Synergetic Use of GPS Water Vapor and Meteosat Images for Synoptic Weather Forecasting

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ABSTRACT

The use of integrated water vapor (IWV) measurements from a ground-based global positioning system (GPS) for nowcasting is described for a cold front that passed the Netherlands during 16 and 17 May 2000. Meteosat water vapor (WV) and infrared (IR) channel measurements are incorporated to analyze this weather situation. A cloud band with embedded cumulonimbus clouds (Cb) preceded the cold front. The GPS IWV showed a clear signal at the passing time of the embedded Cbs over the GPS sites. After the frontal passage a dry intrusion occurred. By comparing Meteosat WV observations collocated in time and space with GPS IWV observations, a rough reconstruction of the vertical water vapor distribution can be made. The case described here shows that, in addition to Meteosat WV/IR images, GPS IWV contained information for nowcasting of the probability of the occurrence of thunderstorms and heavy precipitation.

1. Introduction

Water vapor (WV) is one of the parameters that is highly underdetermined in the current synoptic weather observation systems. Radiosonde measurements provide detailed vertical information but at very low temporal and horizontal resolution. Atmospheric water vapor can also be measured using water vapor radiometers, which measure column-integrated water vapor (IWV). These instruments are very accurate in clear-sky situations, but they are not “all weather,” and, moreover, they are very expensive. IWV can also be obtained from a network of ground-based global positioning system (GPS) receivers, together with a constellation of 24 GPS satellites. The temporal resolution of the observed IWV is high (5–15 min), the accuracy is very good, and a GPS receiver is much cheaper to deploy and maintain. Duan et al. (1996) showed that GPS IWV is in good agreement with IWV observations from water vapor radiometers, with a root-mean-square difference around 1–1.5 kg m$^{-2}$. The difference between near-real-time GPS IWV, with respect to radiosonde and water vapor radiometers, is around 2 kg m$^{-2}$ (Rochon et al. 1997). The network used in this study has an agreement of 2 kg m$^{-2}$ with respect to radiosondes (Klein Baltink et al. 2002). This is in agreement with accuracies found in other comparison studies.

Mazany et al. (2002) showed that the combination of GPS IWV and other meteorological data using a statistical model increases the forecast skill and lead time of a lightning event. The study presented here differs from Mazany et al. (2002) and previous studies because it does not focus on the quantitative information of GPS IWV, but more on the qualitative information.

The network of GPS receivers used in this study is constructed for geodetic research. A GPS receiver measures the delay of the GPS signal for every GPS satellite in view. By processing all observed slant delays within a certain time window, errors and unknowns, such as satellite or receiver clock errors, can be estimated. An estimate of the zenith total delay (ZTD) for any GPS receiver is determined simultaneously. The zenith wet delay (ZWD) can be computed from the signal by differencing the ZTD with the zenith “dry” or hydrostatic delay (ZHD).

$$ZWD = ZTD - ZHD$$ (1)

The ZHD can be approximated using the surface pressure (Saastamoinen 1972), while the ZWD is associated with the vertically integrated column of water vapor overlying the GPS receiver.

$$IWV = \frac{1}{k}ZWD$$ (2)

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where \( k \) depends on the weighted mean temperature of the atmosphere, which in turn can be approximated as a function of the surface temperature (Bevis et al. 1994; Klein Baltink et al. 2002).

Upper-tropospheric water vapor can be inferred by the 6.7-\( \mu m \) channel imager onboard the Meteosat satellite. This instrument measures the thermal emission by upper-tropospheric water vapor. The atmospheric temperature and clouds also affect the emission. Radiation emitted from water vapor low in the atmosphere will be absorbed by water vapor higher in the atmosphere: lower-atmospheric water vapor is obscured by upper-atmospheric water vapor. The geostationary satellite scans the earth every 30 min. The Meteosat WV images are widely used as “control” observations for synoptic weather meteorology. A loop of these images reveals the movement of weather systems and the downward motion of drier stratospheric air. The Meteosat imager scans also in the visible and in the infrared (IR). The IR measures the emission of the atmosphere in a broad band around 12 \( \mu m \) and can, therefore, be used at day and night as with the WV channel. Although the 6.7-\( \mu m \) channel is actually a thermal infrared channel, the commonly used abbreviation is WV channel. The WV and IR emission is reported in brightness temperatures (\( T_b \)) with units of kelvin. The average absorption level of WV emission lies roughly between 300 and 600 hPa (Weldon and Holmes 1991). Very low IR \( T_b \) indicates the presence of high clouds. High WV \( T_b \) implies that emissions from low in the atmosphere reach the detector, which can only occur when the upper troposphere is dry.

Another way to estimate water vapor is by using the Advanced Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (ATOVS). This instrument is onboard the National Oceanic and Atmospheric Administration (NOAA) polar satellites with a frequency of passage of 2 times per day. Using the Advanced Microwave Sounding Unit-B (AMSU-B) an estimate of the total water vapor column is only valid over the ocean (Grody et al. 2001). In this paper this information is not used because of this temporal resolution and the restriction to ocean areas. On the other hand, ground-based GPS water vapor estimates are restricted to land areas but have, as stated before, a good temporal resolution. The case discussed here focuses on the application of the temporal resolution.

2. Cold-front passage

In the evening of 16 May 2002, a sunny period of warm weather came to an end when a cold front passed the Netherlands. Across this cold front a temperature drop of about 10 K in 3 h was observed. In Fig. 1 the weather situations at 1200 UTC 16 and 17 May are shown. In the left panel of Fig. 1, which represents the synoptic situation at 1200 UTC 16 May, two cold fronts are heading toward the Netherlands.

The first front, which extends from Norway, over the North Sea, toward Brittany, France, marks the leading edge of the clouds. This edge is also visible in Fig. 2, which shows IR and WV images observed by Meteosat at 1200 UTC 16 May. The actual active cold front is related to the low pressure south of Ireland. Between these two fronts a large cloud band exists in which air is transported northward between the two frontal systems that are propagating eastward. Instabilities occurred when this cold air was transported over the warm surface, which resulted in mixed embedded cumulonimbus clouds (Cb). Behind the second front a dry intrusion appeared, visible as a dark spot in the WV image in Fig. 2.

The temperature and relative humidity, as observed by synoptic weather stations at Rotterdam, Hoogeveen, and Deelen, Netherlands, during this passage, are shown in Fig. 3’s top and bottom panel, respectively. Both relative humidity and temperature show a clear diurnal cycle during the warm weather. After the frontal passage the diurnal cycle clearly weakens. In Fig. 4 the locations of these weather stations, as well as nearby GPS sites, are shown. The GPS receiver locations are distributed over the Netherlands with a minimum distance of ap-
Fig. 2. (top) The inverted IR image and (bottom) WV as observed by Meteosat. White pixels represent low $T_b$. Both images are retrieved at 1200 UTC 16 May and cover Western Europe, with France in the center. Italy, Corsica, and Sardinia are visible on the IR image.

proximately 100 km. MacDonald and Xie (2003) showed that an accurate analysis of three-dimensional water vapor is possible with a network similar to that used in this study. The variational technique used is promising.

3. Discussion

In Fig. 5 the changes in WV and IR imagery overlying the Netherlands are shown. The upper half of all four panels shows the observed $T_b$ from the water vapor channel by Meteosat at subsequent times; the lower half contains $T_b$ from the infrared channel.

At 1400 UTC 16 May, convective clouds emerged in a region close to the west coast of Belgium and the east coast of England. These clouds are observed in both the WV image and the IR image. At this time large parts of the Netherlands are cloud free, as can be seen from the IR image (Fig. 5a, bottom). These clouds marked the first front running from Norway to Brittany (see Fig. 1, left panel). At 1800 UTC (Fig. 5b) the convective clouds cover the Netherlands almost completely. These Cb move from the southwest toward the northeast. The observed temperature in Rotterdam (see Fig. 3) dropped earlier than in Hoogeveen (the latter lies farther to the east). At 0600 UTC 17 May (Fig. 5c) a dark band in the WV appeared west of the Dutch coast, indicating a dry intrusion and that the amount of water vapor high in the troposphere decreased. At 1000 UTC this dark band has moved eastward and lies across the Netherlands. On the IR image, the cloud-free region in the vicinity of this dark band is visible at both times.

The time series of IWV as observed by the GPS receivers are shown in Fig. 6 (solid line). Also shown in this figure are the brightness temperatures of the WV (open squares) and IR (filled triangles) channels for the same locations. The IWV is presented in kilograms per meter squared with the values on the left vertical axis. The $T_b$ shown here are between 20° and −40°C but are plotted inversely as indicated by the values on the right axis. High $T_b$ values indicate a low average level of WV emission.

The three panels of Fig. 6 correspond to locations that shift in northeasterly directions when read from top to bottom. Figure 6 shows an increase in IWV overlying the GPS locations between 0000 and 1200 UTC 16 May from about 15 to 25 kg m$^{-2}$. The measured WV bright-
ness temperature was nearly constant in this period. The sudden decrease of IR $T_b$ that occurred at the same moment as a minimum in WV $T_b$ is due to high clouds, which contain large amounts of water vapor. The $T_b$ attains a minimum in WV and IR at approximately 1700 UTC in Delft, at 1800 UTC in Kootwijk, and around 1830 UTC in Westerbork. Simultaneously, a maximum GPS IWV occurred, indicating that the Cbs are heavily mixed. Note that the maximum of GPS IWV at Westerbork is less pronounced than over the other two sites. The simultaneous occurrence of high clouds (IR $T_b$), water vapor in the upper troposphere (WV $T_b$), and high GPS IWV estimates could be an indication of the occurrence of a relative extreme weather event. Downstream of Delft, at Schiphol, a rainfall rate $12 \text{ mm h}^{-1}$ has been observed, while near Westerbork, at Hoogeveen, the rainfall is spread over a longer period (see Fig. 7).

GPS IWV measured at Delft slowly decreases from 0000 UTC to 0600 UTC 17 May. At this time the cloud band passes the GPS site. The WV $T_b$ showed a more or less constant value during these 6 h, while the IR $T_b$ did not indicate the occurrence of high clouds. This implies that the water vapor density in the top of the atmosphere is more or less constant while the total amount decreases. This indicates that the lower part of the atmosphere below 600 hPa becomes drier. This decay is also seen in the relative humidity observation for Rotterdam, close to Delft (Fig. 3, top panel: the solid line). The signal is not pronounced, which is due to the fact that these relative humidity measurements, which are measured at approximately 2 m above ground, in

![Fig. 5. The (top) WV and (bottom) IR as observed by Meteosat at (a) 1400 UTC 16 May, (b) 1800 UTC 16 May, (c) 0600 UTC 17 May, and (d) 1000 UTC 17 May. Dark gray tones indicate high $T_b$; lower $T_b$ are light gray.](image)

![Fig. 6. Time series of IWV as retrieved using GPS (solid line) together with the $T_b$ of WV (dotted squares) and IR (solid triangles) overlying the locations (top) Delft, (middle) Kootwijk, and (bottom) Westerbork. The letters (a)(d) mark the times of the image in Fig. 5; that is, (a) 1400 UTC 16 May, (b) 1800 UTC 16 May, (c) 0600 UTC 17 May, and (d) 1000 UTC 17 May.](image)

![Fig. 7. Time series of rainfall (mm h$^{-1}$) at (top) Schiphol and (bottom) Hoogeveen.](image)
general, have a diurnal cycle. The dehydration of the atmosphere below 600 hPa is also observed over the other GPS sites, except that a delay in time is observed. The GPS IWV starts decreasing a little before 0600 UTC for Kootwijk and a little after 0600 UTC for Westerbork. The decrease stops at around 1000 UTC for Kootwijk and 1100 UTC for Westerbork. At these moments, the dry intrusion sets in and the top of the atmosphere dehydrates (increase in water vapor $T_b$), while the total amount stays constant. Note that for all three sites the increase in brightness temperature is nearly the same but that the period is smaller for Delft than for the other two sites.

4. Conclusions

In this article we showed the additional information that GPS integrated water vapor contains in relation to the current Meteosat water vapor and infrared images. The fact that GPS IWV is an all-weather system and can measure with a high temporal resolution is beneficial for interpreting the (coarse) water vapor distribution in a vertical column together with the time series of Meteosat WV/IR brightness temperatures. The GPS IWV system determines the total zenith water vapor column overlying a GPS site, while WV $T_b$ is related to the amount of radiance emitted from a layer of water vapor of unknown depth. The combination of this information gives a rough indication of the distribution of the water vapor in this column. Moreover, the temporal changes of GPS IWV and WV $T_b$ reveal the change in vertical distribution of WV. The case presented here shows that the amount and temporal changes of water vapor in a convective system with Cbs can be estimated by GPS, which, together with information on flow, gives insight into the possibility of the occurrence of a weather situation with heavy rainfall.

REFERENCES