes extending from higher levels down into the lower stratosphere – can also be deduced from a comparison of GPS/MET data with NCEP and ECMWF analyses (not shown), despite their potential upper boundary problem.

A possible explanation of the warm bias of GPS/MET temperatures is the downward propagation of the influence of climatology if the deviation of stratospheric temperature from climatology is large – as during the cold winter of 1997. Evidence has indeed been provided by Healy (2000) that the statistical optimization puts too much weight on the climatological information if vertical error correlations of the climatology are neglected. The warm bias of GPS/MET at low temperatures and the downward extension of large RMS deviations below the 30 hPa level therefore suggest that the influence of climatology used in the retrieval of GPS/MET data is not restricted to altitudes above 40 km, but can significantly affect temperature soundings in the lower stratosphere in winter.

It is also interesting to note that the mean and RMS deviations between GPS/MET and analyses are not larger on the southern hemisphere than on the northern hemisphere. Instead, the region with RMS deviations of less than 1.5 K on the southern hemisphere reaches slightly higher up than on the northern hemisphere, and also covers a wider latitudinal range – despite the sparsity of observational data.

4 Tropospheric water vapor

The global distribution of specific humidity measured by the GPS/MET instrument at the 500 hPa level (around 5 km altitude) during February 1997 is shown in Fig. 4, along with a similar distribution derived from the ECMWF analyses sampled at the profiles' locations. These irregularly distributed data points were resampled onto a regular $2.5^\circ \times 3.75^\circ$ latitude–longitude grid, applying an inverse distance weighted interpolation scheme using the five closest data points. This procedure is not intended to obtain a realistic snapshot of the water vapor distribution at a single moment in time; but it provides a comparable view of the global humidity distribution from both GPS/MET and ECMWF.

Figure 4 indicates that the tropical water vapor distribution, and especially the overall structure of the inner Tropical Convergence Zone (ITCZ), is successfully reproduced by the radio occultation measurements. The tropical convection centers above South America and Africa as well as Indonesia are well represented. A larger southward displacement of the ITCZ over the South American and African continents than over the Indian and western Pacific oceans is also seen. Even small scale structures caused by synoptic transport processes are well captured by the GPS/MET soundings.

Within the moist areas of the ITCZ, specific humidity values are higher in the GPS/MET data by typically 1 to 1.5 g/kg, and lower by nearly the same amount in the subsidence areas related to the tropical Hadley circulation. Similar values hold for a comparison between GPS/MET and NCEP reanalysis data. This is the well-known pattern of errors in the moisture budget of both ECMWF (Vesperini, 1997) and NCEP analyses (Trenberth and Guillemot, 1998). Thus, deviations between GPS/MET and ECMWF (or NCEP) humidity in the tropics highlight known deficiencies of the analyses.

In mid and high latitudes relative errors between GPS/MET and ECMWF are in the order of 50 to 75% (not shown). We already mentioned the necessity to use external temperature information in order to retrieve water vapor profiles from refractivity. In order to test the sensitivity of the iterative retrieval method applied for GPS/MET to uncertainties in the ancillary temperature, we have calculated specific humidity profiles from GPS/MET refractivity using both ECMWF and NCEP temperatures. At the 500 hPa level, the globally averaged RMS deviation of specific humidity is slightly less than 0.2 g/kg. Due to the large abundance of water vapor in low latitudes, this is a small, and probably negligible, error in the tropics; but in mid and high latitudes, where water vapor abundance is small, differences in the temperature fields yield relative errors of more than 50% (Fig. 5). Thus, uncertainties in the ancillary temperature fields, which we simply simulated by using two different temperature analyses, are sufficient to explain a large part of the extratropical deviations between GPS/MET and the analyses' humidities.

The sensitivity of the standard water vapor retrieval scheme is a well-known problem of "exact methods" in remote sensing (Rodgers, 1976). Recently, Healy and Eyre (2000) demonstrated that a 1D variational retrieval algorithm significantly
reduces retrieval errors due to uncertainties in ancillary temperature. This suggests that water vapor retrieval in future radio occultation experiments should be based on statistically optimal methods rather than on the standard retrieval discussed in the GPS radio occultation literature so far.

We would like to note that not all GPS/MET profiles available from the February 1997 A/S off period were used in the construction of the global water vapor map shown in Fig. 4. About 16% of the GPS/MET data set (261 profiles) had to be excluded because they exhibited negative partial water vapor pressures. This is not related to the negative refractivity bias reported by Rocken et al. (1997), since the problem does not affect all profiles in a statistically homogeneous manner – some profiles are not affected at all. It is also unrelated to uncertainties in ancillary temperatures: several profiles exhibit partial water vapor pressures below -10 hPa. This would require temperature errors to be larger than 30 K, which seems to be an unrealistic assumption. Another possible explanation is multipath in the troposphere which would affect only selected occultations. Several advanced correction methods have been proposed to tackle tropospheric multipath effects, e.g. back propagation (Gorbunov and Gurvich, 1998), Fresnel correction (Melbourne et al., 1994; Mortensen and Hoeg, 1998), or the radioholographic method (Hocke et al., 1999). It still needs to be shown that these methods are able to resolve the negative water vapor issue, or if other reasons, e.g. interna of the receiver software, cause the problem.

5 Conclusions

Based on stratospheric temperatures obtained from the GPS/MET mission during February 1997, we have shown that northern hemispheric RMS deviations between GPS/MET and stratospheric analyses at the 30 hPa level are larger than previously anticipated (2.3 K instead of 1.5 K). This number, however, is within the uncertainty of the analyses themselves, and might be caused by an increased uncertainty of the analyses during winter.

The meridional distributions of mean and RMS deviations between GPS/MET and analyses reveal known shortcomings of the analyses, especially a poor representation of the tropo-

Fig. 5. Relative errors in 500 hPa specific humidity arising from different (ECMWF vs. NCEP) ancillary temperatures used in the derivation of water vapor from refractivity.
pause and the tropical QBO. On the other hand, a warm bias of GPS/IMET temperatures in low temperature regions of high latitudes at and above the 30 hPa level is apparently present, and comparable to that of most operational analyses. Radio occultation measurements based on retrieval procedures like those used for the GPS/IMET retrieval are therefore unlikely to improve meteorological analyses in one of their major shortcomings, i.e., the underestimation of PSC formation potential during winter.

500 hPa specific humidity derived from GPS/IMET soundings resolves the low latitude water vapor distribution well; even small scale structures related to transport processes in low latitudes are successfully resolved. Tropical humidity deviations between GPS/IMET and analyses reflect commonly known deficiencies of the analyses.

Outside of the tropics, however, uncertainties in ancillary temperature fields used in the standard retrieval yield large variations (above 50%) in specific humidity. Thus, the standard water vapor retrieval discussed in the literature so far is inadequate for accurate measurements of water vapor in mid and high latitudes. The use of more elaborate variational retrieval methods seems to be required in future radio occultation missions in order to overcome the high sensitivity of current algorithms to errors in ancillary temperatures.

The occurrence of a large number (16% of the data set) of negative values of partial water vapor pressure is a particular source of concern.

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