Research Article

Assessments of GMI-Derived Precipitable Water Vapor Products over the South and East China Seas Using Radiosonde and GNSS

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Satellite remote sensing of the atmospheric water vapor distribution over the oceans is essential for both weather and climate studies. Satellite onboard microwave radiometer is capable of measuring the water vapor over the oceans under all weather conditions. This study assessed the accuracies of precipitable water vapor (PWV) products over the south and east China seas derived from the Global Precipitation Measurement Microwave Imager (GMI), using radiosonde and GNSS (Global Navigation Satellite System) located at islands and coasts as truth. PWV measurements from 14 radiosonde and 5 GNSS stations over the period of 2014–2017 were included in the assessments. Results show that the GMI 3-day composites have an accuracy of better than 5 mm. A further evaluation shows that RMS (root mean square) errors of the GMI 3-day composites vary greatly in the range of 3–14 mm at different radiosonde/GNSS sites. GMI 3-day composites show very good agreements with radiosonde and GNSS measured PWVs with correlation coefficients of 0.896 and 0.970, respectively. The application of GMI products demonstrates that it is possible to reveal the weather front, moisture advection, transportation, and convergence during the Meiyu rainfall. This work indicates that the GMI PWV products can contribute to various studies such as climate change, hydrologic cycle, and weather forecasting.

1. Introduction

Atmospheric water vapor represents a small portion of the total atmosphere mass but is closely linked to climate change, weather pattern, atmospheric radiation, and hydrologic cycle [1–5]. Accurate knowledge of water vapor can not only lead to an enhanced understanding in all of these fields but also to a better correction of wet delay for many space geodetic observations. A variety of water vapor observation techniques therefore have been developed over the past decades. For example, radiosonde has long been the principal *in situ* observation tool for measuring the water vapor throughout the troposphere [6]. The longest record of humidity profiles from the radiosonde network provides

a good data source for climate change studies [7–9]. In addition, remarkable progress in GNSS (Global Navigation Satellite System) meteorology achieved in the last decades has made GNSS being a potent means for observing the water vapor with high spatiotemporal resolution [10–13]. Furthermore, space-based sensor system is widely recognized as the only effective way to monitor the atmospheric water vapor on a global basis [14].

Accurate information of water vapor over the oceans is of great scientific value for studies on weather prediction, global warming, and hydrological circle. Due to the scarcity of *in situ* stations in the ocean, remote sensing from satellite-borne radiometers becomes the main technique in assessing the atmospheric water vapor over the ocean. Satellite

onboard radiometers exploited for water vapor retrieval could be classified into four groups [15]. They are sensors operating at near-infrared wavelengths such as the Moderate Resolution Imaging Spectroradiometer (MODIS) [16], infrared wavelengths such as the Atmospheric Infrared Sounder (AIRS) [17], visible wavelengths such as the Global Ozone Monitoring Experiment-2 [18], and microwave wavelengths such as the Special Sensor Microwave Imager (SSM/I) [19] and the Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E) [20]. Since it is more likely to know the surface temperature and emissivity over ocean, infrared and microwave sensors are typically adopted. The limit of measuring the water vapor by infrared radiometers in cloud-free regions results in a preference toward microwave radiometers, as microwaves can penetrate clouds [21]. The vital significance of remotely sensed water vapor for scientific researches, e.g., hydrologic cycle and climate change, and for assimilation into NWP (numerical weather prediction) models, e.g., ECMWF (European Centre for Medium-Range Weather Forecasts) [22], has justified various missions in implementing microwave radiometer satellites.

Water vapor amount over ocean has been continuously measured with several satellite-borne microwave instruments (e.g., SSM/I instruments carried by DMSP (Defense Meteorological Satellite Program) satellites, AMSR-E sensor launched onboard the NASA's (National Aeronautics and Space Administration) Aqua satellite, microwave imager carried by the TRMM (Tropical Rainfall Measuring Mission), etc.) dating back to the late 1970s. More recently, NASA and JAXA (Japan Aerospace Exploration Agency) initiated the Global Precipitation Measurement (GPM) satellite mission with goals to unify and advance global precipitation measurements from space [23]. A constellation of international satellites carried with microwave radiometers is exploited by this mission to provide the next-generation of atmospheric parameters such as precipitation, water vapor, and wind. Over the years, many assessments have been made for microwave sensors derived PWV (precipitable water vapor). Here, PWV is defined as the total gaseous water contained in a vertical column of atmosphere and is widely used to measure the atmospheric water vapor content. Sajith et al. evaluated the TRMM-derived PWV values against radiosonde data over the coastal regions of Indian Ocean [24]. They obtained an RMS (root mean square) error of 8.1 mm for the TRMM 3-day composite PWV. Studies carried out by Schröder et al. and Chen and Liu both showed that the HOAPS (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data) PWV data, which were generated based on SSM/I observations, agreed well with ECMWF reanalysis products with RMS errors less than 2 mm [25, 26]. In the evaluation reported by Du et al., they compared the AMSR2 PWV retrievals with PWV measurements from the SuomiNet North American GNSS network and achieved an overall RMS error of 4.7 mm [27]. However, rare work has been done regarding the evaluation of the PWV retrievals from GMI (GPM Microwave Imager) over ocean.

In this paper, we assess the GMI-derived PWV with respect to the radiosonde and GNSS measurements over the south and east China seas. One motivation of this work is to examine the usefulness of GMI PWV data for investigating the atmospheric moisture flow over ocean associated with the Meiyu. This paper is structured as follows. Descriptions of PWV datasets from GMI, radiosonde, and GNSS are given in Section 2. Section 3 presents the evaluation results of the GMI PWV datasets by radiosonde and GNSS. The application of GMI 3-day composites in detecting water vapor variations during a Meiyu front is also shown in Section 3. Finally, a summary of this study is given in Section 4.

2. Data Description and Methodology

2.1. GMI PWV Dataset. Built upon the success of TRMM, a mission ended on 8 April 2015 which was designed to measure rainfall and energy exchange of tropical and subtropical regions of the world, NASA and JAXA initiated the GPM mission to unify and advance global precipitation measurements from space [23, 28]. The GPM core observatory was launched in February 2014 to a non-sun-synchronous orbit of 407 km with an inclination of 65°. This orbit design allows a broad latitudinal coverage without being locked into a sun-synchronous polar orbit and offers a full sampling of all hours of the day repeated approximately every 2 weeks. It carries a Ka/Ku-band dual-frequency precipitation radar (DPR) and a multifrequency microwave radiometer, i.e., the GMI. GMI is a dual-polarization, conical-scanning, passive microwave radiometer with 13 radiometric channels ranging in frequency from 10.65 to 183.31 GHz [29]. For the protection of overheating from sun intrusion, the GPM platform undergoes yaw maneuvers approximately every 40 days. More details about the GPM's technologies and its scientific objectives can be found in [29].

In the present study, 3-day composites of PWV over the south and east China seas were evaluated against 3-day averaged radiosonde and GNSS observations for the period of 2014–2017. In addition, the daily PWV products were also evaluated by radiosonde and GNSS measurements from the coastal and island stations. Both the 3-day composites and daily PWV datasets have a spatial resolution of $0.25^\circ \times 0.25^\circ$. The GMI PWV products are provided by the website <http://www.remss.com/missions/gmi/> in near real time.

2.2. Radiosonde. Radiosonde is capable of making observations of atmospheric parameters including pressure, temperature, and humidity at various heights with the balloon ascending. By using the radiosonde measured profiles, PWV can be calculated by [7]:

$$\text{PWV} = \frac{1}{g} \int \frac{0.622e}{p - 0.378e} dp, \quad (1)$$

where g is the acceleration of gravity (unit: m/s^2), p is the pressure (unit: hPa), and e is the water vapor pressure (unit: hPa) that can be estimated from [30]:

$$e = 6.1121(1.0007 + 3.46 \times 10^{-6}p) \cdot RH \cdot \exp\left[\frac{(18.729 - t/227.3)t}{t + 257.87}\right], \quad (2)$$

where RH and t refer to the relative humidity (unitless) and temperature (unit: degrees Celsius), respectively. To ensure the quality of PWV derived from radiosonde, only radiosonde data that contain complete atmospheric profiles up to the height with a pressure equal to or less than 300 hPa are used in our study. The use of 300 hPa is because water vapor content can be negligible beyond this level. Radiosonde derived PWV can reach an accuracy of a few millimeters and thus is often adopted as accuracy standard for assessing water vapor observations from other independent techniques [2, 31].

In this work, we employ the quality-assured radiosonde data provided by the Integrated Global Radiosonde Archive (IGRA) [32] to evaluate the GMI-derived PWV values over the south and east China seas. Subject to the limited island stations, coastal stations are also included to expand the reference database of radiosonde. Water vapor is highly concentrated near the surface; thus, any errors in the correction could represent a disproportionately large fraction of the PWV [15]. For this reason, we chose to exclude stations with altitude greater than 100 m instead of trying to apply a custom PWV correction. In addition, a criterion of 10 km in distance between the radiosonde station to the nearest coast is used. As a result, a total of 14 radiosonde stations (contain 8 island and 6 costal stations) are selected for this study, and their locations (blue squares) are displayed in Figure 1.

2.3. GNSS. GNSS signals are significantly affected by the presence of troposphere while they travel through the troposphere. A zenith total delay (ZTD) is the effect of the troposphere on a GNSS signal coming from the zenith. Since the ZTD is the sum of the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD), ZWD can be extracted from the ZTD by a subtraction of ZHD. Accurate ZHD can be obtained using ZHD model with surface meteorological parameters [31]. Then the PWV could be retrieved from ZWD with a conversion factor by [10]

$$PWV = \frac{10^5}{461.495(k_3/T_m + k_2')} ZWD, \quad (3)$$

where $k_3 = 3.776 \times 10^5$ K²/hPa, $k_2' = 16.52$ K/hPa are the physical constants. T_m is the weighted mean temperature [33]

$$T_m = \frac{\int_H^\infty e/T}{\int_H^\infty e/T^2} dh, \quad (4)$$

where H is the height of the GNSS station, T is the temperature at height h in degrees Kelvin ($T = t + 273.15$). T_m is usually calculated from radiosonde profiles according to Equation (4) or empirical models with surface temperature.

FIGURE 1: Geographical distribution of the 14 radiosonde and 5 GNSS stations selected for this study. The selected stations are located at either the coastal region or the islands.

Based on numerous studies, the GNSS-inferred PWV is likely to have an accuracy of 1~2 mm [34–36].

The International GNSS Service (IGS) regularly publishes the daily GNSS-derived troposphere products on its official website (<http://www.igs.org/>). These products include estimates of ZTD and north and east troposphere gradient components. The troposphere products generated by the GFZ (GeoForschungsZentrum) using the Berenese software [37] are exploited in this study. ZHDs for each site were calculated using the ECMWF reanalysis data for two reasons: (1) surface meteorological data are not available at many IGS stations, and (2) the ECMWF outperforms the empirical ZHD models as reported by [31]. In addition, the weighted mean temperature for each GNSS site was also derived from the ECMWF reanalysis products. Following the same selection criterion as radiosonde, 5 GNSS stations were identified, and they are shown in Figure 1 with red triangles.

2.4. Validation Method. Matchup PWV values from the GMI gridded products are obtained according to each radiosonde/GNSS site's location. Since no location-matched PWV data are available for some coastal sites, in this case, PWV data of the nearest cell to this site will be adopted instead. For quality control, only PWV values less than 80 mm are used in the evaluation. Prior to the assessment, outliers that may be caused by instrumental error, record error, or processing error are rejected from the datasets. An outlier is determined when the absolute difference between its value and the mean is more than the triple standard deviation. Statistics is performed to derive the bias, root

mean square (RMS) error, and correlation coefficient for each individual site. Student's t -test is employed to determine the significance of the correlation coefficients. Scatter plots are constructed and analyzed to compare the variations of GMI-derived PWV with radiosonde and GNSS data.

3. Results and Discussion

Prior to the assessment, a comparison of PWVs derived from radiosonde and GNSS was carried out to examine their discrepancies. Two collocated radiosonde-GNSS stations with their distances less than 30 km are found for the comparison. Since the water vapor varies greatly in the vertical direction particularly in the lower troposphere, PWVs calculated from radiosonde profiles were adjusted to the height of the collocated GNSS site. Figure 2 displays the comparisons of PWV between radiosonde and GNSS. GNSS PWV shows a good agreement with radiosonde PWV as their regression line is very close to 1:1 line with a high correlation coefficient of 0.976. The probability density function (PDF) of PWV difference shown in Figure 2(b) indicates that there is a higher probability of negative PWV difference occurrence. Figure 2(c) further displays the fractional error as percent by radiosonde 5 mm PWV bins. When PWV values less than 20 mm, GNSS PWV has an obvious wet bias relative to the radiosonde. Especially for 0–5 mm bin of radiosonde PWV, a fractional error of –70% is obtained. In addition, dry bias relative to the radiosonde occurs when PWV values are greater than 70 mm. In general, the comparison results confirm the high quality of GNSS PWV, which can be employed as a good data source to assess water vapor measurements from other independent systems.

3.1. Evaluation of the GMI PWV Data. In this study, we first evaluated the 3-day composite of GMI PWV against 3-day averaged radiosonde and GNSS measurements over the period of 2014 to 2017. Figure 3 displays the comparison results, and Table 1 shows the evaluation statistics. The scatter plots in Figures 3(a) and 3(b) show a good agreement between the GMI 3-day composite PWV data and the radiosonde/GNSS measurements. As seen in Table 1, high correlation coefficients of 0.896 and 0.970 are obtained for radiosonde-GMI and GNSS-GMI, respectively. There is a higher probability of a large negative PWV difference for radiosonde-GMI than GNSS-GMI (Figures 3(c) and 3(d)), which is also evident in the fractional error. For the comparison with radiosonde, GMI 3-day composite exceeds a 10% error and has a dry bias when PWV values are greater than 65 mm. While PWV values are less than 20 mm, an obvious wet bias can be observed. For the comparison with GNSS, however, the fractional errors stay within the 5% error bound.

As given in Table 1, the mean PWV differences are both negative, suggesting an overall wet bias for GMI composite to radiosonde and GNSS. In addition, the root mean square (RMS) error of the PWV differences between radiosonde and GMI composite is 8.3 mm, which is almost twice the

RMS error for GNSS-GMI comparison. Figure 4 further exhibits the RMS errors for all the radiosonde and GNSS stations. RMS errors of the radiosonde-GMI PWV differences vary greatly from 6 mm to 14 mm over different sites, while RMS values are less than 5 mm at all GNSS stations. Since the radiosonde (normally twice a day) has a much lower time resolution than GNSS (5 mins), the 3-day averaged PWVs from radiosonde show larger discrepancies with the GMI 3-day composite. Therefore, the evaluation results of GMI 3-day composite by GNSS are much more reliable.

The comparisons of GMI daily PWV data to radiosonde and GNSS are also shown in Figure 5. To compare GMI daily measurements to radiosonde and GNSS, collocation criteria of 2 h and 30 min in time were chosen, respectively. Since radiosonde balloons typically take 1–2 h to ascend through the atmosphere, we determined a larger time range for selecting radiosonde measurements. As shown in Figures 5(a) and 5(b), pretty high correlation coefficients of 0.971 and 0.986 are yielded for comparisons of GMI daily PWV to radiosonde and GNSS. For the evaluation by radiosonde, a bias of –1.90 mm and an RMS error of 5.17 mm are obtained. The evaluation by GNSS achieves much smaller bias and RMS, with values of –0.17 mm and 3.12 mm, respectively. In addition, the fractional errors stay within the 15% and 5% error bounds for evaluations by radiosonde and GNSS, respectively. On the whole, the GMI PWV data show a satisfactory performance in the evaluation and thus will be very useful for studying the water vapor variations over the oceans.

3.2. Distribution and Variability of PWV over the South and East China Seas. Figure 6 shows the spatial distribution of mean PWVs derived from the GMI 3-day composites over the period of 2014–2017. Their standard deviations (STD) are also calculated to show the PWV variability. The mean PWV varies in the range of 13–55 mm over the south and east China seas. Larger mean PWVs occur in the south China seas, and the mean PWVs decrease with the increase of the latitude. Figure 6(b) shows that water vapor has a variation within 7–19 mm. Contrast to the mean PWV, STDs of PWV increase with latitude below 30°N. It can be observed that the east China seas between 29°N–31°N have the largest PWV variation with a STD ~19 mm. This is attributed to the typical monsoon climate that results in large changes in water vapor at different seasons in these regions.

The maps of seasonal means and STDs of PWV for the four seasons spring (December–January–February), summer (March–April–May), autumn (June–July–August), and winter (September–October–November) are displayed in Figure 7. It shows that summer has significantly higher PWV than other seasons, with mean values greater than 10 mm. Winter shows the smallest PWV (less than 10 mm) throughout the surrounding China seas. The STD patterns are very similar with the mean PWV distributions in the corresponding seasons. Extremely large water vapor variations (STDs ~27 mm) can be found to occur in southeast China seas in summer.

FIGURE 2: (a) Scatter plot of radiosonde PWV versus GNSS PWV, (b) PDF of PWV difference between radiosonde and GNSS, and (c) fractional error as percent by radiosonde 5 mm PWV bins.

FIGURE 3: Continued.

FIGURE 3: Scatter plots of (a) radiosonde PWV versus GMI 3-day PWV and (b) GNSS PWV versus GMI 3-day PWV, PDFs of PWV difference between (c) radiosonde and GMI 3-day and (d) GNSS and GMI 3-day, and fractional errors as percent by (e) radiosonde and (f) 5 mm PWV bins.

TABLE 1: Statistical results (unit: mm) for the comparisons between radiosonde and GMI 3-day and GNSS and GMI 3-day.

Comparison	Bias	RMS	Min	Max	Correlation coefficient
Radiosonde vs GMI 3-day	-1.74	8.30	-27.85	24.50	0.896
GNSS vs GMI 3-day	-0.54	4.23	-14.13	13.05	0.970

FIGURE 4: RMS errors of the PWV differences between GMI 3-day and radiosonde (big circles) and between GMI 3-day and GNSS (small circles).

3.3. *Detecting Water Vapor Variations during a Heavy Rainfall Event Using GMI PWV.* In general, the Meiyu occurs from mid-to late spring through early to midsummer.

The weather front forms when the warm moist air from the south and east China seas meets the cool continental air mass. The front often brings prolonged heavy convective

FIGURE 5: Scatter plots of (a) radiosonde PWV versus GMI daily PWV and (b) GNSS PWV versus GMI daily PWV, PDFs of PWV difference between (c) radiosonde and GMI daily and (d) GNSS and GMI daily, and fractional errors as percent by (e) radiosonde and (f) 5 mm PWV bins.

rainfalls and sometimes flooding to eastern China, especially the Yangze and Huai River regions. Thus, the GMI PWV data should be very useful for detecting the moisture flow over ocean before the commencement of heavy rainfall spells.

During the period 18–23 June 2017, the southeast China suffered several large-scale torrential Meiyu rains, which caused major floods and massive landslides in some places.

Figure 8 displays the geographic distribution of the daily accumulated precipitation over the east Asia for the period 18–23, June 2017. The precipitation data are provided by the TRMM, a joint mission of NASA and JAXA to measure rainfall for weather and climate research [28, 38]. On 18 June 2017, as shown in Figure 8(a), a long belt of rain occurred over the coastal regions of the southeast China. Afterwards, the rain belt moved gradually northward into the inland. On

FIGURE 6: (a) Means and (b) STDs of the PWV derived from the GMI 3-day composites for the period of 2014–2017.

FIGURE 7: (a–d) Means and (e–h) STDs of PWV derived from the GMI 3-day composites (2014–2017) for different seasons. (a) Mean of PWV Spring. (b) Mean of PWV Summer. (c) Mean of PWV Autumn. (d) Mean of PWV Winter. (e) STD of PWV Spring. (f) STD of PWV Summer. (g) STD of PWV Autumn. (h) STD of PWV Winter.

23 June 2017 (Figure 8(f)), torrential rains battered lower reaches of the Yangtze watershed.

To study the water vapor variations during the rainfall process, Figure 9 exhibits the evolution of PWV maps derived from GMI 3-day composites for days 15–23 June 2017. It can be observed that the PWV gradually increased to ~ 70 mm (Figures 9(a)–9(c)) over the coastal regions of southeast China before the onset of heavy rain on 18 June 2017. We can also observe that the water vapor decreased greatly over the south China sea during the same period, revealing that the water vapor moved northeasterly. This is consistent with the vertically integrated water vapor transport (IWT; kg/m/s) information shown in Figure 10.

A large amount of moisture from the south China sea flowed into mainland China with IWT values of 100–300 kg/m/s. In addition, an obvious boundary line between the high and low PWV regions occurred around the 30°N . We can infer that the southerly warm moisture met the cold dry air here and thus caused the heavy rainfalls. From Figures 9(e)–9(f), it can be seen that the warm moisture flows continually moved to the northeast, expanding the rain belt to the north above 30°N . Figure 10 demonstrates that the strong northeasterly moisture transport with IWT values of 500–800 kg/m/s occurred between 20°N – 30°N . Overall, high PWV values greater than 60 mm occurred before the commencement of the active spell. The GMI-derived PWV

FIGURE 8: Maps of daily accumulated precipitation from 18 to 23 June 2017. The precipitation data were retrieved from the TRMM with a spatial resolution of $0.25^\circ \times 0.25^\circ$. (a) 18 June 2017. (b) 19 June 2017. (c) 20 June 2017. (d) 21 June 2017. (e) 22 June 2017. (f) 23 June 2017.

FIGURE 9: Evolution of PWV maps derived from GMI 3-day composites from 15 to 23 June 2017. (a) 15 June 2017. (b) 16 June 2017. (c) 17 June 2017. (d) 18 June 2017. (e) 19 June 2017. (f) 20 June 2017. (g) 21 June 2017. (h) 22 June 2017. (i) 23 June 2017.

FIGURE 10: Vertically integrated moisture flux divergences (mm/day) from ERA-Interim products for days from 15 to 23 June 2017. Black arrows present IWT vectors (kg/m/s), with the scale at the top left of each panel. (a) 15 June 2017. (b) 16 June 2017. (c) 17 June 2017. (d) 18 June 2017. (e) 19 June 2017. (f) 20 June 2017. (g) 21 June 2017. (h) 22 June 2017. (i) 23 June 2017.

maps are able to reveal the weather front, moisture advection, transportation, and convergence during the heavy precipitation events.

4. Conclusion

Remote-sensing satellites capable of measuring atmospheric water vapor over the ocean provide import data for numerical weather prediction, reanalysis model, and climate change study. Satellite with microwave radiometer is able to observe the water vapor under all conditions, making it the most effective tool for water vapor observation with large spatial coverage over the ocean.

In this work, we validated measurements of PWV from microwave radiometers made by GMI over the south and east China seas. PWVs from 14 radiosonde and 5 GNSS stations located at islands and coasts are used as references to evaluate the performance of the GMI PWV datasets over the period of 2014–2017. GMI 3-day composites show very good agreements with radiosonde and GNSS measured PWVs with correlation coefficients of 0.896 and 0.970, respectively. In the assessment by radiosonde, GMI-derived PWV exceeds a 10% error and has a wet bias when PWV values less than 20 mm. While PWV values greater than 65 mm, an

obvious dry bias can be observed. For the comparison with GNSS, however, the fractional errors stay within the 5% error bound. RMS errors of the radiosonde-GMI PWV differences vary greatly from 6 mm to 14 mm over different sites, while RMS values are less than 5 mm at all GNSS stations. In addition, assessments of GMI daily PWV data yielded RMS errors of 5.17 mm and 3.12 mm by radiosonde and GNSS, respectively.

We further applied the GMI 3-day composites to study the PWV variations during a heavy Meiyu rainfall event occurred on 18–23 June 2017. The GMI-derived PWV maps are able to reveal the weather front, moisture advection, transportation, and convergence during the heavy precipitation events. This study demonstrates that the GMI PWV data will be very beneficial for detecting the moisture flow over ocean before the onset of heavy rainfall spells. Our future study will focus on using GMI-derived PWV to quantify moisture advection associated with the Meiyu front and the use of PWV as a predictor of rainfall over the southeast China.

Data Availability

The GMI PWV data were provided by Remote Sensing Systems from <http://www.remss.com/>. The ECMWF

ERA-Interim reanalysis products are available online (<http://apps.ecmwf.int/datasets/>). The TRMM rainfall data were provided by <https://pmm.nasa.gov/data-access/downloads/trmm>. The IGRA radiosonde data were obtained from <https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-globalradiosonde-archive> by the National Oceanic and Atmospheric Administration. The reprocessed GPS ZTD products were accessed from <ftp://cddis.gsfc.nasa.gov>.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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