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Water vapor over Europe obtained from remote sensors and compared with a hydrostatic NWP model

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Abstract

Due to its high-variability water vapor is a crucial parameter in short-term numerical weather prediction. Integrated water vapor (IWV) data obtained from a network of groundbased Global Positioning System (GPS) receivers mainly over Germany and passive microwave measurements of the Advanced Microwave Sounding Unit (AMSU-A) are compared with the high-resolution regional weather forecast model HRM of the Deutscher Wetterdienst (DWD). Time series of the IWV at 74 GPS stations obtained during the first complete year of the GFZ/GPS network between May 2000 and April 2001 are applied together with colocated forecasts of the HRM model. The low bias (0.08 kg/m^2) between the HRM model and the GPS data can mainly be explained by the bias between the ECMWF analysis data used to initilize the HRM model and the GPS data. The IWV standard deviation between the HRM model and the GPS data during that time is about 2.47 kg/m^2. GPS stations equipped with surface pressure sensors show about 0.29 kg/m^2 lower standard deviation compared with GPS stations with interpolated surface pressure from synoptic stations. The NOAA/NESDIS Total Precipitable Water algorithm is applied to obtain the IWV and to validate the model above the sea. While the mean IWV obtained from the HRM model is about 2.1 kg/m^2 larger than from the AMSU-A data, the standard deviations are 2.46 kg/m^2 (NOAA-15) and 2.29 kg/m^2 (NOAA-16) similar to the IWV standard deviation between HRM and GPS data.

1. Introduction

Water vapor is a key element in the climate of the Earth and in the hydrological cycle which describes the movement of water within and between the Earth's atmosphere, oceans, and continents. Water vapor is the most variable of the major components of the atmosphere and a critical element in short-term numerical weather prediction. Due to the transfer of energy via its phase changes it drives atmospheric circulations. It is also the dominant greenhouse gas.

To observe the vertically IWV within the atmosphere different groundbased and spaceborne remote sensors are available (e.g., Raman lidar, Global Positioning System receivers, AMSU, Weng et al., 2000; ERS-2/InSAR, Hanssen et al., 1999; SSM/I, SSM/T2, Miao, 1998).

This paper presents a comparison of the IWV data obtained from the high-resolution regional model HRM of the DWD with colocated data from a groundbased GPS network and from AMSU-A data. The objective is to investigate whether GPS and/or AMSU-A IWV data can be assimilated into the HRM model.

Section 2 describes the datasets used and Section 3 shows the IWV comparisons between the HRM and GPS or AMSU.

2. The GPS and microwave sounder data

The US Global Positioning System (GPS) can be used to actively sense properties of the Earth's atmosphere and ionosphere by using groundbased or spaceborne receivers (Kursinski et al., 1997). The signals at both GPS frequencies ($L_1 = 1.57542$ GHz and $L_2 = 1.22760$ GHz) are delayed and refracted by the gases composing the atmosphere. Due to its permanent dipole moment, atmospheric water vapor introduces a significant and unique delay (for other components and their influence see e.g., Solheim et al., 1999).

Here the GPS system together with a dense network of groundbased receivers is used to get a high-spatial and temporal resolution of the vertically IWV over Germany

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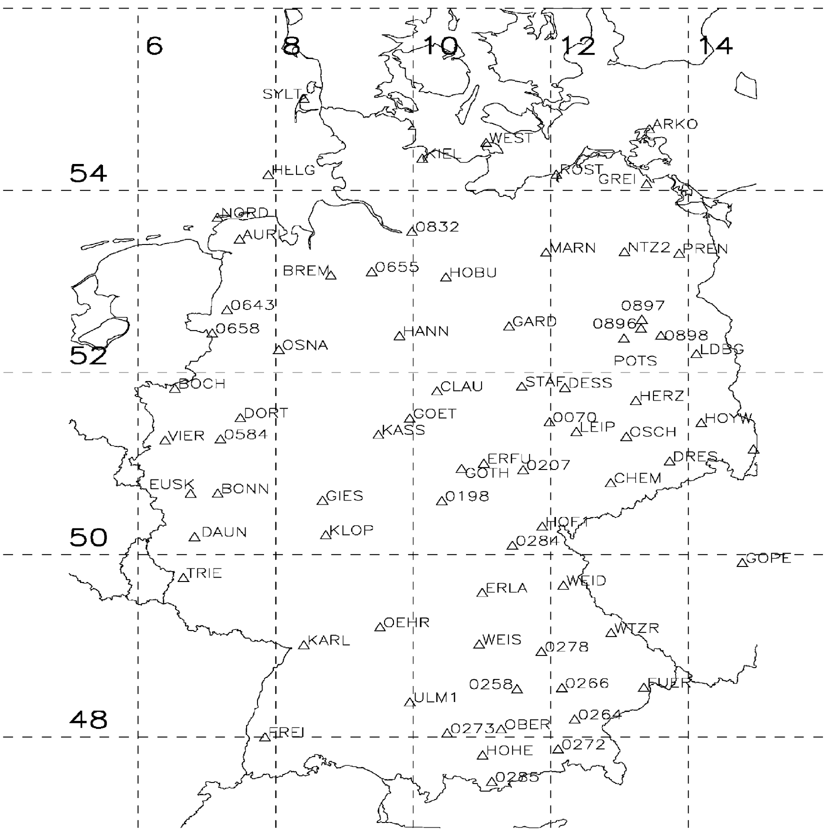

Fig. 1. GFZ/GPS stations mainly within Germany used within this study.

(Fig. 1). The GPS network consists of stations of the SAPOS network (SAtelliten POSitionierdienst) of the German Land Surveying Agencies and stations from the GeoForschungsZentrum (GFZ) build up at the weather stations of the DWD. Details about the processing of the GPS data are given by Gendt et al. (2001). During the first complete year with GFZ/GPS data within the BALTEX/BRIDGE baseline period (from May 2000 to April 2001) altogether 74 stations of the GFZ/GPS network were available. For 24 stations (mainly at the DWD stations) pressure observations could be applied to derive the hydrostatic delay. For the other 50 stations the pressure values were interpolated from the dense synoptic network of the DWD. Statistics from this procedure reveal an error of 0.3 hPa rms (Gendt et al., 2001) corresponding to an IWV error of about 0.12 kg/m^2. This dataset is compared with the hydrostatic numerical weather prediction model HRM of the DWD.

The Advanced Microwave Sounding Unit A (AMSU A) onboard NOAA-15 and 16 allows retrieval of the IWV from passive microwave measurements. To derive the IWV the NOAA/NESDIS Total Precipitable Water (TPW) algorithm is used. It is described in Weng et al. (2000) and is available on-line at http://orbit-net.nesdis.noaa.gov/arad2/MSPPS/html/day2/algorithm_day2.html. Two AMSU-channels are used: 23.8 and 31.4 GHz. In brief the algorithm works because 23.8 GHz is near a water vapor rotation line and is more sensitive to water vapor absorption than to cloud water droplet absorption, whereas 31.4 GHz is in a window region and is more sensitive to cloud droplet absorption than to water vapor absorption. The different characteristics at the two frequencies are exploited to simultaneously retrieve IWV and vertically integrated cloud liquid water under both clear and cloudy conditions. Based on radiative transfer simulations Grody et al. (1999) have shown that the rms error of the AMSU-A/IWV is about 1 kg/m^2. Both frequencies are measured by the AMSU-A instrument, which has 48 km resolution at nadir. The IWV product is available at least four times per day, except near the equator, where there are gaps between satellite swaths.

3. Comparison of the HRM model with GFZ/GPS and AMSU-A data

The hydrostatic high-resolution regional weather forecast model HRM used as boundary conditions 6-hourly analyses of the European Centre for Medium-Range Weather Forecast (ECMWF). The time step was chosen to be 90 s. Consecutive 30 h forecast starting each day at 0 UTC were performed. As the coordinate

Table 1
Mean differences and standard deviations between the IWV determined with the HRM model (HRM), from the GPS data (GPS) and from the ECMWF analysis data (ANA) used as boundary data for the initialisation of the HRM model

P	Meas. no.	HRM-ANA (kg/m^2)	RMS[a] (kg/m^2)	ANA-GPS (kg/m^2)	RMS[a] (kg/m^2)
Int.	27 700	0.03 ± 2.31	2.31	−0.18 ± 2.09	2.10
Obs.	25 071	−0.01 ± 2.30	2.30	0.40 ± 1.81	1.85
All	52 771	0.01 ± 2.31	2.31	0.10 ± 1.99	1.99
P	Meas. no.	HRM-GPS (kg/m^2)	RMS (kg/m^2)	Station no.	
Int.	219 916	−0.20 ± 2.58	2.58	50	
Obs.	205 547	0.36 ± 2.29	2.32	24	
All	425 463	0.08 ± 2.47	2.47	74	

P: surface pressure; int: interpolated; obs: observed.

[a] RMS^2 = Mean difference^2 + Standard deviation^2.

system of the model, a rotated latitude/longitude grid was used with a resolution of 0.125° (about 14 km) and 30 vertical layers up to about 25 km height. The vertical coordinate η of the model defines a so-called hybrid system where $\eta = \eta(p, p_s)$ is a monotonic function of the pressure p and depends also on the surface pressure p_s. To obtain the IWV of the model, the water vapor is integrated from the height of the GPS receiver up to the uppermost level of the model. The model level of the GPS receiver is calculated from the height of the receiver with the help of the hydrostatic equation. The hourly derived forecasts with the HRM model were compared with one hour mean values of the GPS network.

The HRM/IWV as well as the GPS/IWV ranges are between 0 and 49 kg/m^2 within the observation period. Table 1 shows the mean differences and standard deviations between the IWV derived from the HRM model forecast after a 6 h period used as spin up time of the model, from the GPS data and from the ECMWF analysis data. Altogether 425 463 matches between HRM IWV and the GPS/IWV data and 52 771 between the analysis data and the HRM or GPS data were obtained. The HRM model overestimates slightly the water vapor as observed with the GPS receivers. This mean difference can mainly be explained by the difference between the ECMWF analysis data and the GPS data.

The standard deviation at the stations with pressure sensors is about 0.29 kg/m^2 lower than at the stations without pressure sensors. Because the water vapor varies more in the lower atmosphere than in the upper atmosphere more model layers are included in the lower atmosphere. Thus the error introduced by interpolation of the specific humidity to derive the IWV is reduced. Nevertheless, this error together with the interpolation error of the network of the DWD (see above, Gendt et al., 2001) may explain a large part of the rms difference. A small contribution is also introduced through the GPS receiver height level correction with the help of the hydrostatic equation. The IWV standard deviation of all stations increases with the forecast time. During the 6 h spin up time of the model the standard deviation decreases slightly. This is mainly due to the HRM model, the analysis data do not show an increase compared with the GPS data (Fig. 2).

To compare the HRM model results above the sea the Advanced Microwave Sounding Unit (AMSU) A is applied within the BALTEX area. The BALTEX area covers north and middle Europe (see Fig. 1 in Johnsen and Rockel, 2001). Fig. 3 shows 15356 IWV compari-

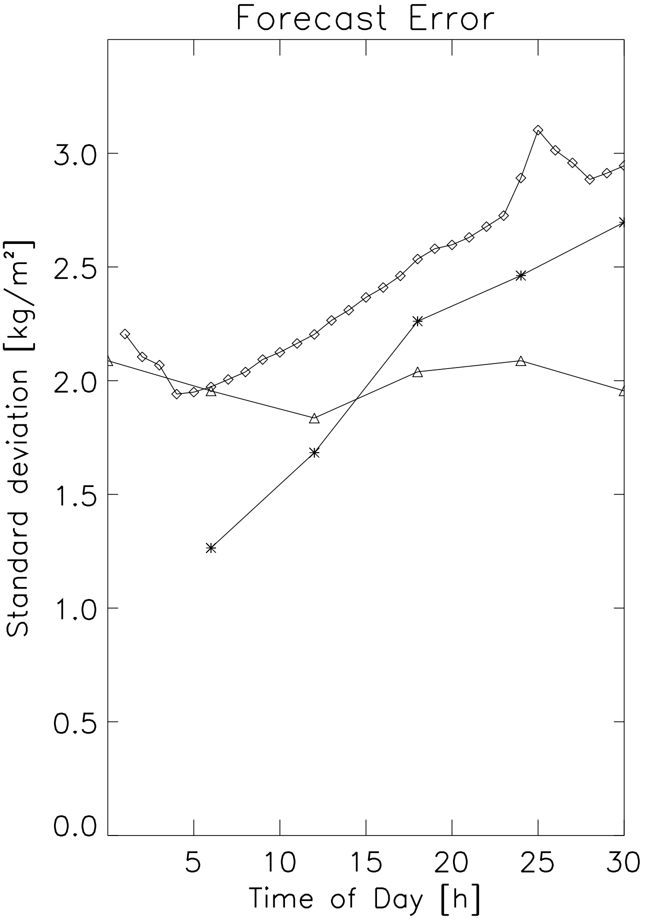

Fig. 2. Standard deviation of the IWV differences HRM-GPS (rhombus), HRM-Analysis (asterisks) and Analysis-GPS (triangles) as function of the forecast time.

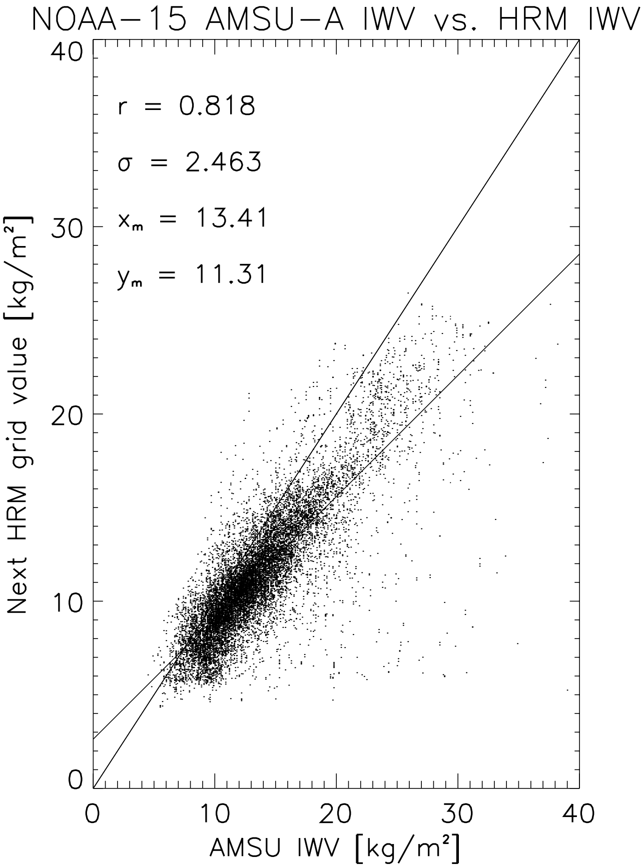

Fig. 3. Integrated water vapor (IWV) derived from AMSU-A data of NOAA 15 between 26th and 30th of April 2001 over the sea within the BALTEX area compared with the IWV of the HRM model. *r* is the correlation coefficient, σ is the standard deviation of the difference (HRM-AMSU), x_m is the mean value of the AMSU IMV, y_m is the mean value of the HRM IWV. The 1:1 line as well as a linear fit are given.

sons from colocated pixels of the AMSU-A and the HRM model for the AMSU passive microwave receiver onboard NOAA-15 between 26th and 30th of April 2001 (the AMSU-A data are available from the 26th of April to present). To avoid spillover effects near land areas an adequate land mask is applied. The HRM shows slightly lower mean values compared with the AMSU-A data (Table 2). While the number of matched pixels is comparably large, like that between the GPS data and the HRM model above land, the standard deviation between both datasets (NOAA-15 ≈ 2.46 kg/m^2, NOAA-16 ≈ 2.29 kg/m^2), as well as the range of IWV values, are also similar. The underestimation of the AMSU-A IWV data increases with increasing water vapor within the atmosphere (see linear fit in Fig. 3). The correlation coefficients of both datasets are with about 0.82 (NOAA-15) and 0.84 (NOAA-16) smaller than the correlation coefficient between the GPS data and the HRM model which is about 0.93.

Table 2
Δ is the mean difference between HRM/IWV and AMSU-A/IWV, *r* is the correlation coefficient and *N* is the number of data compared

	Δ (kg/m^2)	*r*	*N*
NOAA-15	-2.1 ± 2.5	0.82	15356
NOAA-16	-2.2 ± 2.3	0.84	14353

4. Conclusions

In this study two different datasets are compared with the IWV as obtained with the high-resolution regional weather forecast model HRM of the DWD. While the Global Positioning System actively sense properties of the atmosphere the AMSU uses a passive microwave radiometer to determine the IWV. Both receivers complement one another quite well because the GPS network allows a high-temporal resolution over land while the spaceborne AMSU data are taken over the sea.

The IWV as determined from datasets of both receivers show similar standard deviations as compared with the IWV of HRM. Comparisons between GPS data and radiosonde data have also shown similar standard deviations (Emardson et al., 2000; Gendt et al., 2001). GPS stations equipped with surface pressure sensors show about 0.29 kg/m^2 lower standard deviation compared with GPS stations with interpolated surface pressure. Different interpolation errors may explain this difference. The forecast error (standard deviation) of the HRM model increases with time.

The mean differences between the HRM model IWV and the GPS IWV can mainly be explained by the differences of the GPS data and the ECMWF analysis data which are used to initialize the HRM model.

The bias between the AMSU-A data and the HRM model can be used to adjust the algorithm to determine the water vapor from AMSU-A data.

Grody et al. (1999) have shown with radiative transfer simulations that the rms error of the AMSU algorithm is less than 1 kg/m^2. But actual measurements can exceed this theoretical limit by as much as a factor of 3 when compared against radiosonde observations. This larger difference can only be attributed to errors of the radiosonde observations as well as the differences in temporal and spatial resolutions of the microwave sensors compared with the radiosonde (priv. comm.).

Altogether the GPS network is a valuable source of IWV data above the land and consequently the GPS delay data will be used within NWP models for Europe within the near future. To supplement the IWV data over the sea the AMSU-A data are an expedient source and could also be used within NWP models.

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