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Geodesy and Geodynamics

Meteorological applications of precipitable water vapor measurements retrieved by the national GNSS network of China☆

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ABSTRACT

In this study, the Global Navigation Satellite System (GNSS) network of China is discussed, which can be used to monitor atmospheric precipitable water vapor (PWV). By the end of 2013, the network had 952 GNSS sites, including 260 belonging to the Crustal Movement Observation Network of China (CMONOC) and 692 belonging to the China Meteorological Administration GNSS network (CMAGN). Additionally, GNSS observation collecting and data processing procedures are presented and PWV data quality control methods are investigated. PWV levels as determined by GNSS and radiosonde are compared. The results show that GNSS estimates are generally in good agreement with measurements of radiosondes and water vapor radiometers (WVR). The PWV retrieved by the national GNSS network is used in weather forecasting, assimilation of data into numerical weather prediction models, the validation of PWV estimates by radiosonde, and plum rain monitoring. The network is also used to monitor the total ionospheric electron content.

1. Introduction

Water vapor is the principal contributor to the greenhouse effect and helps in understanding the Earth's climate. Precipitable water vapor (PWV) is the amount of vertically integrated water vapor and can be expressed in g/cm^2, or as the height of an equivalent column of liquid water in centimeters. Its spatiotemporal distribution is essential in understanding the hydrological cycle; hence PWV has been adopted

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as an input variable in climatological studies at global, regional, and local scales. Moreover, it can support hydrological, biospheric, and atmospheric modeling at local and regional scales as it is widely used in energy budget and evapotranspiration studies.

The traditional technique for water vapor measurement is to launch radiosondes, normally twice a day. This method is not only expensive but also poor in both spatial coverage and temporal resolution. Temporal changes in atmospheric water vapor occur rapidly and water vapor measurements by radiosondes do not satisfy the needs of research for a variety of variation scales of atmospheric water vapor. Beginning from the 1990s, an observational technique based on the Global Navigation Satellite System (GNSS), which is sensitive to the spatial and temporal distribution of the water vapor content in the atmosphere, has made it possible to retrieve precise and continuous estimates of water vapor, with spatial density governed by the number of receivers deployed. Many GNSS-based estimates of water vapor have been compared with estimates based on radiosondes and water vapor radiometers (WVR). The results show that measurements retrieved by GNSS are generally in good agreement with estimates from radiosondes and WVR. Dai et al. [1] compared PWV estimates from GNSS, radiosondes, and WVR over North America, and their results show that the differences between any two methods are less than 2 mm. Ohtani and Naito [2] reported that the differences between radiosonde and GNSS observations of PWV in Japan are approximately 3.7 mm. Liou et al. [3] examined measurements conducted in tropical regions, where the water vapor burden is higher and less homogeneous. They showed that the difference between estimates by GNSS and WVR is approximately 2.2 mm. Many studies [4–6] show that the differences in PWV between WVR and GNSS are less than those between radiosonde and GNSS.

In recent years, the applications of GNSS-based estimates of PWV have focused on the following aspects: (1) validating PWV measurements by radiosonde and satellite remote sensing; and PWV estimates by numerical weather prediction models; (2) climate change research; (3) weather forecasting; and (4) PWV measurement assimilation in numerical weather prediction models. In this study, we investigate the processing methods in GNSS observations based on the Crustal Movement Observation Network of China (CMONOC), quality control procedures for PWV data, and the meteorological application of PWV measurements.

2. GNSS/MET observation network

By the end of 2013, China Meteorological Administration (CMA) had built 952 GNSS sites, including 260 that belong to CMONOC, and 692 that belong to the China Meteorological Administration GNSS network (CMAGN). As shown in Figs. 1 and 2, CMONOC sites are uniformly distributed throughout the country, while CMAGN sites are located mainly over the south, east, north, and central parts of China, as well as over Jilin province in northeast China. The receivers used include the brands Trimble, Leica, Topacon, Ashtech, and Javad. The GNSS/MET sites were constructed in the following way:

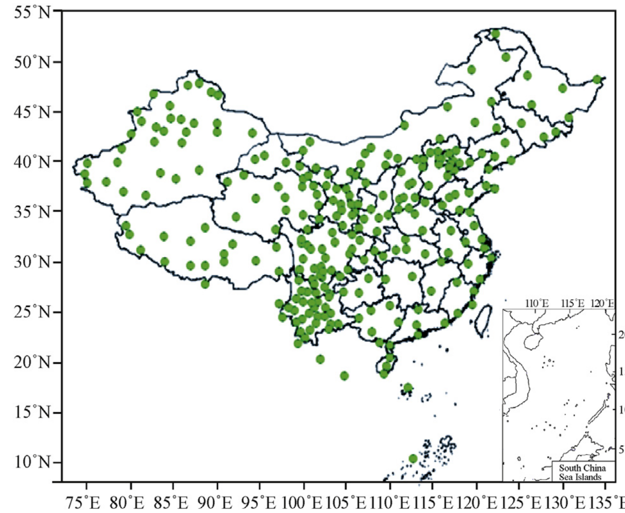

Fig. 1 – Geographical location of CMONOC GNSS sites.

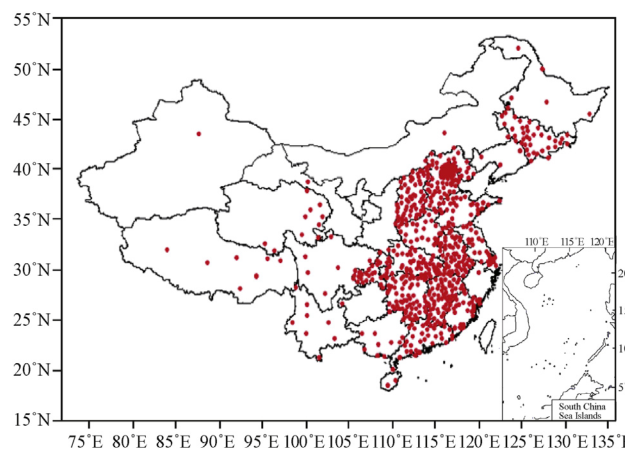

Fig. 2 – Geographical location of CMA GNSS sites.

(1) financed by CMA (for instance, the Beijing-Tianjin-Hebei trial network and early warning system);
(2) sino-foreign cooperative construction (cooperation between China and Japan JICA project, with 26 Trimble receivers);
(3) co-construction between CMA and other ministries (CMONOC: 260 Trimble receivers);
(4) co-construction between a local meteorological bureau and other departments (such as comprehensive GNSS Application Network and Local Meteorological Bureau; Bureau of Surveying and Mapping; Seismological Bureau; Land and Resources Bureau; Planning Bureau).

Observation data measured by the CMONOC network are collected by the China Earthquake Administration. The data is unzipped and organized before sending to the Meteorological Observation Center server through a private network for consistent processing. Observation data derived by CMAGN are compressed into packages and uploaded to the National Meteorological Information Center, and eventually sent to the Meteorological Observation Center for decompressing and processing (Fig. 3).

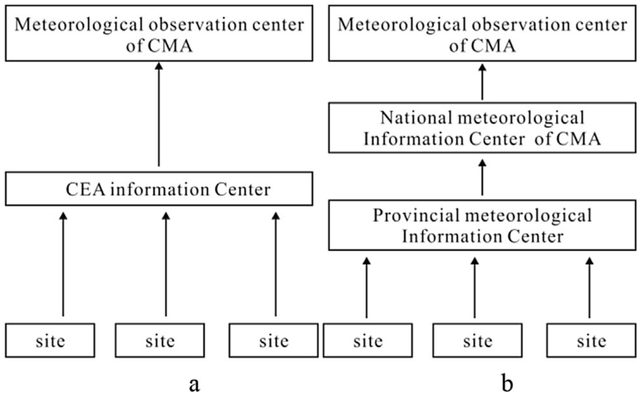

Fig. 3 – Data collection and transmission flow: a. CMONOC network b. sites self-built by CMA.

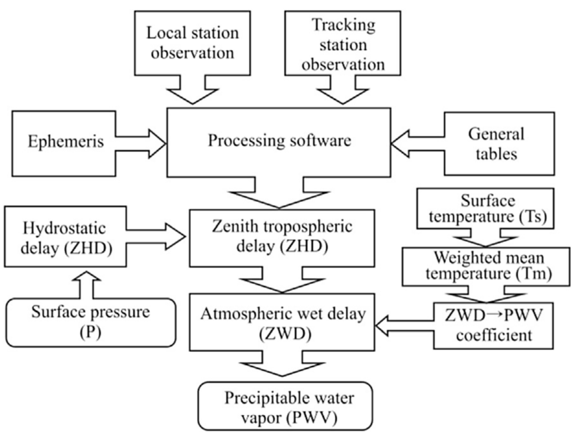

Fig. 4 – GNSS observation processing flow chart.

The commonly used processing softwares are GAMIT and BERNESE, and the data processing flow is illustrated in Fig. 4. A network processing method is used whereby the sites are divided into groups of 20. The zenith tropospheric delay and water vapor content are estimated hourly using the sliding window method, with the window set to 12 h. The PWV data from every station are calculated and sent to the Earthquake Administration Data Center, National Meteorological Information Center, CMA Numerical Prediction Center, and CMA Public Meteorological Service Center. Moreover, the data are published by the CMA Meteorological Observation Center for researchers at universities and other organizations.

3. Application of GNSS/MET observations

3.1. *Primary products*

Atmospheric water vapor outputs include hourly national water vapor distribution charts (as shown in Fig. 5) and single-station water vapor change charts (as shown in Fig. 6). The following quality control algorithms are used in the data processing :

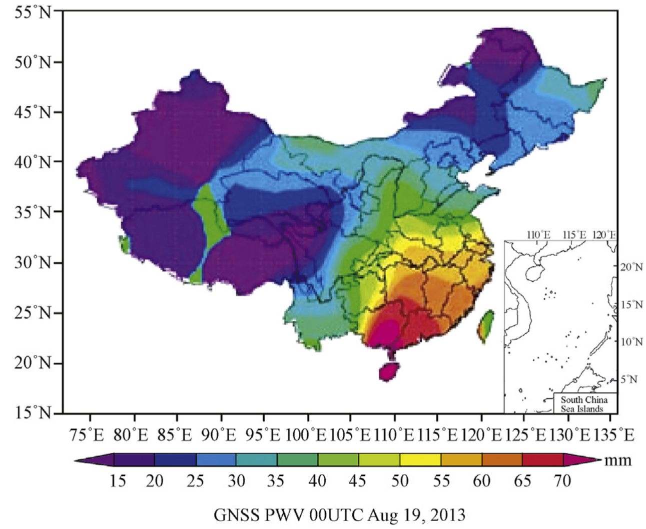

Fig. 5 – Near real-time spatial distribution of PWV over China.

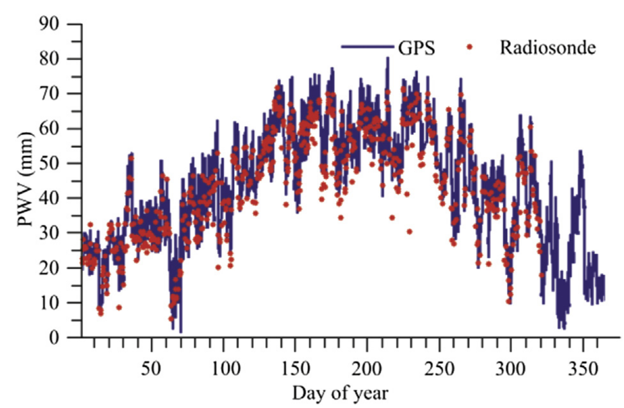

Fig. 6 – Comparison of PWV determined by GPS and Radiosonde in 2013 at Shantou site, Guangdong province.

(1) Monitoring the working status of receivers and antennas. Multi-path effects of observation environment, as well as the length of the time-line window and the number of observation epochs, are checked using the software package TEQC. Meanwhile, poor observation data are eliminated, based on related quality control indexes;
(2) Quality control for tropospheric zenith total delay (ZTD) is based on the standard deviation threshold method. Poor ZTD data are eliminated.
(3) Quality control for surface air pressures and temperatures at GNSS sites is undertaken through checking climate thresholds and extreme values, plus internal consistency testing and a classification of stations. The effects of pressure and temperature increases on PWV estimates are effectively eliminated by these quality control procedures.

Measures of PWV determined by GNSS and radiosonde are compared. The results show that the differences in PWV as measured by GNSS and radiosonde is approximately 2 mm (Fig. 7) and that differences as measured by GNSS and WVR is approximately 1.8 mm. Thus, GNSS estimates of water vapor are in generally close agreement with measurements by radiosondes and WVR.

3.2. *Product applications*

3.2.1. *Weather forecast*

Near real-time water vapor outputs have been used for the weather diagnoses and forecasting applications of the Meteorological Center of CMA. Prior to most precipitation, PWV values increase rapidly by more than 4–5 mm within 1–3 h. An increment of approximately 5 mm PWV within 2 h at single station is used for the index and statistics, showing that the correlation between index and precipitation is up to 70%. Additionally, the index generally reaches 5 mm within 3–4 h before precipitation (Fig. 8). Combined with radar observations, the index should indicate a high level of forecasting ability skill for impending weather, as in heavy rain at Beijing, July 21st, 2012, when the water vapor outputs reflected that the PWV came from a southwesterly airstream. Since noon on that day, moisture content had been abundant (above 60 mm) and this was maintained to the following day, July 22nd. In addition, water vapor outputs can be used to monitor the moisture changes brought about by typhoons.

3.2.2. *PWV data assimilation*

The GRAPES_RAFS model (version 1.3.3) with 0.1°latitudinal × 0.1°longitudinal horizontal resolution was used in this study. Using the compressible, non-static and semi-implicit semi-Lagrangian scheme, the Arakawa-C jump-point format was in a horizontal direction, the Charney–-Phillips jump distribution was in vertical direction, and vertical coordinates for terrain-following were used in the GRAPES_RAFS model. The pressure at the model top was approximately 10 hPa. The assimilation system was GRAPES 3-dvar data assimilation system with 50 vertical levels and the 0.1°latitudinal × 0.1°longitudinal horizontal resolution. The GRAPES_RAFS was commenced afresh twice a day, at 00:00 and 12:00 UTC respectively. The background field data used as the model input were created by a single large-scale model. The GRAPES_RAFS model generated an hourly forecast for background analysis and intermittent assimilation analysis every 3 h. Additionally, the GRAPES_RAFS generated 24 h-forecast analysis every 3 h and the meso-scale numerical weather forecast was updated eight times each day.

In order to estimate the effect of PWV data assimilation into GRAPES_RAFS model on rainfall forecasting skill, two numerical weather forecast tests were designed, to be undertaken for 10 days (21^{st}–31st July, 2013). Test 1 was a control test, and only the meteorological operational observations were assimilated into the GRAPES_RAFS model. Test 2 involved meteorological operational observations and PWV as determined by GNSS being assimilated into model.

(a) Analysis of effect of assimilation

The results showed that the error between observation and background field clearly decreased after assimilating GNSS PWV into the GRAPES_RAFS model, and that the heterogeneity in the humidity field diminished significantly. Differences in humidity estimates decreased in a northerly to southerly direction; the accuracy of humidity observation significantly improved,

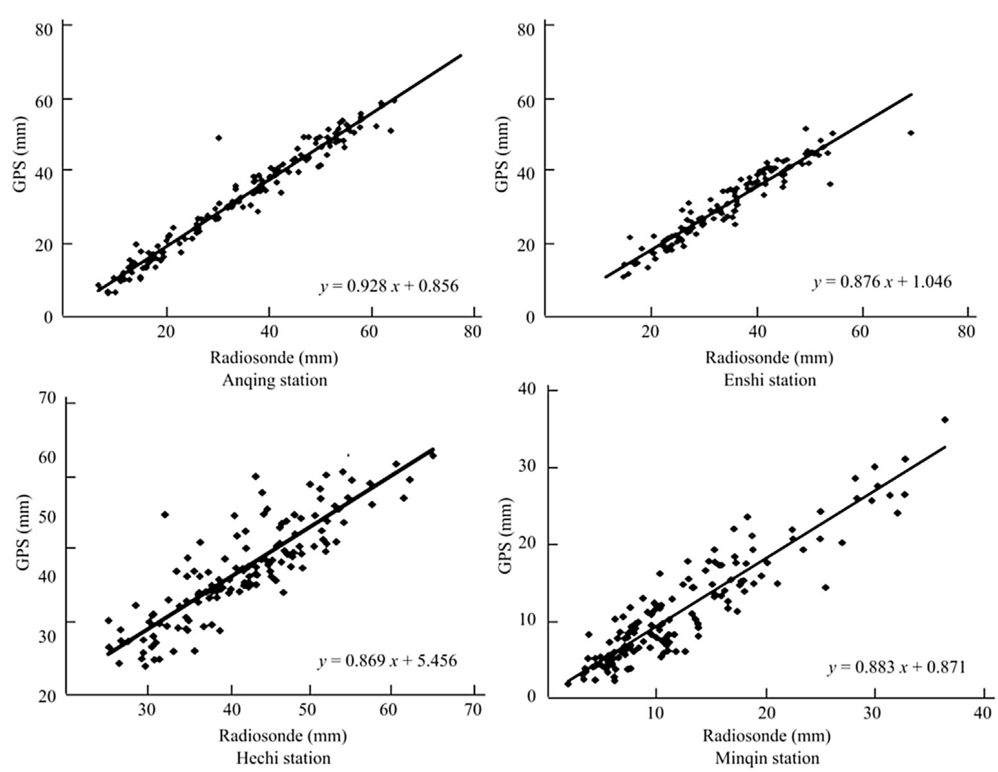

Fig. 7 – Comparison of PWV determined by GPS and Radiosonde in 2012 at Anqing, Enshi, Hechi and Minqin sites.

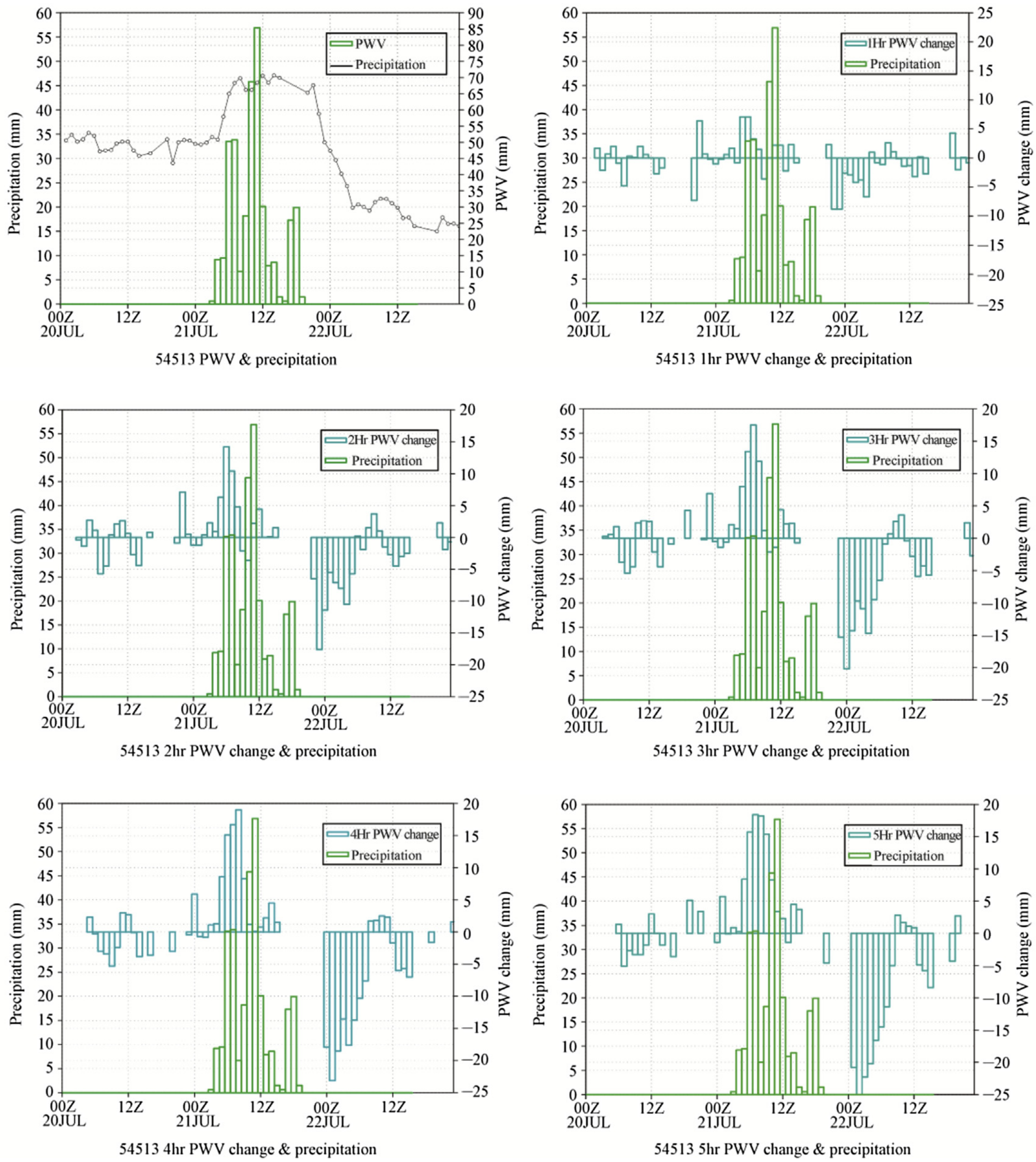

Fig. 8 – Relationship between hourly variations in PWV and in precipitation.

especially compared to that of the previous year in North China. Assimilation circulation retained higher-quality sites from regional distribution and the effect was positive (Fig. 9).

(b) Evaluation of precipitation forecasting

We classified precipitation into five grades (≥0.1; ≥10; ≥25; ≥50; and ≥100 mm: light rain; moderate rain; heavy rain; rainstorm; and torrential rain). The forecast period for this validation test was 21st–31st July, 2013. According to the results of the TS and the ETS scores, there was an improvement in forecast effectiveness when PWV measurements determined by ground-based GNSS were assimilated into the GRAPES model for precipitation forecasting, and higher scores were achieved in Test 2 (incorporating the GNSS-PWV data) than in Test 1, based on precipitation forecasting for moderate and heavy rain (Fig. 10).

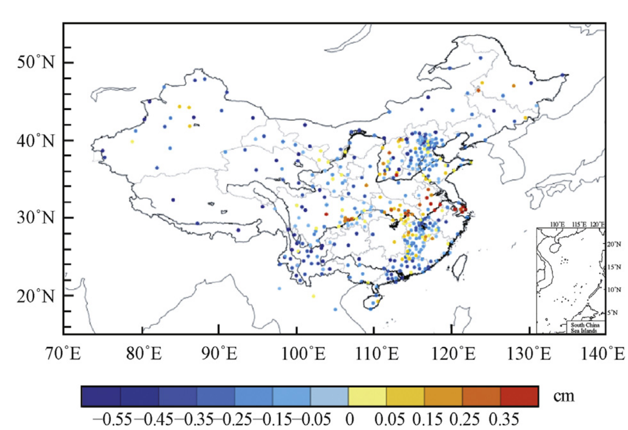

Fig. 9 – Differences in PWV between GNSS and GRAPES background output.

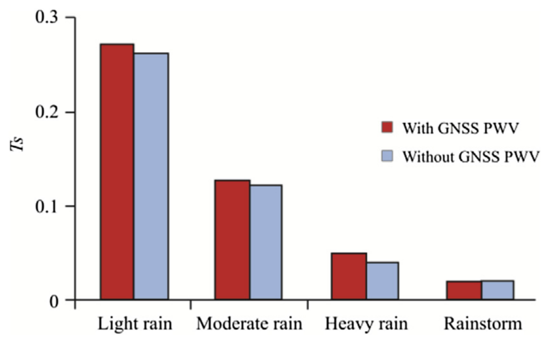

Fig. 10 – Histogram of difference in 3-h *Ts* forecast scores between GRAPES model results, with and without assimilation of GNSS PWV data.

The analysis of the difference between ground GNSS-PWV data and the GRAPES model indicated that the problem of heterogeneity and relative humidity represented a significant improvement over that provided by the meteorological observation center of CMA. After assimilating ground GNSS-PWV data into the GRAPES model, the precipitation forecast showed some improvement; there was significant improvement in forecasting heavy rain and rainstorms at the "miss" and "false alarm" levels, moreover the TS scores improved in terms of forecasting heavy and moderate rain (Fig. 10).

3.2.3. *Comparison of PWV determined by GNSS and radiosonde*

Due to the high precision and high stability of GNSS/MET remote sensing of atmospheric PWV, it has been compared to radiosonde internationally (as in Fig. 11). GNSS/MET remote sensing inversion of PWV was shown to be highly consistent with radiosonde observations.

3.2.4. *Plum rain monitoring*

GNSS/MET remote sensing inversion of PWV is also used for climate monitoring, such as plum rain monitoring in the Yangtze River Delta region, before the Meiyu period. PWV in the Yangtze River Delta region is generally 20–40 mm, but after the plum rain rises to 50–70 mm, an increase of as much as 30 mm. This is of great value for monitoring the Meiyu period (as shown in Fig. 12).

3.2.5. *Ionosphere TEC monitoring*

GNSS/MET is also used to monitor the ionosphere. GNSS ionospheric total electron content (TEC) outputs play an important role in space weather monitoring, and support the quality of the national aeronautics and space weather services (as shown in Fig. 13).

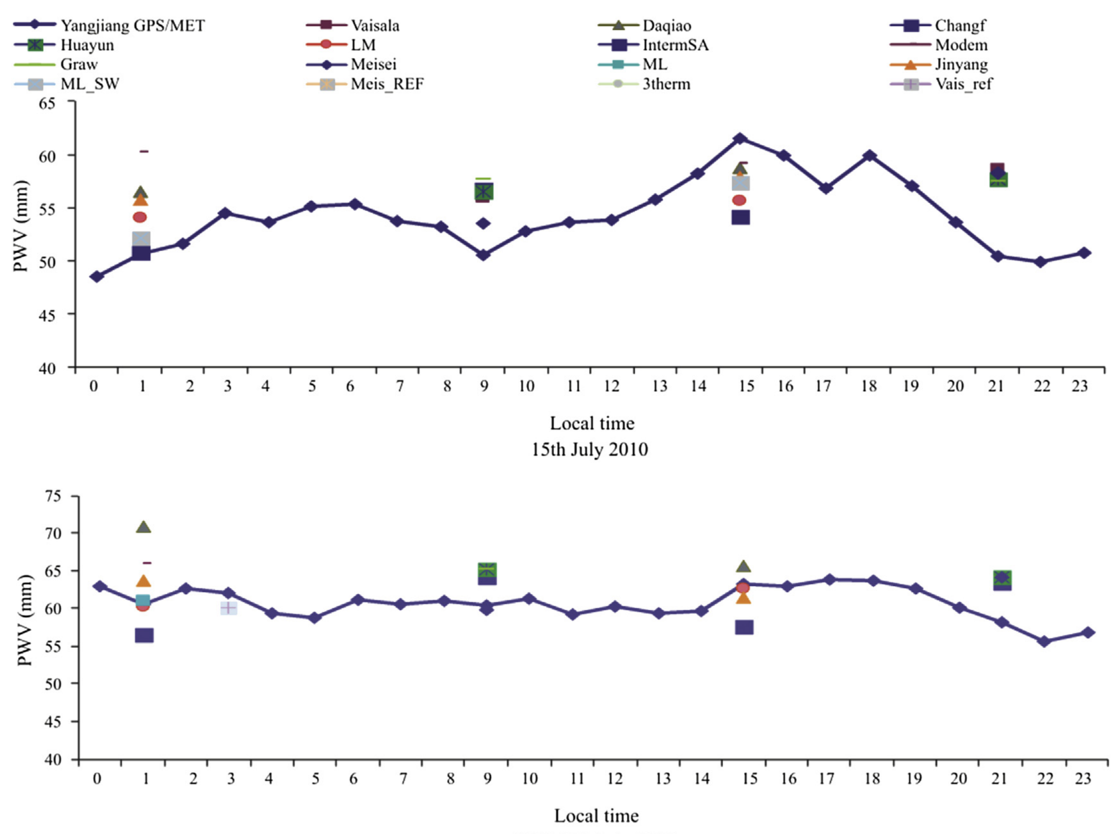

Fig. 11 – Comparison of PWV determined by GNSS and radiosonde, launched in 2011 at Yangjiang, Guangdong province, during the radiosonde international comparison campaign.

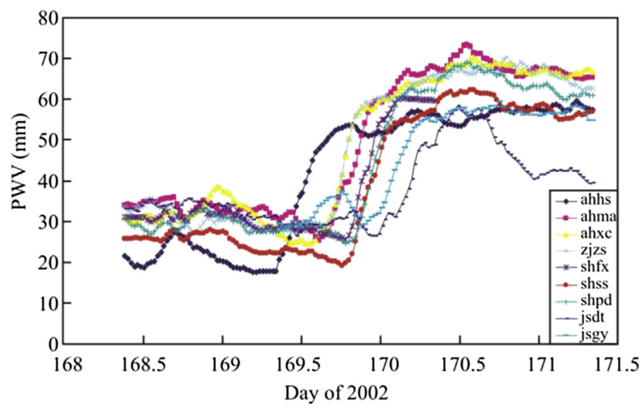

Fig. 12 – Variations of PWV in Yangtze River Delta region during the early plum rain period.

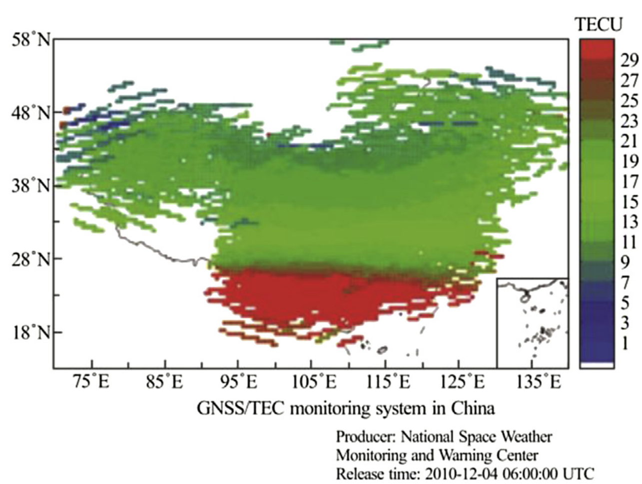

Fig. 13 – Spatial distribution of TEC over China on December 4th, 2010.

4. Summary

The national GNSS network is introduced, which may be used to monitor atmospheric PWV over China. The national GNSS network is also used to monitor the ionospheric TEC. This network consists of two GNSS sub-networks: CMONOC, with 260 continuously operating reference stations, and CMAGN, with 692 continuously operating reference stations at the end of 2013. Additionally, GNSS observation procedures for collecting and processing data are described, and the methods for PWV data quality control investigated.

The software package TEQC was applied to GNSS observations. PWV determined by GNSS and radiosonde were compared. The results showed the GNSS estimates of water vapor are generally in good agreement with measurements by radiosondes and WVR. The PWV retrieved by the national GNSS network was applied to weather forecasting, and the data assimilated into the numerical weather prediction model, the validation of PWV estimates by radiosonde, and plum rain monitoring.

The proposal is to establish a synoptic-scale and meso-scale GNSS network. The mean distance between any two stations in the national GNSS network will be approximately 150 km. The mean distance between any two stations in eastern China will be approximately 100 km and the mean range between any two stations in western China will be less than 200 km. The spatial density will be governed by the number of GNSS receivers deployed. In the area affected by atmospheric water rivers dominated by the South China Sea monsoon and the India monsoon, and some other special areas the density of GNSS receivers will be far greater than the mean across the network.

This GNSS network will be used to monitor the distribution and synoptic-scale variation of water vapor in China, and the distribution of electron density in the ionosphere. In several economically developed cities and suburbs, the mean distance to be established between any two stations for meso-scale PW monitor purposes will be 10–40 km. The main task of the meso-scale GNSS network will be to monitor water vapor and its variation, and to obtain water vapor profiles based on the tomography technique. The purpose is to monitor meso-scale convection and to provide service for "nowcasting" and numerical weather prediction.

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Dr Liang Hong received his PhD in atmospheric science from the University of Chinese Academy of Sciences in 2012. He is an associate researcher at the Meteorological Observation Center of the China Meteorological Administration, with interests focused mainly on monitoring precipitable water vapor (PWV) by ground-based GNSS. His research includes (1) validating PWV estimates measured by satellites and radiosondes using PWV measurements derived from ground-based GNSS; (2) Calibration methods for systematic errors of PWV estimates by radiosondes over the Tibetan Plateau; (3) Diurnal variability and long-term changes in PWV over the Tibetan Plateau; (4) The radiative effect of atmospheric water vapor and ozone over the Tibetan Plateau. He has completed more than three scientific studies and has issued over 25 professional theses.