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Measuring regional atmospheric water vapor using the Swedish permanent GPS network

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Abstract. We investigate the application of a geodetic network of ground-based GPS receivers in Sweden to the measurement of atmospheric water vapor. Using data acquired during four days in December 1993, we show that it is possible to study the detailed motions of air mass systems. Estimates of water vapor from GPS data agree with those from radiosonde and microwave radiometer data to within 1 mm RMS.

Introduction

Water vapor plays a fundamental role in the transport of energy in the atmosphere on a wide range of temporal scales. It is thus an extremely important quantity for short- and long-term climatological studies, and even for short-term weather prediction. Furthermore, water vapor is an efficient greenhouse gas, which fact increases its importance for climatological purposes. Atmospheric water vapor is also itself an indicator of global warming since warmer air will hold more water vapor.

Our ability to measure time varying global and regional water vapor distributions is severely limited. The traditional method for measuring the amount of atmospheric water vapor uses radiosondes. These instruments yield good information on the vertical distribution of moisture, but their geographic sparseness and the low frequency of their launches (typically twice per day) are not suitable for measuring the water-vapor field with high resolution. Spaceborne sensors such as the 6.7 μm channels on the GOES and TIROS satellites have a great potential, although their highest accuracy is found for the upper troposphere [e.g., *Soden and Bretherton*, 1996].

The determination of the integrated precipitable water vapor (IPWV) in real- or near-real-time from Global Positioning System (GPS) phase measurements is an attractive potential alternative to these other techniques. In this paper, we investigate the use of GPS for understanding the temporal and spatial variations of atmospheric water vapor over a regional (1000 km) scale.

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Experimental description

We used data from the Swedish permanent GPS network, which was designed to measure glacial isostatic adjustment [*BIFROST Project*, 1996]. This network has been operational since August, 1993.

We made a case study of the four-day period beginning Dec 17, 1993, a time of extremely variable weather across Scandinavia. The purposes of the case study were (1) to establish the accuracy of the determinations of IPWV across a broad region during a period of rapidly varying conditions and (2) to determine whether the GPS-derived IPWV field yielded a coherent picture of water-vapor variations.

The determination of the atmospheric propagation delay from space geodetic data is well covered in the literature [e.g., *Bevis et al.*, 1992]. Figure 1 summarizes the method we used to derive IPWV from GPS data. A stochastic filter is used to provide time-dependent estimates of the zenith propagation delay for each site. GPS phase data were acquired every 30 s, but we decimated the data set to provide an estimate of IPWV every 300 s. The sites were equipped with TurboRogue GPS receivers and Dorne-Margolin antennas. We used the GIPSY software [*Webb and Zumberge*, 1993] to perform free network solutions of 24-hr long data sets, using dry and wet mapping functions derived by *Lanyi* [1984] and an elevation cut-off angle of 15°. Anti-Spoofing was not activated during this time period.

Assessment of accuracy

Figure 2 shows the GPS-derived IPWV estimates. The study period was characterized by a rapid increase in IPWV, followed one day later by a nearly equal decrease. For most sites the IPWV more than doubled, and in some cases it quintupled from ~5 mm IPWV to ~25 mm. Such high amounts of tropospheric water vapor could be made possible only by increased temperatures. During the 24-hr period commencing at about 18 UT Dec 18 maximum ground temperatures reached values of 9 °C, whereas maximum ground temperatures

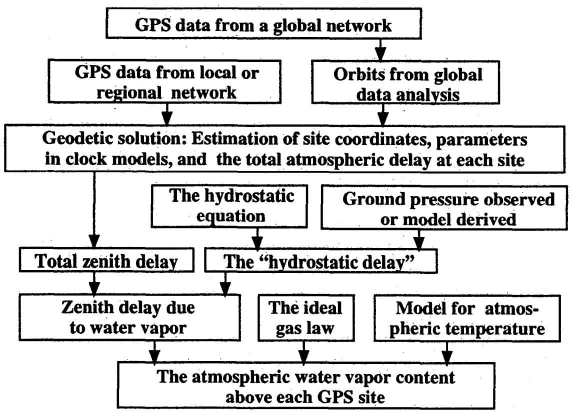

Figure 1. Flow-chart describing the method for obtaining IPWV from GPS data. We obtained the GPS orbit parameters from the IGS [*Mireault et al.*, 1996].

were only slightly above 0 °C on Dec 17 and Dec 20 (Figure 3).

For the first part of our study, we attempted to assess the accuracy of our IPWV measurements. This assessment was provided by comparing the GPS-derived IPWV to the results from radiosonde data and from ground-based microwave water-vapor radiometer (WVR) data [*Elgered*, 1993]. Three GPS sites have radiosondes launched within a distance of 40 km; a WVR

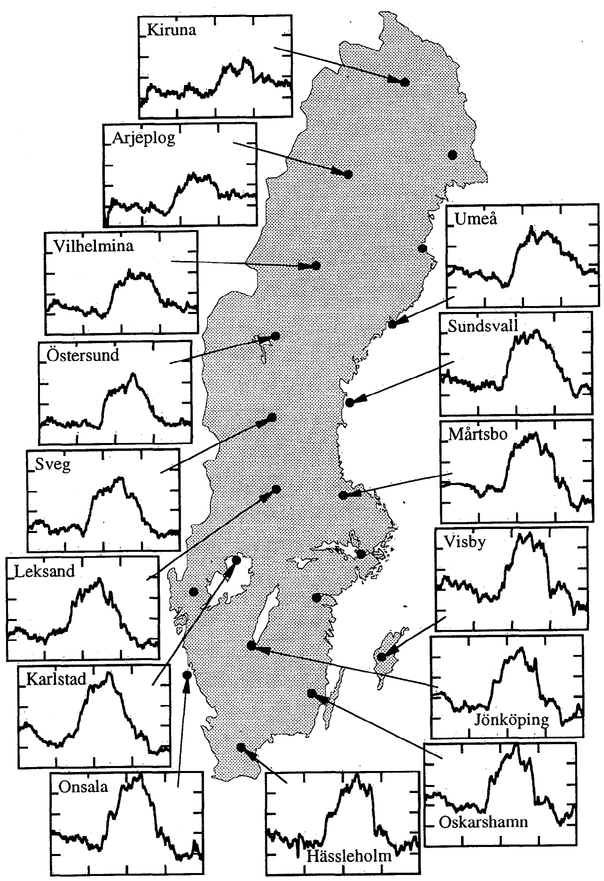

Figure 2. Estimated time series of IPWV used in the study. Horizontally, each plot spans four days beginning at 0 UT Dec 17. Vertically, each plot spans 0–25 mm.

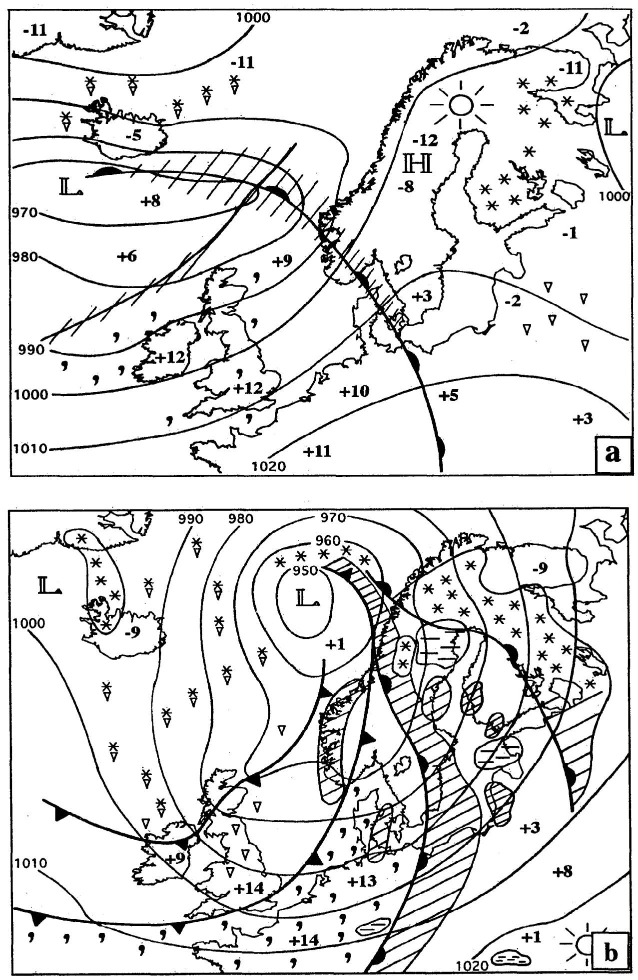

Figure 3. Weather maps for 12 UT on (a) Dec 18 and (b) Dec 19. The passages of the warm front (thick line with filled half circles) on Dec 18 and the following cold fronts (thick line with filled triangles) in the evening of Dec 19 are consistent with the GPS results, but the latter provide for much increased temporal resolution. Dashed areas denote rain; open triangles, showers; commas, drizzle; stars, snow; open triangles with stars, snow squall; and horizontal dash, fog/mist. Temperatures (bold numbers) are in °C . Isobars (thin solid lines) are in mbar.

is located at the Onsala site [*Davis and Elgered*, 1997]. The results of the comparison are shown in Table 1. The radiosondes are routinely launched every 12 hr. The mean GPS-radiosonde difference is less than 1 mm for all GPS-radiosonde pairs, with a root-mean-square (RMS) difference of about 1 mm. The maximum difference observed was 4 mm for the Onsala-Landvetter pair at 12 UT Dec 18. This difference may reflect true spatial variation in IPWV given the rapid temporal variation observed at Onsala and sites further to the east. This single large difference explains the excess RMS value for this pair when compared to the other entries in Table 1.

The WVR data have a time resolution much better than 60 s. Previous GPS-WVR comparisons with this WVR and with others have yielded typical differences of 1–2 mm [e.g., *Duan et al.*, 1996]. Figure 4 shows our

Table 1. Comparison of IPWV from GPS, radiosonde (RS), and WVR data

GPS site	Comparison instr.	dist. km	No. of data pairs	RMS Diff. mm	Mean GPS-Ref mm
Onsala	WVR	0	1440	1.13	0.31
Onsala	RS	37	9	1.65	0.37
Visby	RS	1	9	0.91	0.01
Sundsvall	RS	7	9	0.77	0.39

GPS-WVR comparison. The WVR data exhibit larger short-period variations than do the GPS data. Part of these differences is due to errors in the WVR method. For example, large raindrops in the WVR's field of view cause the algorithm, used to separate the influence from water vapor and liquid water, to break down. Part of the difference is due to the filtering of short-period fluctuations in the GPS determinations [*Elósegui et al.*, 1996]. It is clear from the comparison that nearly all features in the GPS time series agree well with the WVR data.

The time-dependent IPWV field

The largest IPWV signal in our data set is the "pulse" of IPWV beginning at approximately 12 UT Dec 18. Figure 5 shows details of the IPWV series from four nearly equal-latitude sites: Onsala, Jönköping, Oskarshamn, and Visby. The Jönköping and Oskarshamn series especially have many similarities. Pairwise cross-correlations of the four time series yield differential time lags, from which we conclude that the IPWV "pulse" propagated from west to east. Assuming that the airmasses are carried by a westerly wind, we estimate a mean wind velocity of 21 m/s. This velocity can be compared to that obtained from the observed wind profile, which indicates a consistent west-south-west direction and a speed of 9 m/s at the ground increasing to 29 m/s at a height of 3 km. The wind profile was obtained by the rawinsonde launched at 18 UT Dec 19 at Landvetter Airport located between Onsala and Jönköping.

To obtain a better picture of the time variable IPWV field over this area, we have created color contour images of IPWV for every 6 hr between 12 UT Dec 18 and 12 UT Dec 20, the period of rapid IPWV changes (Figure 6). The images were obtained by linear interpolation within Delauney triangles, followed by smoothing, of the IPWV determinations for the different sites at each epoch. The advantage of this procedure is that it is simple to produce maps of the instantaneous IPWV field. The disadvantage of the procedure is that the instantaneous IPWV field includes all the high-frequency variations of IPWV that are evident in Figures 2 and 5. An alternative analysis is given by *Davis and Elgered* [1997].

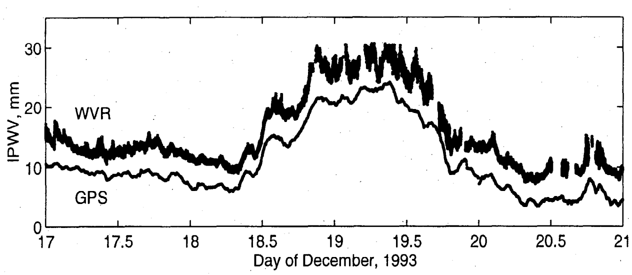

Figure 4. Comparison of the IPWV at the Onsala site inferred from GPS and WVR data. The WVR data have been offset by 5 mm for better visibility.

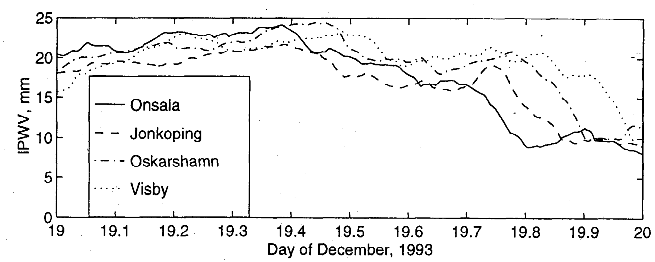

Figure 5. IPWV series for Dec 19 for four nearly equal-latitude sites. From the time offset between the curves the east-to-west motion of the dry airmass may be inferred.

High-frequency variations notwithstanding, the resulting depictions of the IPWV field are highly useful for understanding the time- and space-dependence of the exchange of airmasses. The warm air mass proceeds from the southwest towards the northeast. The direction of motion is clearly evident from the 12 and 18 UT Dec 18 frames of Figure 6. This observation is supported by the weather map shown in Figure 3a. By 0 UT Dec 19 the progress of this front has stalled somewhat. The increase in IPWV has not maximized, and the airmass throughout the central part of the network is rather mixed. However, before high IPWV values reach the most northern sites, a colder/drier airmass begins to thrust its way in from the west towards the east. This encroachment, which can be seen in Figure 3b also, explains why the northern sites never reach the high values of IPWV obtained by the southern sites. By 18 UT Dec 19, very high IPWV values (> 20 mm) are to be found only in the southeast, and by 00 UT Dec 20 the flow of the cold/dry airmass has become more westerly. By the last frame, 12 UT Dec 20, all sites report IPWV values less than 10 mm.

Conclusions and future work

We can immediately identify two applications for which our results might be useful: weather forecasting and climate studies. GPS determinations of IPWV provide a different type of information than is generally used for these applications. For a reasonable investment in equipment and a small operational cost GPS can provide determinations of water vapor which are more densely sampled in time and space than the current network of radiosondes and which are more sensitive to lower-troposphere water vapor than are satellite remote sensing determinations.

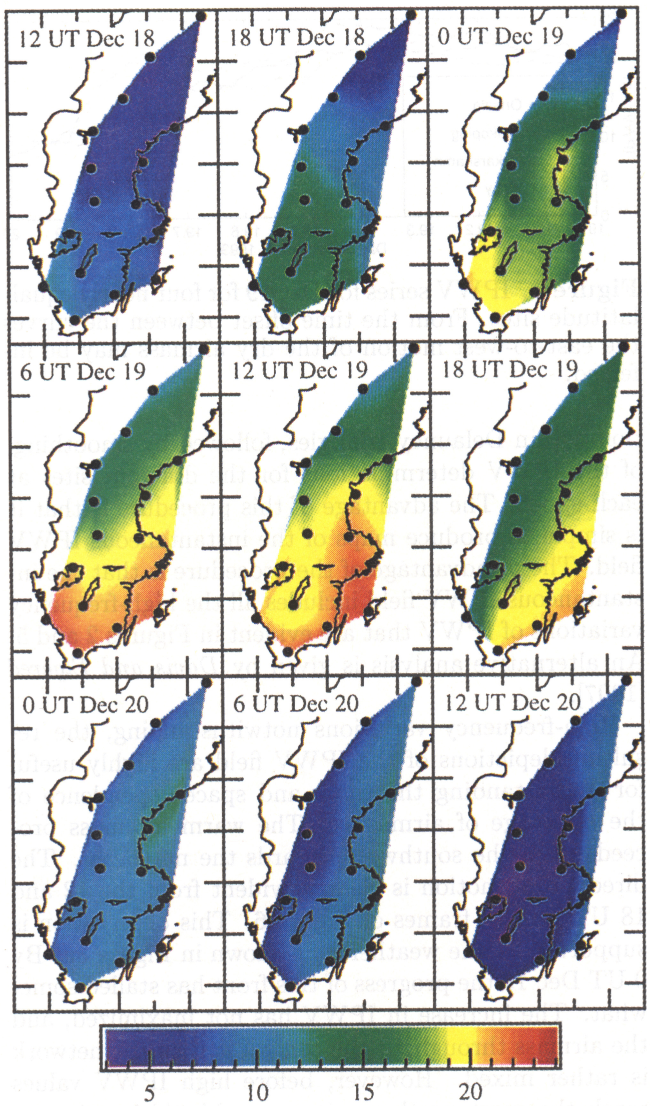

Figure 6. Nine images of the GPS-derived field. The top left and center frames may be compared to the large-scale weather maps of Figure 3. The frames cover 10–22°E and 55–68°N. A complete "movie" of the IPWV field during this time period is available at http://cfageod4.harvard.edu/swepwet.html.

We have so far made no attempt to produce IPWV fields in real or near-real time. For weather forecasting, reduction of the delay between data acquisition and dissemination of the final product is crucial. The most time-limiting element of GPS data analysis is the determination of satellite orbits. Others have been developing the capability for near-real-time determination of regional water-vapor. *Van Hove et al.* [1996], for example, discuss the processing of 1-hr segments of GPS data combined with predicted satellite orbits.

There are a number of applications, on the other hand, for which near-real time determinations of IPWV are not required. For example, an ongoing project involving the assessment of the energy-water balance in the catchment area of the Baltic Sea uses GPS-derived water-vapor information to evaluate atmospheric models [*Elgered et al.*, 1997]. When using GPS-derived water-vapor time-series for climate studies it is important to have a validated archive of the data quality. The challenge is thus to assess the long-term stability of the algorithms used to estimate the water-vapor field from GPS data. One can imagine, with careful data archiving, that it will be possible to (re-)analyze consistently many years of GPS data and thereby to be sensitive to signals in the water-vapor field on long time scales.

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