Remote sensing of water vapour in all–sky situations

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Abstract

Water vapour is an inhomogeneous quantity on all temporal and spatial scales. Its natural variability plays a crucial role in the climate system. Through positive feedback water vapour takes an important part in anthropogenically induced changes in climate resulting from increases in carbon dioxide and other greenhouse gases. Hence, determining its spatial and temporal variability is a challenging task. The development of a complete and accurate global water vapour data set is critical to an adequate understanding of the Earth's climate system. This data is essential for studies concerning the energy and water cycle including poleward energy transports, radiation budget studies, general circulation model verification and global change research. The demands on the water vapour climatology are increasing in terms of temporal and spatial resolution.

The first climatologies were based on radiosonde measurement. Radiosonde measurements take place primary over land at distant points and do not show small scale water vapour variations. The use of satellite instruments enables global measurements. Different methods based on the different spectral channels are in use. IR and VIS techniques offer measurements with a sufficient spatial resolution but they only work in the absence of significant cloud cover. Over the oceans additional informations are determined by microwave instruments. Here clouds are translucent. The SEVIRI instrument on METEOSAT-8 enables the retrieval of total precipitable water (TPW) with a high spatial and temporal resolution for clear-sky scenes only. A water vapour climatology based on clear–sky measurements will lead to an underestimation in TPW when the cloudy-skies contain more water vapour than clear-skies. This effect is called *clear–sky bias*.

1 Introduction

The question, therefore, arises whether there is a difference in mean values between TPW in cloudy– and clear–sky observations? It is important to know at which time scales this bias is most apparent and how it can be corrected. It seems obvious that the atmospheric water vapour in cloudy skies exceeds the TPW in clear skies. Warm front clouds are associated with advection of warm humid air. Otherwise, convective clouds transport moisture from the boundary layer into the free atmosphere. Gaffen and Elliot (1993) found out that the climatological collumn water vapour content of clear–sky atmospheres derived from north hemispheric radiosoundings is significantly lower than for cloudy–skies. The magnitude of the bias is lower in tropical regions than at midlatitudes where the largest values are found in winter. The variability cannot be explained by variations in surface temperature or by instrument biases. However, quantitative estimates of the variation of TPW with cloud cover are lacking. Crewell et al. (2002) estimate the difference between mean TPW in cloudy to clear skies from ground based microwave radiometer measurements. For the European area they retrieve the excess water vapour (TPW (cloud) /TPW (clear)) of 1.2 to 1.3, showing a slight dependency on latitude. These values were derived from only two month of measurements.

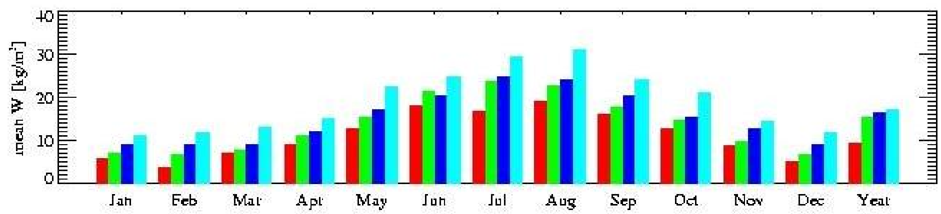
In clouds the relative humidity usually remains close to 100 % although considerable departures from these value have been observed. In cumulus clouds the relative humidity ranges from 80 % at the cloud boundary to supersaturation in the centre of the cloud exceeding 107 %. The median of the supersaturation is given with 0.1 %. Outside the cloud the relative humidity drops to values near 70 % due to turbulent mixing. Flights through clouds over Montana show supersaturation ranging from - 0.5 % to + 0.5 %, but averaged to 0 % (see Pruppacher and Klett (1997), Chapter 2).

To constitute a TPW climatology from ground based measurements (using the advantage of high temporal resolution, measurements under all–sky situations, long time series) would lead to several problems. These observations are limited to land surfaces and the distribution of these stations is inhomogeneous over the continents. A global coverage is only available from satellite measurements on an inhomogeneous temporal resolution, depending on number of overpasses per surface point, satellite type (orbiting or geostationary) and number of satellites used. The majority of TPW satellite estimates over land is derived using thermal measurements. This limits the observations to clear–sky situations. Over oceans TPW can be retrieved using microwave frequencies; here all–sky observations are possible. A bias is introduced by systematically omitting cloudy atmospheres with their larger TPW. Therefore clear–sky cases are overestimated in the climatologies and a dry bias is present. Beside the systematic error, Lanzante and Gahrs (2000) introduced the temporal sampling bias (TSB) in TPW climatologies based on satellite data. They investigated the difference between continously observing radiosondes (6 times per day) and satellite based measurements which are maximum twice per day over an individual radiosonde station. A satellite TPW is available when at that time the atmosphere is cloud free. So, the satellite misses potentially moist cases and with two measurements per day, it cannot resolve diurnal cycle. The temporal sampling bias, TSB, ranges from -1 to 21 % relative humidity in the 500 hPa level for the different stations.

The focus of this study is the estimation of the TPW in all–sky situations based on ground based measurements. The examination of the difference in TPW for clear and cloudy situations will lead to a quantification of the climatological excess water vapour (EWV). Which in turn may be used to correct TPW climatologies based on clear–sky measurements. This EWV will correct for the omitted cloud scenes, not for the sampling error. A more global investigation will be performend using a microwave satellite instrument (AMSU).

2 Case study

A: Mean water vapour path



B: Number of cases

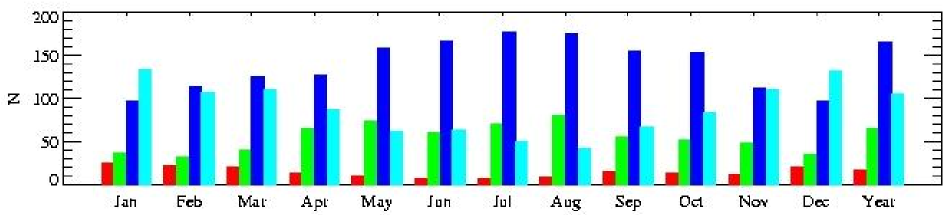


Figure 1: *10 years of data from Lindenberg sorted by the observed cloud cover: clear–sky in red, scattered cloudiness (1-4 octas) in green, broken cloudiness (5-7 octas) in blue, and overcast in cyan.* **A** *gives the monthly mean water vapour path in the cloud cover classes.* **B** *gives the number of observed cases. The last block gives the number per cases over all month (ordinate number times 100).*

Based on a case study the difference in TPW for cloudy and clear–sky atmospheres is estimated. 10 years of radiosonde ascents with corresponding cloud cover observations are used. The acents are sorted by the cloud cover in clear–sky, scattered cloudiness (1-4 octas), broken cloudiness (5-7 octas), and overcast situations. For each class the mean total precipitable water (TPW) is calculated. For the station Lindenberg, figure 1 shows the seasonal cycle of mean water vapour with larger TPWs in summer. The clear–sky cases contain less water vapour the the cloudy cases. The number of ascents per class show largest values for broken cloudiness. In summer the number of clear–sky observations is low. Actually, there are not many clear–sky observations at all. Gaffen and Elliot (1993) define bias estimators to express the relation of the mean TPW of cloudy situations towards a weighted overall mean TPW. For the investigated stations all bias estimators show significant more water vapour in cloudy cases. This result compares well with the results from previous studies.

Aim of this study is to relate all–sky TPW to clear–sky TPW. In figure 2 monthly mean TPW for four German stations are shown. Large clear–sky TPW are observed in the summer month whereas low TPW occure in the winter time. The excess water vapour is largest for low clear–sky TPW and decreases towards humid clear–sky atmospheres. On monthly mean and seasonal mean the excess water shows similar behaviour.

A: Monthly mean **B: Seasonal mean**

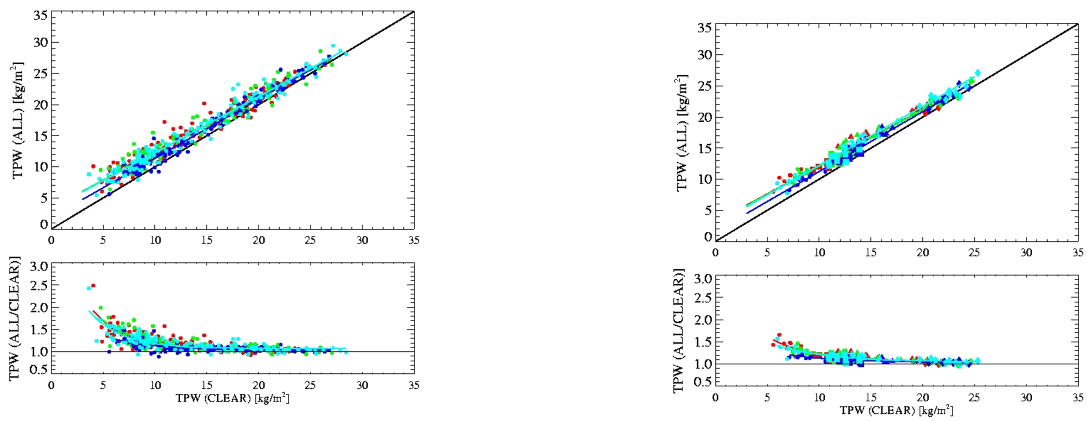


Figure 2: *All–sky versus clear–sky water vapour path for 10 years of radiosonde measurements from the stations Schleswig (red), Lindenberg (cyan), Essen (green), and Stuttgart (Blue). The upper panel presents the clear–sky total precipitable water (TPW) versus the all–sky TPW. The lower panel shows the clear–sky TPW in relation to the excess water vapour (TPW(all–sky)/TPW(clear–sky)).* **A** *covers the monthly mean and* **B** *the seasonal mean.*

3 Satellite based measurements

Satellite remote sensing enables observations on global scales. Over all surfaces water vapour path is retrieved with infrared techniques in clear sky scenes. Microwave emission is not influenced by clouds. Retrieval in this spectral range work in all–sky situations as long as the background emission is known to be low, like over ocean areas. For this study measurements of the Advanced Microwave Sounding Unit (AMSU) on the NOAA polar orbiting satellites are used. For the retrieval of TPW and vertical integrated cloud liquid water (LWP) the two frequency algorithm published by Grody et al. (2001) is used. The LWP is used for cloud detection.

Figure 3**A** shows the monthly mean all–sky TPW for January 2004 over the North Atlantic. The mean clear–sky TPW (figure 3**B**) looks quite similar. The excess water vapour (figure 3**C**) markers the difference in all–sky to clear–sky TPW. Mainly the excess water vapour is larger than 1. Some regions show lower values, here the cloudy cases contain less water vapour than the clear–sky cases. An explanation is the coupling of humidity and air temperature. South of New Foundland convection increases when north–westerly winds blow cold and dry air from the American continent over the gulf stream. The clear–sky cases are related to southerly flow with warmer air.
In July (see figure 4) the difference in air masses related to cloudy and clear situations is smaller than in January. The tropics show small differences in all–sky TPW to clear–sky TPW, the excess water vapour is close to one. For the mid–and high–latitudes the excess water vapour increases. Largest variability in excess water vapour is found in the cyclogenesis regions in the mid–latitudes. As for the case study, the excess water vapour decreases with increasing clear–sky TPW.

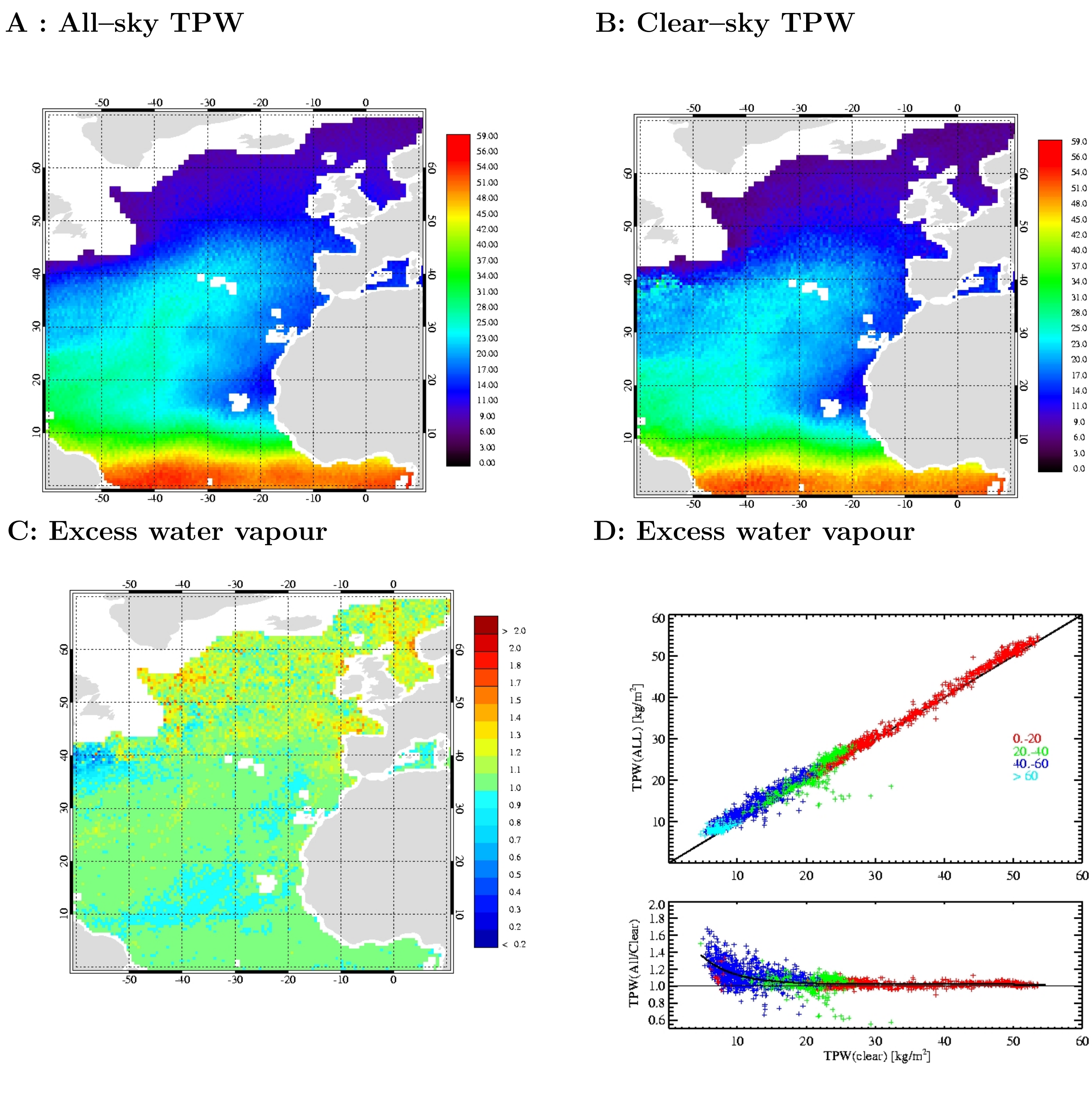


Figure 3: *Monthly mean vertical integrated total precipitable water (TPW) in [kg/m^2] derived from AMSU measurements for January 2004.* **A** *gives the all–sky mean TPW,* **B** *the clear–sky mean and* **C** *the excess water vapour (TPW(all–sky)/TPW(clear–sky)).* **D** *shows the relation of all–sky TPW to the clear–sky TPW (upper part) and the excess water vapour (TPW(all–sky)/TPW(clear–sky)) to the clear–sky TPW (lower part). Latitude bands are colour coded: 0-20° N in red, 20-40° N in green, 40-60° N in blue and north of 60° in cyan.*

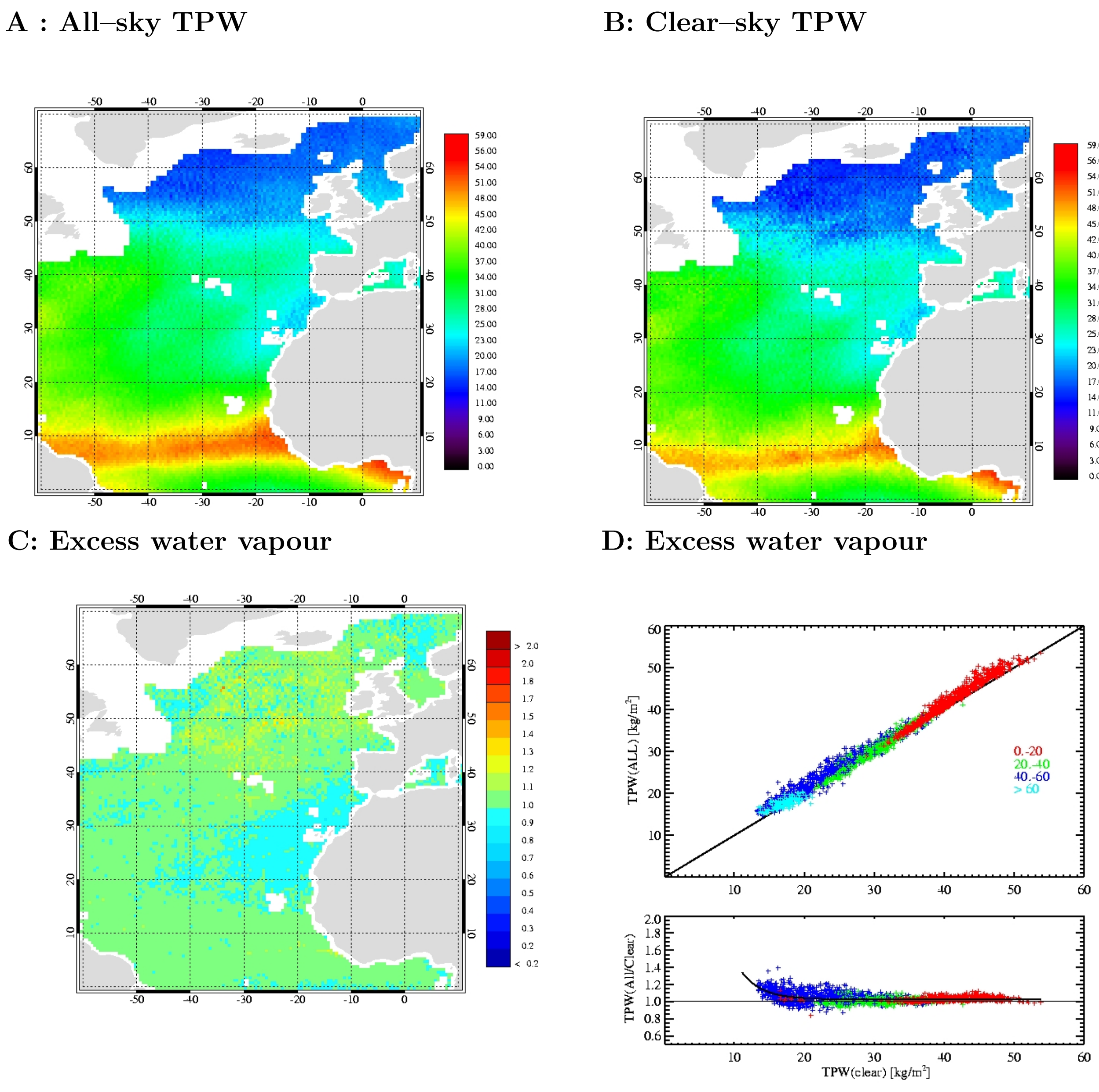


Figure 4: *Monthly mean vertical integrated total precipitable water (TPW) in [kg/m^2] derived from AMSU measurements for July 2004.* **A** *gives the all–sky mean TPW,* **B** *the clear–sky mean and* **C** *the excess water vapour (TPW(all–sky)/TPW(clear–sky)).* **D** *shows the relation of all–sky TPW to the clear–sky TPW (upper part) and the excess water vapour (TPW(all–sky)/TPW(clear–sky)) to the clear–sky TPW (lower part). Latitude bands are colour coded: 0-20° N in red, 20-40° N in green, 40-60° N in blue and north of 60° in cyan.*

A: Underestimation **B: Latitudinal dependency**

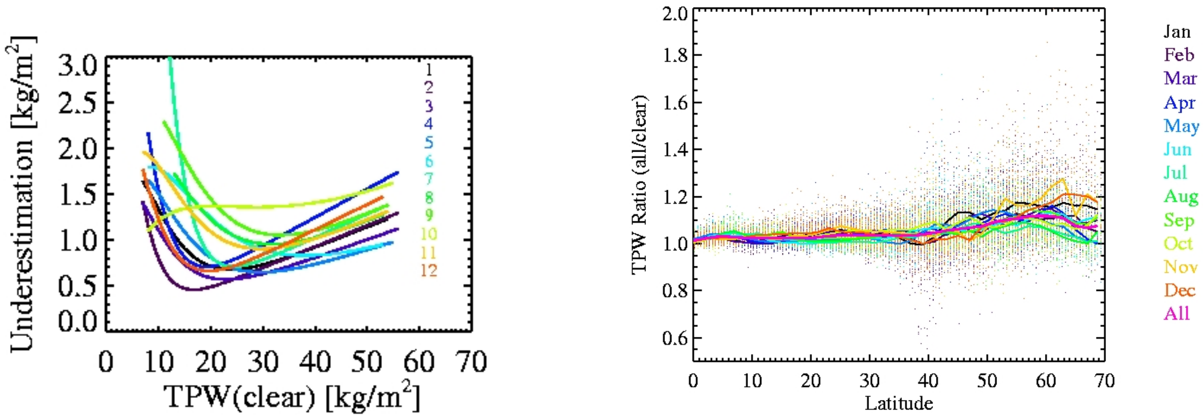


Figure 5: **A** Clear–sky water vapour bias as derived from the excess water vapour in figure 3 **D** and 4 **D**. Colours denote the month. The underestimation is given in relation to the clear–sky water vapour path used in a climatology. **B** Zonal mean excess water vapour for the north Atlantic. Colours denote the month. Magenta given the overall mean value.

The excess water vapour characterises the underestimation in relation to clear–sky TPW used in a climatology. Figure 5**A** gives the clear–sky water vapour bias in terms of kg/m^2. For atmospheres with low clear–sky TPW the bias is larger compared to humid clear–sky atmospheres. A seasonal variability in the relation is found. The zonal mean excess water vapour (figure 5**B**) increases with latitude. North of 30° the excess water vapour lies between 10 and 20 %.

4 Conclusions

In this study the relation of the water vapour in clear–sky and all–sky situations is determined from microwave remote sensing measurements of water vapour over the ocean and radiosonde relative humidity profiles from four stations within Germany. The radiosonde profiles and corresponding cloud observations are used to compare all–sky and clear–sky atmospheres. It is shown that atmospheres containing clouds store significantly more water vapour than those without clouds. This statement is in good agreement with previous work, e.g. Gaffen and Elliot (1993).

From microwave remote sensing the horizontal ditribution of monthly mean all–sky TPW and clear–sky TPW is investigated. Due to the strong coupling of water vapour and air temperature the TPW decreases from equator polewards. The excess water vapour increases with latitude. The difference in airmasses related to clear–sky to cloudy–sky situations are largest in the mid– to high latitudes. Here the frontal systems transport airmasses with different attributes. The excess water vapour is largest in winter month and in high latitudes. In the tropics the difference in TPW in all–sky to clear–sky situations is small. Here the excess water vapour is close to one. These results are determined from radiosonde measurements as well.

For the North Atlantic this study assesses the systematic underestimation of TPW in relation to the clear–sky TPW used in a climatology. For cold and dry clear–sky atmospheres in the mid–latitudes this underestimation is about 2 kg/m^2. There is a dependency on the month and on latitude. Future work will focus on the retrieval of excess water vapour climatologies over the global ocean based on four years of AMSU-A/NOAA-16 observations.

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