Assimilation of GPS Data for Short-Range Precipitation Forecast

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Abstract

Atmospheric remote sensing making use of radio signals transmitted from Global Positioning Systems (GPS) has evolved as prominent atmospheric measurement techniques over the past decade. There are two primary methods for GPS atmospheric remote sensing. The first technique, known as ground-based GPS Meteorology, measures the integrated water vapor along the line of sight between the ground-based GPS receiver and the GPS satellites. The second technique, known as the space-based GPS Meteorology, or the GPS radio occultation technique, provides vertical profiles of atmospheric bending angles and index of refraction, from which profiles of atmospheric temperature and water vapor can be derived. This paper will (i) describe the basic measurement technique of ground-based GPS water vapor sensing, (ii) review recent work on the assimilation of ground-based GPS water vapor measurements on short-range precipitation forecasts, and (iii) discuss possible future applications of ground-based GPS water vapor sensing in the Taiwan area.

1. Ground-based GPS meteorology

The delay in the propagation of radio signals from a GPS satellite to a ground-based GPS receiver introduced by water vapor is referred to as the "wet delay" and is nearly proportional to the quantity of vapor integrated along the signal path. A ground-based GPS receiver measures the carrier phase of radio signals transmitted by GPS satellites. If the position of the receiver is accurately known and the effects of ionosphere are accounted for, delays caused by the electronically neutral atmosphere can be estimated. The delays can be divided into two parts: a hydrostatic delay and a wet delay. With surface pressure measurements, the hydrostatic delay can be estimated fairly accurately. Businger et al. (1996) showed that the zenith hydrostatic delay could be estimated to better than 1 mm, given surface pressure measurements accurate to 0.3 mb or better. The use of ground-based GPS receiver to estimate integrated precipitable water (PW) is a fairly mature technique. Experiments have shown that zenith integrated PW can be obtained with better than 2 mm absolute accuracy (e.g., Bevis et al., 1992; Rocken et al., 1993, 1995, 1997).

The integrated amount of water vapor along the path of an individual satellite to a receiver is called slant water (SW) (Ware et al., 1997; Braun et al. 2001). Braun et al. (2003) performed a comparison of line-of-sight SW measurement from a ground-based GPS receiver and a microwave radiometer during 47 days of observations in May and June 2000. The linear correlation of the observations between the two instruments is 0.99 with a rms difference of GPS water vapor to a linear fit of the microwave radiometer of 1.3 mm. With these encouraging results, MacDonald et al. (2002) proposed to deploy a dense network of GPS receivers for three-dimensional water vapor sensing over the U.S. Japan has established a GPS meteorology project building upon their GPS Earth Observation NETwork (GEONET), which is composed of 1000 ground-based GPS receivers, for water vapor sensing, since 1997.

2. The impact of ground-based GPS water vapor data on precipitation prediction

Kuo et al. (1993) first demonstrated the potential value of ground-based PW data. They showed that the assimilation of PW into a mesoscale model was effective in recovering the vertical structure of water vapor. Moreover, the improved moisture analysis due to PW assimilation led to improved short-range precipitation forecasts. Zou and Kuo (1996) showed that the PW data could provide powerful constraints on rainfall assimilation, and significantly improve its performance and its impact on subsequent rainfall forecasts. Guo et al. (2000) studied a 1996 squall line case in central U.S., and showed that the assimilation of ground-based GPS PW data had a significant impact on short-range (3 h) rainfall prediction. With an objective to assess the added value of line-of-sight SW data, Ha et al. (2003) performed a series of observing system simulation experiments using MM5 and its 4D-Var systems. They showed that the assimilation of SW is superior to the assimilation of PW in recovering the three-dimensional water vapor structure between the GPS stations. The improved moisture analysis also led to improved short-range precipitation forecast both in terms of rainfall distribution and intensity.

More recently, Iwabuchi et al (2005) performed assimilation of ground-based GPS PW data during BAMEX 2003 using the WRF 3D-Var system, and found that the assimilation of GPS PW data were able to improve WRF precipitation forecasts for mesoscale convective systems. Here we showed two cases from their study. In the first case, which took place on 24 May 2003, the 4-km WRF model initialized with the operational ETA 40-km analysis did not capture a mesoscale convective system that was producing significant rainfall over the Oklahoma-Kansas border. The assimilation of hourly ground-based GPS PW data together with the wind profiler data was very effective in capturing the mesoscale convective system and in enhancing the precipitation over the Oklahoma-Kansas border.

For the second case, the 4-km WRF model initialized with the 40-km ETA analysis produced an erroneous mesoscale convective system over southern Oklahoma. With the assimilation of hourly GPS PW and wind profiler data, the 4-km WRF model was able to weaken and subsequently dissipate the erroneous convective system. Additional experiments showed that the assimilation of GPS PW data in itself was able to improve precipitation forecast. However, the assimilation of both GPS PW and wind profiler data produced the best results.

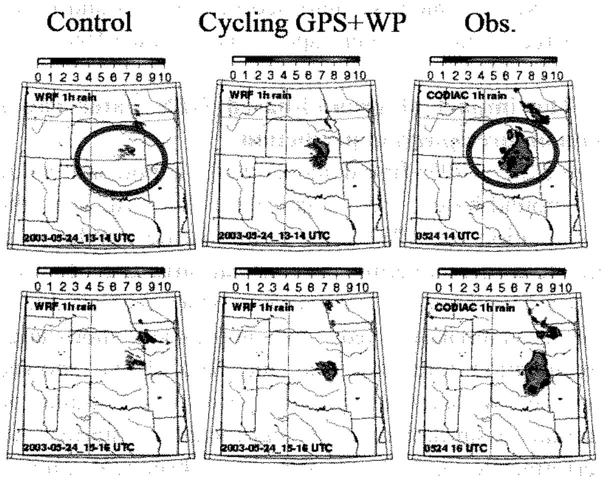

Fig. 1. Hourly precipitation from 4-km WRF and observation. Left panels are rainfall forecasts from control run initialized with ETA 40-km analysis. The middle panels are WRF forecasts with the assimilation of hourly GPS PW and wind profiler data. The right panels are observed hourly rainfall. The top panels are valid at 1400 UTC on 24 May 2003 (2 hour after assimilation cycle), and the bottom panels are valid at 1600 UTC 24 May 2003 (4 hour after assimilation cycle). [From Iwabuchi et al. 2005.]

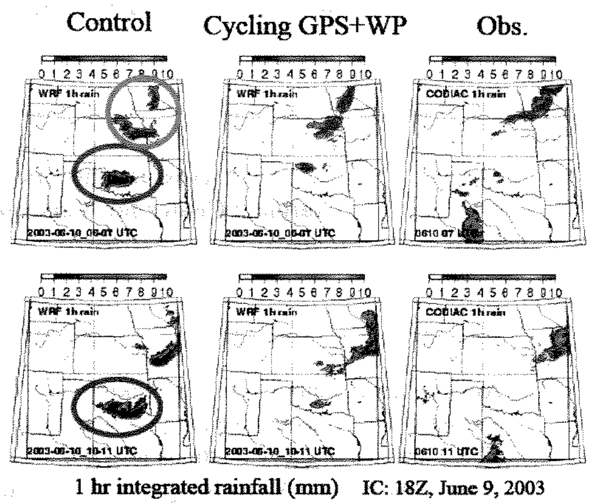

Fig. 2. Similar to Fig. 1, except the top panels are for 0700 UTC 10 June 2003 (7 hour after assimilation cycle), and the bottom panels are for 1100 UTC 10 June 2003 (11 hour after assimilation cycle). [From Iwabuchi et al. 2005.]

3. The 10 July 2004 Beijing flood case

On 10 July 2004, a severe local heavy rainfall event took place in the metropolitan area of Beijing. Six-hour accumulated rainfall ending at 1200 UTC 10 July exceeded 125 mm. Many parts of the Beijing City were flooded, causing severe traffic jam during the afternoon rush hour. Satellite imagery showed that this heavy rainfall event was associated with the formation and development of a meso-β-scale (50 km x 120km) convective system. Operational NWP forecast at the Beijing Meteorological Bureau (BMB) based on the 15-km MM5 failed to provide useful guidance on this heavy rainfall event. In this study we performed numerical experiments using the WRF model at cloud-resolving (4 km) resolution. We found that the NCEP Global Forecast System (GFS) analysis at 1200 UTC 9 July was too dry in the boundary layer and too stable over the Beijing area, even though the large-scale aspects of the GFS analysis was essentially correct. As a result, the 4-km WRF model initialized with the GFS analysis failed to produce any precipitation over the Beijing City (Exp. GFS). The enhancement of the GFS analysis using local upper-air, surface, and automatic weather station (AWS) data provided by BMB through the WRF 3D-Var system improved the analysis considerably (Exp. BMB). Moderate amount of precipitation was predicted over the Beijing City. The best result was obtained when the PW measurements from the eight BMB ground-based GPS stations were assimilated together with upper-air, surface and AWS data (Exp. BMB+GPS). The BMB GPS stations were located about 50 km to the southwest of the Beijing City, and provided valuable information on moisture upstream of convective development. The GPS PW data significantly improved the low-level moisture analysis, and increased the convective available potential energy (CAPE) over the Beijing area. This allows the mesoscale convective system to develop and migrate into the Beijing metropolitan area. Table 1 shows the comparison CAPE and CIN (convective inhibition) for the three experiments.

We compared the PW estimated from the Beijing (54511) radiosonde observations with that estimated by a ground-based GPS station (YSDD), which was located about 30 km away from the radiosonde station, and found that the Beijing radiosonde consistently underestimated the PW. For the July 10, 2004 flood case, this can be as large as 10~15% at times (see Fig. 3).

Table 1. Comparison of CAPE and CIN for the initial condition of the three experiments at a location near the Beijing radiosonde station valid at 1200 UTC 9 July 2004. Unites are Joul per kilogram.

	CAPE	CIN
GFS	24	-362
BMB	436	-232
BMB+GPS	756	-183

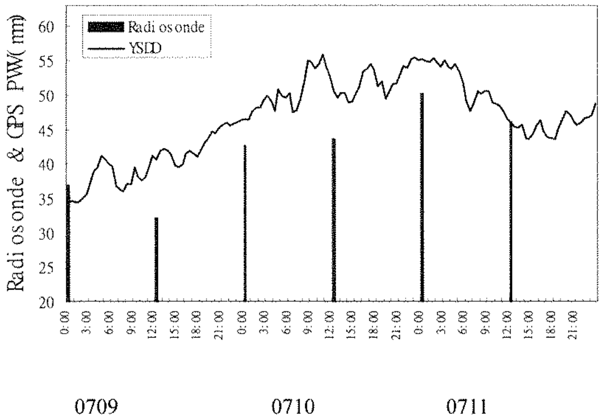

Fig. 3. Comparison of PW estimated by Beijing radiosonde (54511) and ground-based GPS at station YSDD during the three-day period of 9-11 July 2004.

Comparison of PW estimated by a International GPS Service (IGS) station, which is located about 50 km away from the Beijing radiosonde station, over the month of August 2004 indicated that the Beijing radiosonde (which is a Chinese made GTS1 system) gave a persistently lower value (dry bias about 4 mm) (See Fig. 4). Recently, Nakamura et al. (2004) performed a comparison of RS-80A radiosonde system with ground-based GPS estimated PW, and found systematic dry bias of radiosonde PW observation on the order of 3~4 mm. A comparison of GTS1 and RS-80A indicated that GTS1 tends to give lower relative humidity below 500 mb. These results showed that when model was initialized with only the radiosonde observations, the moisture content in the lower troposphere can be significantly under-estimated. As a result, convective system could not form and develop in a timely manner.

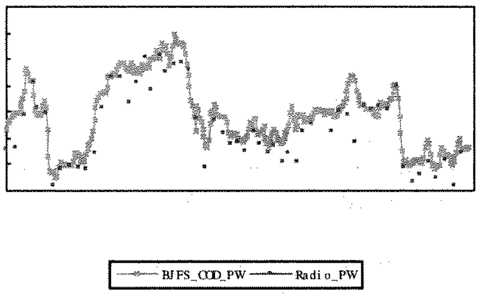

Fig. 4. Comparison of GPS PW with radiosonde PW at the Beijing radiosoonde stations for the month of August 2004. [Figure provided by Y. L. Chu, BMB]

5. Application of ground-based GPS in Taiwan

The Central Weather Bureau is in the process of establishing a network of ~150 ground-based GPS stations for seismology purposes. It would be highly desirable to augment the network with PW and SW sensing capability. The real-time high-resolution water vapor information from such a network can be assimilated into the CWB regional analysis and forecast system for short-term precipitation prediction and flood mitigation.

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