THE DESIGN AND APPLICATION OF NETWORK OF GROUND-BASED GPS WATER VAPOR MONITORING STATIONS TO IMPROVE PRECIPITATION PREDICTION IN THE GREATER BEIJING METROPOLITAN AREA

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ABSTRACT:

In the Greater Beijing metropolitan area of North China (Beijing-Tianjin-Hebei areas), a mixed single- and dual-frequency ground-based GPS water vapor monitoring network is established to support operational weather forecasting and scientific research. In this paper we briefly summarize the progress of this collaborative operational GPS-Met network on network design, retrieval methods for precipitable water vapor content, slant path water vapor content, and 3D-tomography. In particular, we discuss the results of the pilot experiment using the mixed single- and dual-frequency GPS network over the area sensitive to sever weather events in the vicinity of Beijing, and the impact of retrieved atmospheric water vapor on precipitation forecasts and short-rang numerical weather prediction. Results show that the mixed network with a station separation of 5-10 km can provide accurate retrieval of single-frequency GPS observations, meeting the practical requirement after correcting the ionosphere-delay error with a high-resolution ionosphere-delay error correction model. Moreover, with specific purpose to assess the impact of GPS water vapor monitoring on precipitation prediction, typical severe rainfall weather events are analyzed in detail using GPS-Met observations, and numerical forecasting experiments with MM5/WRF modeling and data assimilation system. Analyses indicated that precipitation episode and hourly rainfall intensity are associated with a sharp increase of PW followed by a sharp decline in GPS/PWV, and the prediction of the timing, location, and intensity of two heavy rainfall events are significantly improved with the assimilation of the ground-based GPS precipitable water vapor data at the initial time.

1. INTRODUCTION

Remote sensing of atmospheric water vapour with the ground-based receivers of Global Positioning System (GPS) is a new technique developed since 1990s. The GPS receivers provide an estimate of total integrated water vapour along the ray path because the GPS satellite radio signals are slowed by the Earth's atmosphere, which results in a delay in the arrival time of the transmitted signal from that expected if there are no intervening media (Bevis, et al. 1992, 1994; Rocken, et al. 1993). Near real-time total precipitable water vapour (PWV) is available at each site every 15-minute based continuous observations of ground-base receivers, and then could provide high time-resolution monitoring information of atmospheric water vapour (Rocken et al. 1997).

Water vapour is one of the most significant constituents of the atmosphere since it is the means by which moisture and latent heat are transported to produce mesoscale weather events. And remote sensing of water vapour with GPS receivers is superior to other traditional measurement methods either on temporal resolution or accuracy. Hence, exploiting the roles of regional fine-resolution water vapour data retrieved from GPS is crucial to improve forecasting skill closely related to weather events, especially on urban environment, heavy rainfall, hail, and waterlogging and flood.

In the Greater Beijing metropolitan area of North China (Beijing-Tianjin-Hebei areas), a mixed single- and dual-frequency ground-based GPS water vapor monitoring network, with 8 single-frequency stations and 38 dual-frequency stations, has been established and carried out to support operational weather forecasting and scientific research. This operational GPS-Met network (hereafter, the BJ-GPS-Met network) is an important result from several jointed projects by close collaboration with the Institute of Urban Meteorology of China Meteorological Administration, the National Center for Atmospheric Research of U.S.A, the Beijing Information Resources Management Center, the Tianjin Meteorological Bureau and the Hebei Meteorological Bureau. Based on the BJ-GPS-Met network, many researches and applications have been conducted successfully in recent years. For example, Zhang Chaolin et al. (2003, 2005, 2006a), Chu et al. (2007), and Chen et al. (2008) evaluated the impacts of retrieved atmospheric water vapour on weather forecasts and short-rang numerical weather prediction (NWP). These results show that the assimilation of GPS/PW observations with the 3 dimension variational data assimilation method (3DVAR) significantly improves the moisture analysis of the initial condition of the numerical forecasting model, and subsequently improves the prediction of location, intensity and evolution of heavy rainfall events. Braun et al. (2004) conducted moisture monitoring experiments in the planetary boundary layer using ground-based GPS stations, Chu et al. (2006) compared water vapor measurements among radiosonde soundings, GPS and WVR, and found a dry bias in the radiosonde soundings of Beijing. Xie et al. (2006) conducted atmospheric water vapor experiment

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with the mixed single- and dual-frequency ground-based GPS receivers and described data processing method with Bernese and GAMIT software, Zhang Jingjiang et al. (2005, 2006, 2007) discussed the remote automatic transfer/control system for data collection. Liu et al. (2006) compared MODIS atmospheric water vapour retrieval with the results derived from GPS, and studied the application of MODIS atmospheric water vapour retrieval to InSAR atmospheric correction (Liu et al. 2007). Furthermore, Liang et al. (2003), Li et al. (2007) and Chu et al. (2007) conducted in-depth diagnostic investigations on heavy rainfall events. In this paper the collaborative operational BJ-GPS-Met network is briefly introduced, key results on pilot experiment from this network, and applications to improve precipitation prediction are presented in detail. In Section 2, we describe the network design, operational application of retrieval products such as PWV, slant path water vapor content (SWV), and 3D-tomography. In Section 3, we discuss major results of the pilot experiment using the mixed single- and dual-frequency ground-based GPS receivers. The applications to improve precipitation prediction are summarized in Section 4, and concluding remarks are presented in Section 5.

2. DESIGN AND APPLICATIONS OF THE GROUND-BASED GPS WATER VAPOR MONITORING NETWORK IN THE GREATER BEIJING METROPOLITAN AREA

2.1 Network design and its distribution

The mixed single- and dual-frequency BJ-GPS-Met network is set up according the following principles: 1) To meet the requirement of monitoring and investigating the atmospheric water vapour continuous evolution on the fine-resolution scale (stations spaced 30-50 km distance apart), 2) To share and integrate the sub-networks between meteorological bureaus and governments effectively, and 3) To set up intense GPS-Met sub-network (spaced 5-10km) over two regions that are sensitive to sever weather events within Beijing for water vapour tomography using the mixed single- and dual-frequency ground-based receivers. Currently, the BJ-GPS-Met network is composed of 38 dual-frequency GPS stations and 8 single-frequency GPS stations, and has been used to support operational weather forecasting and scientific research (see Figure 1). Figure 2 shows that the windward areas of the mountains are climatically rainy, and leeward areas are generally drier in Beijing, and two major precipitation centres (based on ten year climatology) are located over the southwest part (Fanshang county) and north part (Huairou county) of Beijing. The two dense mixed sub-networks of GPS-Met highlighted in Figure 1 are placed over these regions with a goal to help severe weather forecasting. Moreover, the design considerations for the southwest dense GPS-Met sub-network within the Fanshang county include two aspects. Firstly, the underlying surface and topography are relatively simple there, and suitable for conducting tomography experiments of atmospheric water vapour. Secondly, this region is climatically the upstream area of water vapour transportation for Beijing, and therefore important to operational short-range NWP over Beijing downtown.

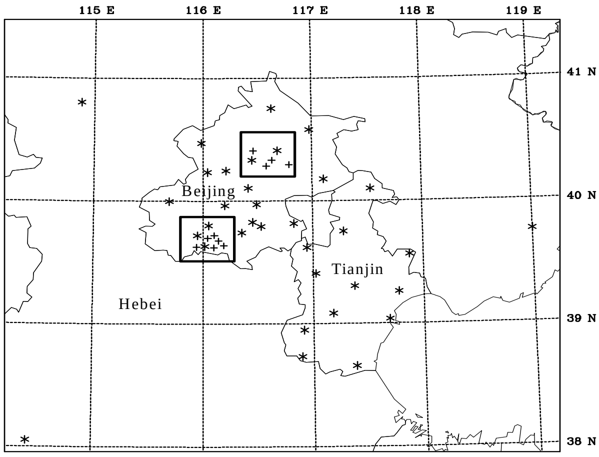


Fig. 1. Distribution of the BJ-GPS-Met network. Single- and dual- frequency GPS stations denote with asterisk and plus sign, respectively. Two bold squares highlight the dense observation sub-networks over the sensitive areas to sever weather events (especially heavy rainfall) within Beijing using the mixed single- and dual-frequency ground-based GPS receivers.

The design considerations of the north dense GPS-Met sub-network within the Huairou county also include two major purposes. One is is to complement the southwest dense GPS-Met sub-network to enhance the monitoring ability for severe convective weather events in the rainfall season of Beijing. Anther one is to examine the transport, accumulation, and evolution of atmospheric water vapour in details with comparison of data from the upstream sub-network in the Fanshang county.

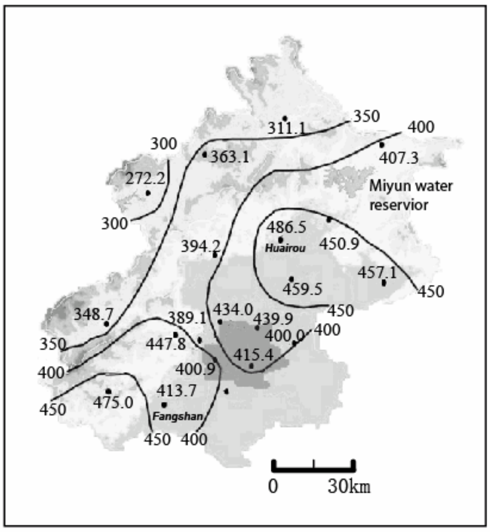
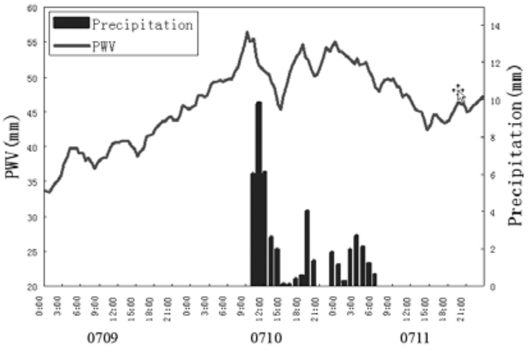


Fig. 2. Distribution of ten-year climatology of summer (June-August) precipitation (mm) in the Beijing area for 1991-2000. The light shades represent high elevations and light-gray for low elevations, and dark-gray areas represent Beijing city downtown.

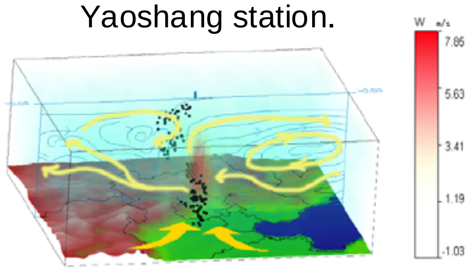
As shown in Fig. 1, the single-frequency GPS-Met stations are surrounded with proportionally spaced dual-frequency stations. The mixed station distribution is to meet the practical requirement of retrieval accuracy of the single-frequency GPS observation after correcting the ionosphere-delay error with the high resolution ionosphere-delay error correction model based on dual-frequency ground-based GPS receivers.

2.2 Operational Applications in weather forecasting of bureaus within the Beijing-Tianjin-Hebei areas

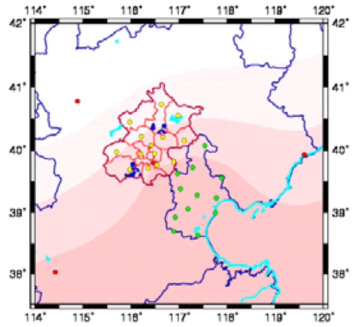
The BJ-GPS-Met network consists of five systems (Zhang Chaolin, 2006b), including: 1) monitoring system of ground-based GPS receivers and surface meteorological instruments for atmospheric temperature, relative humidity and pressure elements, 2) remote automatic transfer/control system with GPRS/CDMA wireless communication technology, 3) the pre-processing, analysis, and retrieval system for GPS data, 4) WEB-GIS system for delivering and servicing operational products, 5) data assimilation system for NWP. These five systems include nine key techniques: (a) remote transfer/control method on GPS data (Zhang Jingjiang et al. 2005, 2006, 2007), (b) data processing scheme (Xie et al. 2006), (c) ionosphere-delay error correction on mixed GPS-Met network (Rocken et al. 2000), (d) PWV retrieval (Bevis, et al. 1992, 1994; Rocken et al. 1993), (e) SWV retrieval (Ware et al. 1997), (f) multi-path effect correction (Braun, 2004b), (g) tomography application (Braun, 1999) (h) data assimilation method in NWP model (Zhang Chaolin et al. 2003, 2005), and (i) WEB-GIS deliver method. The BJ-GPS-Met network has provided an important operational demonstration on how to design a regional mixed single- and dual-frequency GPS-Met network, to apply the retrieval data to operational weather forecasting.



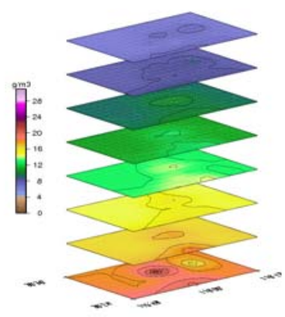
Change of PWV (black curve) and hourly accumulated rainfall amount time during the period from 9 to 11 of July at Yaoshang station.



operational application to short-rang NWP with the 3DVAR method



PWV at 200608151230 (BJT)



tomography products

List of near real-time GPS operational products

Description	Update	Format	Station/region
Atmospheric pressure at sea surface level	30 min	Table list and 24h time serial chart for each station	each station
Surface temeprature	30 min	Table list and 24h time serial chart for each station	each station
Surface relative humidity	30 min	Table list and Table list and 24h time serial chart for each station	each station
PWV at the zenith direction	30 min	24h time serial chart for each station	each station
PWV at the zenith direction	30 min	2D chart for whole region	region
Tomography product	15 min	3D chart for whole region	region

Fig. 3. Near real-time operational products of the mixed GPS network in the Greater Beijing metropolitan areas.

Many operational products have been widely used daily by meteorologists after the BJ-GPS-Met network became operational (see Fig. 3). For operational forecast applications, PWV and SWV retrievals are available at each site or within the entire region every 30-minutes, and 3D tomography charts are available in shorter time interval of 15-minute. The near real-time PWV data from the BJ-GPS-Met network have been assimilated into the operational 3-hours rapid-updated cycling system (RUC, with 3km horizontal resolution) at the Beijing Meteorological Bureau eight times every day. The advanced data assimilation and forecasting RUC system, making use of real-time GPS data, will be part of an advanced operational system in support of weather forecasting for the 2008 Olympics Game. In addition, these new GPS-Met operational products make it feasible to better investigate intensity and trace of severe rainfall around the Beijing metropolitan area.

3. PILOT EXPERIMENT ON OBSERVATIONS WITH THE MIXED SINGLE- AND DUAL-FREQUENCY GROUND-BASED GPS RECEIVERS

Since the single-frequency receiver TOPCON can be upgraded into dual-frequency receiver with official software support, a pilot GPS-Met experiment on the feasibility of mixed receivers was performed in July-August 2003. In the two month experiment, each single-frequency receiver is updated to dual-frequency one. Then, the single frequency results can be validated by comparison with those under all dual-frequency receivers. Figure 4 shows the ionosphere delay correction for the pilot experiment on 25 July 2003. The good consistency between two schemes, with correlation coefficient of 0.96 and root mean square error of 3 mm, indicates that the retrieval accuracy of the single-frequency GPS observations can meet the practical requirement after correcting the ionosphere-delay error with the high resolution ionosphere-delay error correction model HiRIM (Rocken et al. 2000). Because 1 mm estimation error from total ionosphere delay only can introduce about 0.25 mm error on total atmospheric water vapour estimation along the GPS signal line, the results from this pilot experiment shows that it is reasonable for the dense sub-network to have 5-10 km station separation to support meteorological applications.

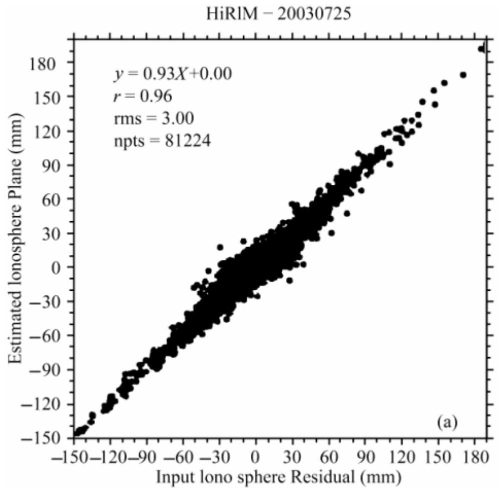
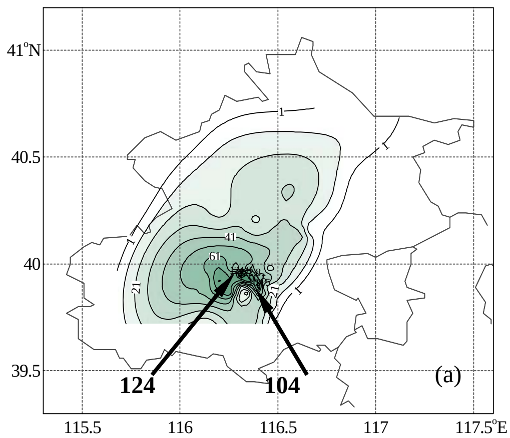


Fig. 4. Ionosphere delay correction on 25 July 2003

4. IMPACTS OF GPS WATER VAPOR OBSERVATIONS ON PRECIPITATION PREDICTION

Considerable progress has been made for assessing the impacts of GPS water vapour observations on precipitation prediction over the Beijing areas. Based on the data from the BJ-GPS-Met network, Li et al. (2004) investigated the relationship between the variation of PWV in the rainstorm events during the 2004 flood season, and found that the increase of PWV was often associated with the local weather system. While surface and upper weather systems help to transport warm and moisture air mass into the Beijing area, the PWV values always increase 13-14 hours ahead the rainstorm; However, if there is a convective system moving eastward or a developing mesoscale weather system, the values of PWV increase significantly 3-4 hours ahead the rainstorm. Heavy precipitation often occurs after the values of PWV exceeds a threshold, but there is no obvious relationship between the values of PWV, PWV increments and total rainfall amounts. Furthermore, in an effort to assess the impacts of the topographic effects and the individual components of meteorological observations (ground-based GPS PWV data, automatic and conventional meteorological observations) on the torrential rain event of 4 - 5 July, 2000 in Beijing (with 24 h accumulated precipitation reaching 240 mm), Zhang Chaolin et al. (2003, 2005, 2006a) conducted 24 h observation system experiments by using the MM5/WRF 3DVAR system and the nonhydrostatic MM5 model. Their results indicated that better initial fields and improved 24 h simulation of the severe precipitation event are achieved when the non-conventional GPS observations are directly assimilated into the initial analyses by the 3DVAR system. Building upon the supplemental information from the other meteorological observations, the ground-based GPS PWV data can be effectively assimilated into the model initial conditions and improve the precipitation forecast. By incorporating the PWV data from the ground-based GPS network into the 3DVAR analyses at the initial time, the threat scores (TS) with thresholds of 1 , 5 , 10 and 20 mm are increased by 1 % - 8 % for 6 and 24 h accumulated precipitation. Recently, Chu et al. (2007) investigated a high impact heavy rainfall Event (10 July 2004, Beijing) using the ground-based GPS PWV data. They analyzed observational PWV data and found that the temporal variation of 30-minutes PWV data are very useful for understanding the storm evolution. The GPS PWV data are also very important for the analysis and prediction of this heavy rainfall event. Their 36-h numerical experimental results, using the WRF model and its 3D-Var system with two-way two-nested grids of 12/4 km, showed that the assimilation of GPS/PW observations significantly improved the moisture analysis at the initial time, and subsequently improved the prediction of the location, intensity and evolution of this heavy rainfall event (see Figure 5).

Recently, by utilizing the operational 3-hours WRF-RUC system at Beijing Meteorological Bureau, Chen et al. (2008) assessed the influences of PWV data of the BJ-GPS-Met network on precipitation simulations of 28 rainfall events over the Beijing area in August 2006, and June-August 2007. Comparison of the forecast skills of the WRF 9-km model covering Beijing-Tianjin-Hebei areas, Chen et al. showed that almost all of the equitable threat score (ETS) and BIAS for the 6-h accumulation rainfall amounts at the different thresholds are significantly improved with the assimilation of GPS PWV data using the 3DVAR system. This is particularly robust for the first 6 hour forecast (see Fig. 6).



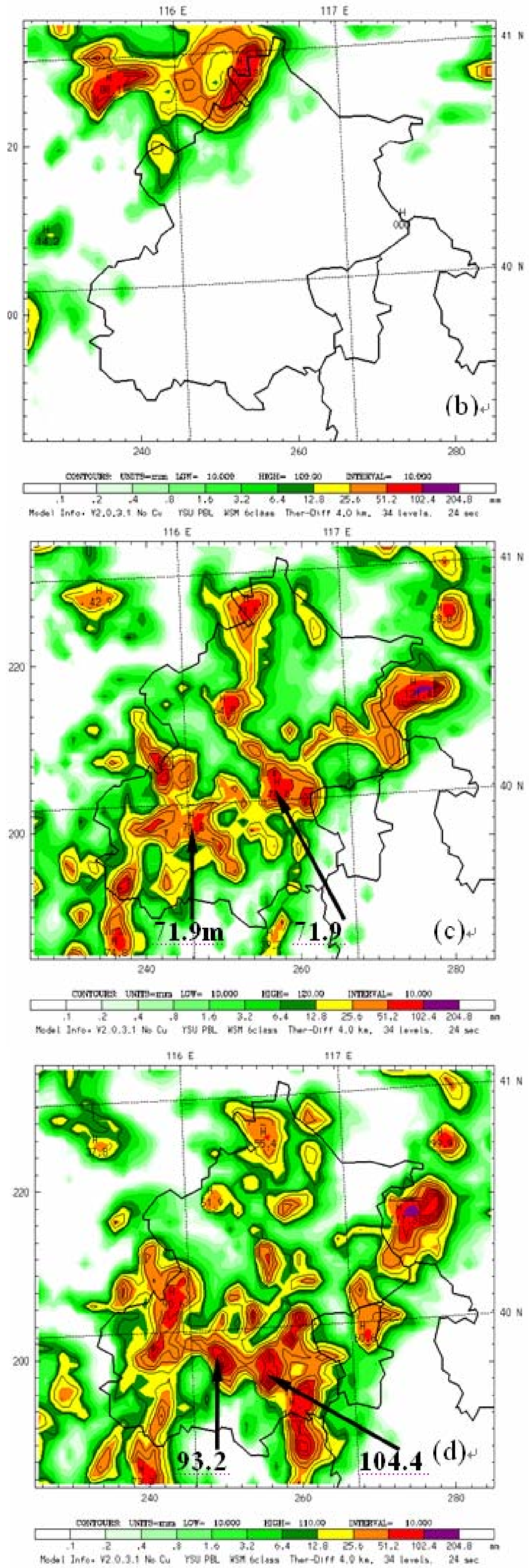


Fig. 5. The 6-hour accumulated rainfall amounts for 14- 20 LST 10 July 2004 over Beijing area. (a) observations; (b). numerical experiment with NCEP GSF data as initial condition; (c) same as (b), but assimilated routine surface and upper air meteorological observations and AWS stations; (d) Same as (c), but assimilated some PWV data of the BJ-GPS-Met network in addition to the surface, AWS, and upper air observations.

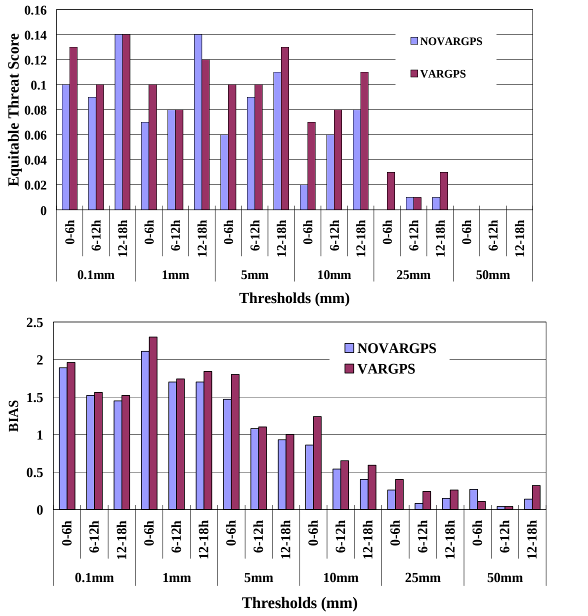


Fig. 6. The forecast skills of equitable threat score (ETS) and BIAS for the 6-h accumulated rainfall amounts at the different thresholds. VARGPS denotes experiments with the assimilation of GPS PWV data using the 3DVAR system, NOVARGPS denotes experiments without GPS PWV data assimilation. Precipitation verification scores are calculated with respect to the observations of 121 surface auto weather stations within the Beijing area.

5. SUMMARY

In this paper major advances on the mixed single- and dual-frequency ground-based GPS water vapor monitoring network in the Beijing-Tianjin-Hebei areas are summarized. It provides useful demonstration on how to establish dense regional ground-based GPS-Met network with low cost single-frequency GPS receivers, and on the application of GPS-Met data improve short-range precipitation prediction. Further investigations on single-frequency GPS measurement, tomography application and SWV data assimilation will be conducted in the future.

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