Ground-based GPS: Benefit in the data sparse Arctic region

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Abstract: The relevance of water vapour for the radiative budget of the atmosphere as well as aerosol growth, cloud formation and weather forecasting contrasts strongly with the availability of humidity data in the Arctic. Acting as the most important greenhouse gas, the water vapour distribution influences the ground temperatures, while especially in the Arctic the surface temperature feeds strongly back by expansion or shrinking of permanently frozen ground and sea ice extension. About 80 radiosonde stations are located north of 60°N, launching in most cases between one and two sondes per day. Up to now this irregular distributed humidity data set is the most extensive, but the reliability of this humidity measurements under Arctic conditions is still under discussion. Additional information like e.g. radiometer data is sparse. An increasing number of ground-based GPS receivers complements the database, providing integrated water vapour (IWV) information, if meteorological ground data is available. An evaluation of IWV data from ground-based GPS even under the low humidity condition of the Arctic will be presented. The possibility of the retrieval of IWV data from GPS soundings combined with meteorological data from radiosondes or numerical models will be discussed.

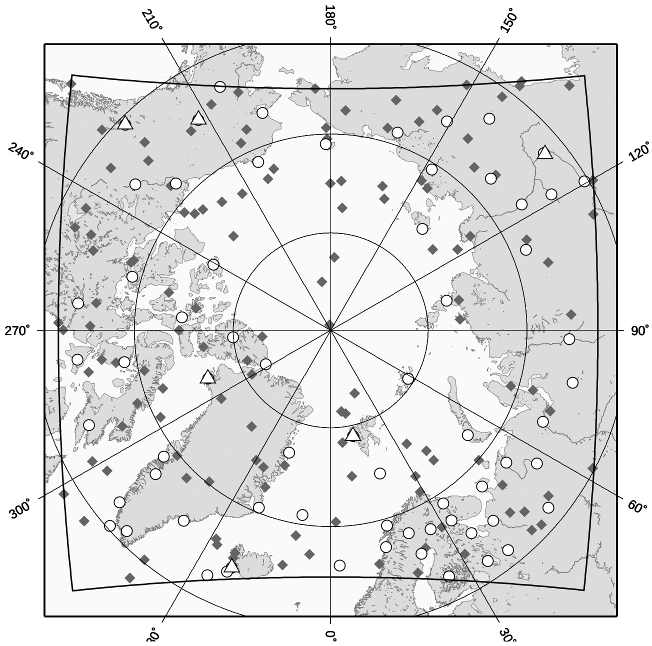

Fig. 1: Map of the Arctic region with the used radiosonde stations (circles), the GPS ground-stations (triangles) and the HIRHAM area (large quadrangle). The diamonds show the positions of GPS/MET radio occultations in February 1997 (not mentioned here). The Figure is taken from *Weisheimer and Gerding* [2001].

1. Introduction

Water vapour is the dominant greenhouse gas in the Earth's atmosphere. Additionally to radiative interactions, water vapour affects the energy balance of the atmosphere by transport of latent heat by evaporation of cloud water as well as ocean and freshwater, by sublimation and condensation. Thus, the spatial water vapour distribution plays an crucial role in the vertical stability of the troposphere and is coupled to the distribution of clouds and precipitation. Water vapour is involved in many chemical processes that occur in the atmosphere. But water vapour is also the most variable of the major trace gases in the atmosphere. The water vapour distribution especially in Arctic regions is only poorly known and suffers from a limited reliability of some observational standard methods like radiosondes [*Elliot and Gaffen*, 1991]. Moreover, there is a lack of dense, comprehensive, and regular observations in large parts of the Arctic region, e.g. at the Greenland ice sheet and over the Arctic Ocean (comp. Fig. 1).
The limited availability of comprehensive humidity data contrasts strongly with the need of such data for several research applications, including numerical weather forecasting and the assessment of climate change.
Experiments with General Circulation Models (GCM) used for the atmosphere-ocean-ice system on climatological time scales indicate that the Arctic region plays a key role for the Earth's climate with a high sensitivity to atmospheric changes. Typical simulation scenarios with doubling the CO_2 show the strongest temperature signal over the Arctic Ocean. Most GCMs general agree in simulating a future warming of the Arctic. But there is a tremendous variance in precipitation among the different models [*Walsh*, 2001]. Existing and upcoming data records of atmospheric humidity may help to compare the different atmospheric models and to reveal inaccuracies in the model formulation and parameterizations. Therefore, reliable and continuous measurements of the humidity content of the Arctic atmosphere are essential.
The present paper examines the benefits of ground-based GPS observations of integrated water vapour (IWV) in the data sparse and dry Arctic regions. Comparisons with radiosonde data sets from the Global Telecommunications System (GTS) of the World Meteorological Organisation (WMO) will be made as well as with objective analyses from ECMWF and the regional climate model HIRHAM (see, e.g. *Christensen et al.* [1996], *Rinke et al.* [2000]). GPS data are kindly provided by the International GPS Services (IGS). The focus of this paper is on climatological aspects. Therefore, all comparisons are limited to integrated water vapour (IWV). Zenith path delays (ZPD), which can

also be calculated from radiosonde or model data, are not taken into account.

2. Time series of integrated water vapour

For IWV calculation from GPS ground-based observations additional meteorological information on temperature and pressure is needed. In the Arctic region northern of 60°N latitude only the Fairbanks site (65°N, 148°W) provides this data regularly. Recently, also for Reykjavik (64°N, 23°W) meteorological data is provided by IGS. For comparison, data from two to four additional stations can be used, depending on season. In these cases, meteorological data is interpolated from nearby radiosonde sites. To prevent strong biases, temperature and pressure data are interpolated to the altitude of the GPS receiver.

Fig. 2 shows the time series of IWV at Fairbanks and Ny-Ålesund (79°N, 12°E) in February 1997. The high natural variability of the water vapour content of the atmosphere is obvious in all observed and modelled data sets. The GPS-based observations additionally exhibit fast variations in IWV. These oscillations, having periods of about 12 h, can not be resolved by the radiosonde data (every 12 to 24 h) and are not reproduced by the ECMWF and HIRHAM model (6 h resolution). They will be further examined in the next section. Although the oscillations occur at least in part of the data, the correlation between the radiosonde and GPS-IWV is higher than 0.9, when all data is interpolated to the sonde's time grid. Also between modelled data and GPS-observations the correlation is high (0.77 for both GPS-HIRHAM and GPS-ECMWF at Fairbanks, 0.70 for GPS-HIRHAM and 0.88 for GPS-ECMWF at Ny-Ålesund [*Weisheimer and Gerding*, 2001]). Table 1 shows the correlation coefficients between GPS and radiosonde data for all available data sets. Coefficients for August 2000 are shown for comparison. During summer, the IWV at the various Arctic sites is higher by about a factor of 3 compared with winter season.

Table 1: Correlation coefficients of IWV time series from radiosondes and ground-based GPS

	Ny-Ålesund (79°N/12°E)	Reykjavik (64°N/22°W)	Fairbanks (65°N/148°W)	Whitehorse (61°N/135°W)
February 1997	0.98	0.85	0.93	0.94
August 2000	0.91	0.96	0.98	0.98

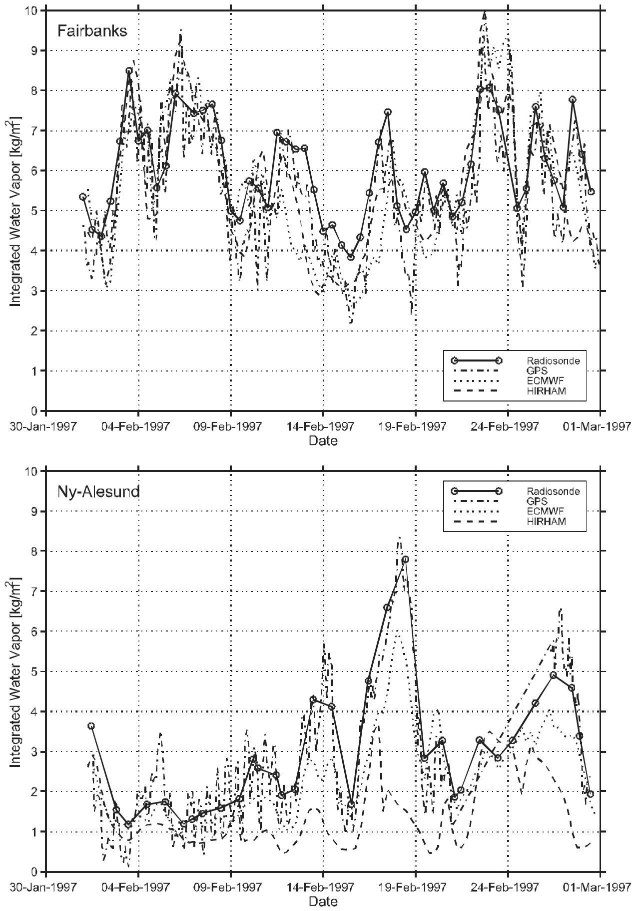

Fig. 2: Time series of integrated water vapour for radiosondes, ground-based GPS data, ECMWF analyses, and HIRHAM model at Fairbanks (65°N, 148°W) and Ny-Ålesund (79°N, 12°E). The Figure is taken from *Weisheimer and Gerding* [2001].

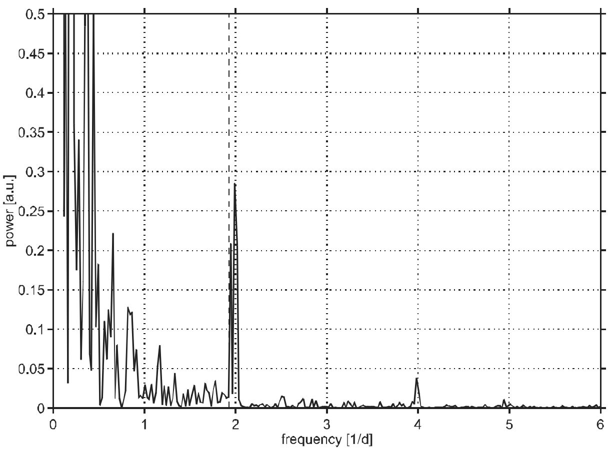

Fig. 3: Power spectrum of IWV time series from ground-based GPS observations at Fairbanks (65°N, 148°W) in February 1997.

3. Oscillations in GPS-based IWV data

Oscillations with semidiurnal period are apparent in both GPS-based time series in Fig. 2 and also in the GPS data from Reykjavik (Iceland) and Whitehorse (Canada). Such oscillations have also been discussed by *Ray et al.* [1994] and attributed to ocean tides. Fig. 3 shows the results of a Fourier analysis for the Fairbanks IWV data for February 1997 from GPS observations. The frequency spectrum reveals strong local maxima for frequencies of about 1.94 and 2.00 oscillations per day. These are the frequencies of the moon tide and ocean tide, respectively. Similar power spectra are obtained for more recent periods and other locations, but with less prominent tidal structure. And most spectra show only longer-periodic, synoptic scale contributions. Therefore artificial oscillations in GPS-derived IWV data are an apparent problem, though the incidence of such effects is low.

4. Use of model data for IWV retrieval from ground-based GPS

Meteorological data of temperature and pressure are neccessary for IWV retrieval from ground-based GPS observations (see, e.g. *Bevis et al.* [1994]). These can be either provided by meteorological sensors at the GPS station or by synoptic weather observing stations and radiosonde launch sites in the vicinity of the GPS receiver. To perform accurate pressure correction in order to compensate for altitude differences between sites, pressure profiles from radiosondes are preferred. In the Arctic, joint GPS and radiosonde stations are sparse and lack totally on the Greenland ice sheet and the Arctic Ocean. Meteorological data from objective analyses or high-resolution models can bridge the gap in observational data. Fig. 4 gives an example for the IWV time series at Thule (Greenland, 77°N, 69°W) for August 2000. The station and time are chosen for comparison, because here nearly regular radiosonde launches have been performed. During other periods radiosonde data has been delivered only irregular to the GTS, or the humidity data was less reliable. Therefore at this site meteorological data from high-resolution model can provide additional information compared with sondes. The IWV data in Fig. 4 is retrieved from GPS observations with the pressure and temperature interpolated from radiosondes or the HIRHAM model. The IWV calculated from radiosonde humidity data is shown for comparison. The differences between the both GPS retrievals are mostly smaller than compared with radiosonde data. The bias of 1.05 kg/m^2 is in the order of the typical error of ground-based GPS observations.

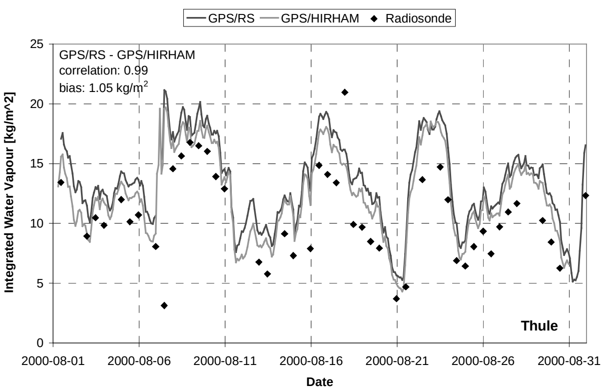

Fig. 4: Time series of IWV data from GPS observations combined with radiosonde and HIRHAM data, compared with radiosonde humidity data.

5. Summary

Ground-based GPS observations can provide integrated water vapour data with comparatively high temporal resolution. Even under Arctic conditions the accuracy is in the order of 1-2 kg/m^2 or better. Where meteorological data for IWV retrieval is not available from IGS, radiosonde data can be used after interpolation of pressure and temperature to the altitude of the GPS site. Unfortunalety the number of radiosonde sites is low in the remote Arctic region, despite this region plays a crucial role in the understanding of climate change. To retrieve additional humidity information, meteorological data from high-resolution models can be used. While improved humidity calculations in the models are still a point of interest, the pressure and temperature simulations are reliable for the use in GPS retrieval.

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