



GPS-based PWV for precipitation forecasting and its application to a typhoon event

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ABSTRACT

The temporal variability of precipitable water vapour (PWV) derived from Global Navigation Satellite System (GNSS) observations can be used to forecast precipitation events. A number of case studies of precipitation events have been analysed in Zhejiang Province, and a forecasting method for precipitation events was proposed. The PWV time series retrieved from the Global Positioning System (GPS) observations was processed by using a least-squares fitting method, so as to obtain the line tendency of ascents and descents over PWV. The increment of PWV for a short time (two to six hours) and PWV slope for a longer time (a few hours to more than ten hours) during the PWV ascending period are considered as predictive factors with which to forecast the precipitation event. The numerical results show that about 80%–90% of precipitation events and more than 90% of heavy rain events can be forecasted two to six hours in advance of the precipitation event based on the proposed method. 5-minute PWV data derived from GPS observations based on real-time precise point positioning (RT-PPP) were used for the typhoon event that passed over Zhejiang Province between 10 and 12 July, 2015. A good result was acquired using the proposed method and about 74% of precipitation events were predicted at some ten to thirty minutes earlier than their onset with a false alarm rate of 18%. This study shows that the GPS-based PWV was promising for short-term and now-casting precipitation forecasting.

1. Introduction

The water vapour content in the low atmosphere cycle is one of the most important parameters for water vapour monitoring and precipitation forecasting, but its rapid rate of change makes it difficult to monitor (Li et al., 2012); however, sufficient water vapour content is a prerequisite for any precipitation event. A large-scale and successive or concentrative precipitation event would lead to flooding, with risk to lives and livelihoods. In addition, precipitation is also one of the most important water sources for many regions. Therefore, a short-term precipitation monitoring and forecasting service, especially for high-intensity rainfall, is of vital significance for reducing risk to life and property, and increasing the utilisation of water resources (Chiang et al., 2009).

Traditional water vapour observation methods cannot be applied to the monitoring and forecasting of precipitation events owing to the limitations of their tempo-spatial resolution. For example, the distance between adjacent radiosonde stations is about 200–300 km, and the

sounding balloon is launched two or four times per day; such spatial and temporal resolutions are not enough for the monitoring and forecasting needed at the meso- or small-scales. Microwave radiometers are very expensive and cannot work on rainy days, so, their use is not extensive in practice (Bevis et al., 1994; Baker et al., 2001). Since Bevis et al. (1992) proposed the concept of GPS meteorology, ground-based GNSS has gradually become one of the most important means with which to acquire the integrated water vapour (IWV) data and analyse precipitation events. The Global Navigation Satellite System (GNSS) has undergone more than twenty years' development, many cities have established their own Continuously Operating Reference Station (CORS) networks. For instance, there are more than five thousand continuously operating ground-based GNSS stations evenly distributed across each province of China, which is sufficient to meet the requirement for water vapour analysis at meso- and small-scales.

Currently, GNSS-based PWV is mainly derived from two techniques, one is the precise point positioning (PPP) technique based on non-differenced observation; the other is the baseline or network

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calculation based on double-differenced observations (Zumberge et al., 1997; Dow et al., 2009; Caissy et al., 2012). Compared to the latter, the PPP technique can be used without introducing the assisted station with a baseline longer than 500 km, the resolution of a single station based on the PPP technique is both effective and time-efficient. A series of studies have shown that, whether it is based on non-differenced or double-differenced observations, the accuracy of PWV derived from GPS are comparable in precision with classical measurements from water vapour radiometers, radiosondes, or radar (Bevis et al., 1992; Rocken et al., 1995; Seco et al., 2012; Ortiz de Galisteo et al., 2014). Li et al. (2012) used ZTD, and increments therein, for the rainstorm now-casting. Benevides et al. (2015) proposed a simple algorithm with which to forecast rain in the 6 h after a significant increase in the GPS PWV at a single station.

The aim of this study is to analyse the PWV derived from the PPP technique using GPS data and relevant precipitation information, so as to explore the relationship between PWV and precipitation and provide useful information for short-term, real-time forecasting. One full year of hourly precipitation data for the experimental precipitation stations were accumulated and hourly PWV data for relevant GPS stations were processed in Zhejiang Province, China using the developed PPP software. According to the correlation between PWV and precipitation events, a novel precipitation forecasting model was proposed and also was tested using data derived from other areas. The proposed model was also used for a typhoon event based on the PWV time series derived from the RT-PPP.

2. GPS observation processing

The data-processing software used for GNSS observations includes GAMIT/GOBK and Bernese GNSS Software V5.2, which all provide the zenith troposphere delay (ZTD) above the station with a high accuracy. The ZTD is obtained using the mapping function which projects the slant path delay into the zenith direction at the station, which generally consists of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The main contribution to ZTD (about 90% of ZTD at sea level), which is determined by the altitude and surface pressure of the station, is called ZHD, and can be obtained precisely using the empirical model. Another contribution is ZWD (about 2–20% of ZTD), which takes place at different signal frequencies and is mainly influenced by the dipolar moment of water vapour molecules that lead to a delay in signal propagation. In addition, a few hours before the precipitation event, the signal propagation is also affected by the zenith delay of hydrometeors (ZHMD, about 0–3% of ZTD), which exhibits a relative high variability before, and after, precipitation (Solheim et al., 1999; Hajj et al., 2002; Brenot et al., 2006).

ZHD above the station can be calculated precisely using the observed surface pressure based on the Saastamoinen model (Saastamoinen, 1972):

$$ZHD = \frac{0.002277 \cdot P_s}{1 - 0.00266 \cdot \cos(2\varphi) - 0.00028 \cdot H} \quad (1)$$

Where P_s is the surface pressure (unit: hPa), φ is the latitude, and H represents geodetic height (unit: km). ZHD is a function of surface pressure after the station is determined. An increment of 1 hPa surface pressure only causes about 0.2 mm of ZHD error (Tregoning and Her- ring, 2006).

Usually, an accurate ZWD is extracted from ZTD by subtracting the ZHD, and the PWV is then obtained by conversion from ZWD (Bevis et al., 1994).

$$PWV = \frac{10^6}{\left(k'_2 + \frac{k_3}{T_m}\right) \cdot R_v \cdot \rho} \cdot ZWD \quad (2)$$

Where, $k'_2 = 16.48K \cdot hPa^{-1}$ and $k_3 = (3.776 \pm 0.014) \times 10^5 K^2 \cdot hPa^{-1}$ are constants, $R_v = 461(J \cdot kg^{-1} \cdot K^{-1})$ represents the ideal gas constant for water vapour, ρ is the density of the water vapour density, T_m is a mean temperature of the atmospheric column. Usually, T_m is calculated using the observed surface temperature based on the empirical model constrained by sufficient radiosonde or reanalysis data (i.e. ECMWF data) (Bevis et al., 1994). In our study, the value of T_m is estimated according to the empirical model established for the east of China using a yearly set of radiosondes located in the east of China (20° – 50° N, 100° – 130° E).

PWV is the total water vapour content of a unit area in the atmospheric column (unit: kg/m^2), which is equal to the liquid water content at the same height (unit: mm), and is related to the integrated wet profile above the station (Benevides et al., 2015). After the ZWD above the station is determined, PWV is only correlated with T_m : an experiment has been implemented by Bevis to validate that the error caused by Eq. (2) is 1%–2% (Bevis et al., 1994). Brenot et al. (2006) also found that the PWV error is less than 0.3 mm (based on Eq. (2)), which is more accurate than the PWV derived from direct meteorological observations.

3. Experimental data and processing

3.1. Introduction and selection of data

Zhejiang Province is located in the eastern coastal region of China, and has a sub-tropical monsoon climate and meteorological disasters often take place such as typhoons, severe rain, droughts, and floods. This area is characterised by its large spatial-temporal variability of water vapour and spatial precipitation heterogeneity, the annual mean precipitation ranges from 980 to 2000 mm and mainly occurs in summer (May to July). In our study, the GPS and meteorological data were collected from a CORS network constituted by 86 grounded-based stations evenly distributed across Zhejiang Province. Hourly precipitation information about typhoon CHAN-HOM 1509 was provided by Water Conservancy Bureau of Zhejiang. In addition, one GNSS station with meteorological data and one precipitation station in Wuhan City, Hubei Province were also selected (data provided by International GNSS Service (IGS) and Wuhan Municipal Water Affairs Bureau, respectively).

As for obtaining the PWV data, GPS observations were processed by using the newly-developed PPP software, and then accurate PWV data were obtained by combining the observed meteorological data. In spite of the dense GNSS station coverage in Zhejiang Province, unfortunately, the ground-based GPS stations around radiosonde 58457 (green rectangle, Fig. 1(b)) are not equipped with meteorological sensors, so an accurate PWV measure is unavailable. Therefore, one radiosonde (station 45004) and the corresponding GPS station HKSC in the Hong Kong Satellite Positioning Reference Station Network (SatRef) are selected to compare the accuracy of PWV derived from the developed PPP software, as shown by the green rectangle and black triangle in Fig. 1(a), respectively.

Fig. 1 illustrates the geographical distribution of the GNSS stations (black triangles), jointly with the tracking path of typhoon CHAN-HOM 1509 and it also gives the location of the radiosonde station (green rectangles) as well as the collocated precipitation station (red circles) used in our study. Six GPS stations with the nearby precipitation stations were selected for revealing the relationship between PWV and precipitation, in which the elevations vary from 28 m at WUHN to 170 m at ZJXC. The 5-minutely PWV of three GNSS stations (JIAX, ZHOS, and YYAO) were considered for this forecast of real-time precipitation, based on the RT-PPP, during a typhoon event from 10 to 12 July, 2015.

3.2. Accuracy analysis of PPP ZTD

It is reported that the internal accuracy of ZTD derived from PPP module in Bernese GNSS Software (v5.2) reaches ± 1.3 mm, with the mean bias being less than 7 mm (Kyoung Min, 2014; Wilgan, 2015). In addition, the external accuracy of estimated ZTD parameter by GAMIT

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