Comparative Analysis of Precipitable Water Vapor Acquired from CORS (Continuously Operating Reference Station) and Radiosonde under Extreme Weather

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Abstract. The observation data from the CORS stations in Nanning, Wuzhou and Baise were processed with GAMIT software in this paper, and the accuracy and reliability of CORS data inversion results were verified with the help of Inverse Distance Weighted (IDW) simplified analysis process. Furthermore, the time-series variation of precipitable water vapor in the three regions under extreme weather was analyzed in a selectively manner in combination with the meteorological data from radiosonde and actual rainfall. The results showed that the PWV obtained from CORS data inversion was well consistent with that acquired from the meteorological data from radiosonde, and the overall variation trend was basically consistent with the actual rainfall before and after typhoon. Characterized by all-weather operation, high spatiotemporal resolution, and continuous monitoring of water vapor variation and etc., it could effectively supplement the shortcomings of existing upper-air meteorological detection means, so it is of great reference value for water vapor monitoring, extreme weather warning and other aspects.

1. Introduction

Affected by the complex maritime airflow in the southeast direction, Guangxi is invaded by typhoons from Guangdong every year. Wuzhou, Yulin, Nanning-Beihai-Qinzhou-Fangchenggang, Chongzuo-Baise and other prefecture-level cities are the only way through which typhoons invade China. These regions have suffered from enormous losses in production and living due to the heavy rainfall and transient extreme weather brought by typhoon. Therefore, it is of great positive benefits to the people’s livelihood to conduct short-term monitoring of climate characteristic variations with scientific means before, during and after the invasion of typhoons, and strive to predict the change of extreme weather in advance.

The high intensity short-duration rainfall caused by several typhoons every year could provide an experimental environment for the research in this paper. Guangxi Beidou High-precision Reference Station Network (Guangxi CORS Network) constructed by the Surveying and Mapping Bureau of Guangxi Zhuang Autonomous Region provided a large amount of data base for the research in this paper. The analysis and modeling of key tropospheric parameters in GNSS space environment, GNSS tropospheric water vapor inversion and etc. provided technical support for the research in this paper [1].

Based on the observation data from several CORS stations close to the radiosonde stations within the regions over which typhoons passed, GAMIT software and related meteorological elements were employed to calculate the precipitable water vapor (hereinafter referred to as CORS/PWV); moreover,
the PWV of radiosonde stations was calculated according to the meteorological data acquired from radiosondes (hereinafter referred to as Radio/PWV) [2], and then the time-series variation and correlation of Radio/PWV and CORS/PWV were analyzed to verify the applicability of CORS/PWV in water vapor monitoring; in addition, the calculated PWV values and actual rainfall distribution were analyzed based on the path of typhoon, so as to verify the corresponding relationship between PWV variation and actual rainfall.

2. Data sources and methods

2.1 Data sources

No. 13 Typhoon Hato formed over the Western Pacific at 2:00 on August 20, 2017, and invaded Guangxi from Cenxi, Wuzhou to Yulinrong, Wuzhou at 20:00 on August 23, 2017. Based on the path of Typhoon Hato, this paper selected the observation data from the CORS stations in Nanning, Wuzhou and Baise for processing, demonstrated the introduction of four IGS station data of BJFS, LHAZ, TWTF and CUSV as external auxiliary stations, and carried out comparative analysis of the meteorological observation data from the three radiosonde stations in the three regions at the same period. The time span selected was August 15 - August 31, 2017, with the CORS data from Guangxi CORS Network, and the radiosonde data from the Website of Wyoming University (http://weather.uwyo.edu/yoming/). The distribution of CORS stations and radiosonde stations in the three regions is shown in figure 1 (△: CORS station, ○: radiosonde station) [2]. Based on the experimental data processed with GAMIT software, the PWV before and after typhoon was calculated in combination with the atmospheric weighted average temperature model formula of Guangxi region established earlier and etc[3]. The Radio/PWV was calculated based on the air pressure, temperature, humidity and other data obtained from the radiosonde data released twice a day (0:00 and 12:00, UTC) by the local meteorological system. The PWV calculated by the two methods was compared and analyzed.

Figure 1. Distribution map of CORS stations and radiosonde stations used in the experiment.
2.2 Experimental principle and demonstration

2.2.1 CORS data processing and PWV extraction. After the comparison surveying of the data from Guangxi CORS stations and the selected IGS station data with OSS (open source software) GAMIT, the precise ephemeris, clock correction, satellite altitude cutoff angle, as well as the number of auxiliary stations outside, the atmospheric weighted average temperature, and other parameters were optimized according to parameters for optimal solution demonstrated in the preliminary experiment, and then the zenith tropospheric delay (ZTD) was calculated. In the calculation process, the tropospheric delay correction model was set to the general Saastamoinen model [4], also known as SA model (equation(1)), so as to calculate the Zenith Hydrostatic Delay (namely, dry delay) ZHD.

\[
\Delta s = \Delta s_d + \Delta s_w = \frac{0.002277}{\sin \varepsilon} \left[ P_s + \frac{1255}{T_s} + 0.05 \varepsilon - \frac{B}{\tan^2 \varepsilon} \right] W(\phi, h_s) + \delta R 
\]

\[
W(\phi, h_s) = 1 + 0.0026 \cos 2\phi + 0.00028 h_s
\]

Where, \(\phi\) is the latitude of observation station, \(B\) is the \(h_s\) related parameter, \(\delta R\) is the relevant parameter of \(\varepsilon\) and \(h_s\), \(\Delta s\) is the tropospheric refraction correction value (unit: \(m\)), \(\Delta s_d\) is the tropospheric dry correction, \(\Delta s_w\) is the tropospheric wet correction. \(T_s\) is the absolute temperature (unit: \(K\)) of observation station, \(P_s\) is the air pressure (unit is) of observation station, \(h_s\) is the elevation (unit: \(m\)) of observation station, \(h_d\) is the height of the upper troposphere boundary (unit: \(m\)), \(\varepsilon\) is the altitude angle of satellite (unit: \(^\circ\)), and \(\varepsilon_s\) is the water vapor pressure of observation station (unit: \(hPa\)).

The zenith wet delay ZWD was obtained after the subtraction between ZTD and ZHD calculated (equation(3)). The meteorological data of radiosonde station was utilized to calculate the water vapor conversion factor \(\Pi\) (equation(4)), and the product of ZWD and dimensionless constant was the PWV of objective region (equation(5)) [5].

\[
ZTD = ZHD + ZWD
\]

\[
\Pi = \frac{10^6}{\rho_w R_v \left( k_2 + k_3 / T_m \right)}
\]

\[
PWV = \Pi \cdot ZWD
\]

In the formula above, \(T_m\) is the weighted average temperature of the atmosphere; \(\rho_w\) is the density of liquid water; \(R_v = 461.1 \cdot 495 \cdot kg^{-1} \cdot K^{-1}\) is the gas constant of water vapor; \(k_2 = 16.48 K \cdot hPa^{-1}\) in equation(4) is the physical constant related to refractive index, which is only an empirical constant and varies with specific circumstances [6]. The fixed constant value provided by Boudouris or Thayer with the highest accuracy was generally adopted. \(\Pi\) can also be called the dimensionless constant, namely, the conversion coefficient between ZWD and PWV, which represents the conversion ratio between ZWD and PWV. The dimensionless constant is 0.15 as a matter of experience. That is to say, 1mm of PWV will cause a signal delay of 6.4 or 6.5 mm [7].

2.2.2 Calculation principle of Radio/PWV. The Radio/PWV could be calculated based on the parameters acquired by the radiosonde balloons in the three regions at different heights, such as atmospheric pressure, temperature, relative humidity, intensity of pressure and etc. The calculation steps and equations are as follows [6]:

\[
ZTD = ZHD + ZWD
\]

\[
\Pi = \frac{10^6}{\rho_w R_v \left( k_2 + k_3 / T_m \right)}
\]

\[
PWV = \Pi \cdot ZWD
\]
\[ e = 6.1078 \cdot e^{\frac{aT_d}{b + T_d}} \]  
\[ q = \frac{622e}{p - 0.378e} \]  
\[ W = -\frac{1}{g} \sum_{i=0}^{n} q_i \Delta p \]

Equation (6) is to calculate the corresponding vapor pressure \( e(\text{hpa}) \) based on the dew point temperature at each elevation level: \( t_d \) is the dew point temperature (°C), the conditions for empirical constant coefficients, \( a \) and \( b \), are: when the temperature is below 40°C, \( a = 21.87, b = 265.49 \); when the temperature is higher than 0°C, \( a = 17.26, b = 237.29 \); when it is intermediate, the coefficients should be calculated by linear interpolation. Equation (7) is to calculate the specific humidity according to the water vapor pressure \( e(\text{hpa}) \), \( P \) is the atmospheric pressure at each level. Equation (8) is to calculate the Radio/PWV (mm), \( q \) is the specific humidity (g/kg), and \( g \) is the gravitational acceleration on the Earth.[8-9].

The radiosonde balloons could reach a maximum flight altitude of 25-38km under different weather conditions, and the maximum flight altitude of radiosonde balloons used in this paper was 25-32km. Since water vapor was mainly concentrated below 8Km, it had no influence on the PWV acquisition accuracy. There was an error of about 2mm in the Radio/PWV due to the influence of temperature, air pressure and relative humidity errors in radiosonde observation [10].

3. Case analysis

3.1 Comparative analysis of calculation results between CORS/PWV and Radio/PWV

The time-series trend charts of CORS/PWV in the three regions were made respectively. As could be seen from figure 1- figure 3, the data of CORS stations in the three regions showed the basically same trend, and the larger fluctuation of PWV value was mainly concentrated on August 21-24, completely consistent with the time when typhoons passed over. As could be seen from figure 1, the numerical inversion of PWV of different CORS stations in Nanning showed the smallest difference, with the completely consistent trend as a whole. According to figure 2, the distribution range of numerical differences of PWV inversion of different CORS stations in Wuzhou was larger than that in Nanning, but less than that in Baise. It could be seen from figure 3 that, the PWV inversion of each station in Baise was basically consistent in the overall trend, but the value size of each station was uneven, and the distribution range of numerical differences was the largest among the three regions. After the analysis in combination with the regional elevations in table 1, the inversive CORS/PWV in Baise mountainous areas with long-span altitudes showed poor consistency as a whole, as well as the largest difference distribution; while, the overall consistency of inversive CORS/PWV received a significant boost in the low-elevation plain areas, and the numerical values of inversive PWV became closer, thus reflecting the local climatic change characteristics more clearly.

The trend of CORS/PWV was basically the same as that of Radio/PWV, and good consistency could be seen in both overall variation trend and peak point. Nevertheless, it was found that CORS/PWV was larger than Radio/PWV on the whole in the statistics of differences, which was most obvious in Baise, with the mean difference up to 7.32mm, the smallest in Nanning, with the mean difference of 0.21mm, and 1.67mm in Wuzhou. This was caused by many factors, such as the end effect in the data, the difference of self-adaptive regional weighted average temperature model, and the different altitudes of radiosonde stations and CORS stations.
Figure 2. PWV trend in Nanning.

Figure 3. PWV trend in Wuzhou.

Figure 4. PWV trend in Baise.
Table 1. Statistical table of elevations of CORS stations in the three regions.

| Surveying region | Longitude / (°) | Latitude / (°) | Altitude of radiosonde station/m | Average altitude of CORS/m | Highest altitude of CORS/m | Lowest altitude of CORS/m |
|------------------|----------------|----------------|---------------------------------|---------------------------|---------------------------|--------------------------|
| Nanning          | 108.21         | 22.63          | 126                             | 96                        | 120                       | 70                       |
| Wuzhou           | 111.30         | 23.48          | 120                             | 83                        | 180                       | 30                       |
| Baise            | 106.60         | 23.90          | 175                             | 430                       | 900                       | 90                       |

The data statistics of CORS/PWV and Radio/PWV could show the correlation between CORS/PWV and Radio/PWV in the same region. Based on the elevations of stations in each region, it could be seen that the average elevation and difference value was highest in Baise, but lowest in Nanning, located in the plain. It showed that, the CORS/PWV was the closest to Radio/PWV owing to being less affected by other factors in the plains and other places with lower elevations. However, the CORS stations and radiosonde stations in the mountainous areas with high elevations were affected by more uncertain and unestimable factors, so the large gross error could be seen in the calculated PWV. Therefore, the mean difference between the two and other accuracy indexes were worse than those in the low-altitude regions, so it was essential to take further regional model means to weaken the error and conduct high accuracy analysis.

Table 2. Distribution of differences and mean precision indexes of CORS station and Radio/PWV.

(a)

| Region   | Station | MEAN /mm | MAX /mm | MIN /mm | STD (standard deviation)/mm | RMS (root-mean-square value) /mm | R (correlation coefficient) |
|----------|---------|----------|---------|---------|------------------------------|---------------------------------|-----------------------------|
| Nanning  | jz02    | -0.306   | 7.620   | -12.980 | 4.415                        | 4.426                           | 0.867                       |
|          | jz04    | 0.273    | 7.290   | -15.170 | 4.821                        | 4.829                           | 0.839                       |
|          | jz05    | 0.519    | 8.060   | -13.050 | 4.059                        | 4.092                           | 0.888                       |
|          | jz14    | 0.747    | 10.340  | -19.370 | 5.551                        | 5.601                           | 0.793                       |
|          | jz28    | 0.659    | 8.290   | -17.730 | 5.146                        | 5.188                           | 0.815                       |
|          | jz57    | -1.741   | 6.240   | -7.890  | 3.336                        | 3.470                           | 0.893                       |
|          | jz60    | 0.566    | 9.310   | -1.496  | 4.545                        | 4.580                           | 0.858                       |
| Mean value |         |          |         |         |                              |                                 | 0.21                        |

(b)

| Region   | Station | MEAN /mm | MAX /mm | MIN /mm | STD (standard deviation)/mm | RMS (root-mean-square value) /mm | R (correlation coefficient) |
|----------|---------|----------|---------|---------|------------------------------|---------------------------------|-----------------------------|
| Wuzhou   | gxgg    | 1.553    | 15.640  | -12.430 | 7.644                        | 7.800                           | 0.495                       |
|          | gxrx    | 1.727    | 10.030  | -7.290  | 4.608                        | 4.921                           | 0.791                       |
|          | gxwz    | -0.954   | 6.240   | -7.890  | 3.336                        | 3.470                           | 0.893                       |
|          | j100    | 1.086    | 11.200  | -11.010 | 5.176                        | 5.288                           | 0.700                       |
|          | j102    | 0.999    | 10.160  | -9.480  | 4.630                        | 4.736                           | 0.771                       |
|          | j103    | 0.403    | 9.270   | -11.970 | 4.942                        | 4.959                           | 0.733                       |
|          | j105    | 0.722    | 9.020   | -6.200  | 4.024                        | 4.088                           | 0.832                       |
|          | j106    | 4.453    | 10.150  | -2.900  | 3.937                        | 5.944                           | 0.844                       |
|          | jz22    | 2.880    | 12.490  | -7.320  | 6.136                        | 6.778                           | 0.658                       |
| Region | Station | MEAN/mm | MAX/mm | MIN/mm | STD(mm) | RMS(mm) | R(correlation coefficient) |
|--------|---------|---------|--------|--------|---------|---------|---------------------------|
| Baise  | gxbs    | 3.692   | 11.700 | -3.840 | 3.448   | 5.052   | 0.822                     |
|        | gxtd    | 2.072   | 15.730 | -8.860 | 4.767   | 5.198   | 0.715                     |
|        | jz47    | 5.931   | 13.260 | 0.880  | 3.039   | 6.665   | 0.850                     |
|        | jz48    | 5.876   | 11.670 | -3.840 | 3.492   | 6.835   | 0.822                     |
|        | jz50    | 3.692   | 11.680 | -3.350 | 3.371   | 4.999   | 0.827                     |
|        | jz51    | 8.243   | 18.630 | 0.300  | 3.626   | 9.005   | 0.797                     |
|        | jz53    | 14.833  | 26.160 | 8.100  | 3.490   | 15.238  | 0.801                     |
|        | jz54    | 12.357  | 24.920 | 4.480  | 3.935   | 12.968  | 0.781                     |
|        | jz56    | 14.081  | 26.600 | 7.610  | 3.785   | 14.581  | 0.797                     |
|        | jz57    | 2.926   | 22.490 | -11.280| 6.075   | 6.743   | 0.599                     |
|        | jz58    | 11.939  | 27.340 | 2.660  | 4.661   | 12.817  | 0.716                     |

Mean value | 7.32 |

It was impossible to conduct targeted data analysis due to the large number and scattered distribution of CORS stations selected in each region in the experiment. In order to make the experimental analysis more clear and intuitive, the calculation accuracy of CORS/PWV and Radio/PWV was further optimized. In this paper, the Inverse Distance Weighted (IDW) was employed to effectively normalize the inversion data of several CORS stations around radiosonde stations to the vicinity of radiosonde stations, namely, the PWV values of radiosonde stations were calculated with CORS/PWV reversely, and a comparative analysis was made with Radio/PWV.

The calculated PWV with IDW method was statistically analyzed, and the trend chart was made by combining the radiosonde data, as shown in figure 5- figure 7. As could be seen from the figures, the PWV calculated by IDW in the three regions was very consistent with the trend of Radio/PWV, and the locations of peaks remained highly consistent, indicating that the PWV calculated by IDW was of good reference value, and could reflect the corresponding changing characteristics of water vapor.
Figure 5. Comparison between IDW/PWV and Radio/ PWV in Nanning.

Figure 6. Comparison between IDW/PWV and Radio/ PWV in Wuzhou.

Figure 7. Comparison between IDW/PWV and Radio/ PWV in Baise.

The data analysis of IDW/PWV and Radio/ PWV was carried out, as shown in table 3. According to the statistical data in table 3, the correlation coefficients of Nanning, Wuzhou and Baise were
greatly improved by IDW. Among them, the IDW/PWV and Radio/ PWV in Nanning were highly overlapped, while the coincidence degree in Baise was the worst; however, the overall correlation had exceeded the correlation between CORS/PWV and Radio/PWV, all of which were greater than 0.8, with the minimum value of 0.80. It could be seen that, the IDW/PWV after regionalization was more consistent with Radio/PWV compared with CORS/PWV. Through data statistics, the mean differences between IDW/PWV and Radio/PWV in Nanning, Wuzhou and Baise were 0.2, 0.3, 4.7 respectively, while the mean differences between CORS/PWV and Radio/PWV in the three regions calculated before were 0.21, 1.67 and 7.32 respectively, which indicated that the introduction of IDW could significantly improve the calculation accuracy of PWV in various aspects, such as correlation, mean value, standard deviation and etc.

Table 3. Analysis and statistics of the differences between IDW/PWV and Radio/PWV.

| Region  | MEAN/mm | MAX/mm | MIN/mm | STD (standard deviation)/mm | RMS (root-mean-square value)/mm | R (correlation coefficient) |
|---------|---------|--------|--------|-------------------------------|---------------------------------|-----------------------------|
| Nanning | -0.2092 | 5.5057 | 0.035  | 2.3558                        | 3.3608                          | 0.8568                      |
| Wuzhou  | -0.2967 | 7.0314 | 0.036  | 3.6252                        | 3.6374                          | 0.8352                      |
| Baise   | -4.6992 | 13.0798| 1.185  | 3.3139                        | 5.7502                          | 0.8050                      |

Figure 8. Correlation analysis of IDW/PWV and Radio/PWV in Nanning.
Figure 9. Correlation analysis of IDW/PWV and Radio/PWV in Wuzhou.

Figure 10. Correlation analysis of IDW/PWV and Radio/PWV in Baise.

As could be seen from figure 8- figure 10, IDW/PWV and Radio/PWV were basically distributed on both sides of the function $y=x$. Since the radiosonde data was collected only twice a day, the corresponding matching data samples were insufficient; especially when the water vapor changed greatly, the error weight of external factors would increase, thereby resulting in a large data deviation. The linear slope $K$ of data fitting by IDW/PWV and Radio/PWV was 0.81 at the minimum, and 0.86 at the maximum. The both had highly consistent sequence variability, which could be used for CORS/PWV monitoring, water vapor prediction and so on.

The maximum RMS (root-mean-square) error, 5.75nm, occurred in Baise with the highest altitude. The root-mean-square error in Nanning and Wuzhou was far less than that in Baise, which indicated that under a certain distance, the higher the altitude, the greater the RMS value between IDW/PWV and Radio/PWV, namely, the greater data dispersion degree. The differences between the two are shown in figure 11- figure 13. It could be seen that the maximum difference between the two was still 13.1mm in Baise, which also proved that different terrains and elevations had different effects on RMS under the same condition.

According to the comparative analysis above, CORS/PWV, IDW/PWV and Radio/PWV were highly consistent in the variation sequence, among which the correlation between IDW/PWV and Radio/PWV was the optimal. Under the same condition, the PWV difference and RMS were the largest, while the correlation coefficient $R$ was the smallest in the high-altitude mountainous areas.
3.2 Comparative analysis of CORS/PWV characteristic changes and actual rainfall

The actual rainfall data was obtained by referring to the meteorological data of the three regions, and
The mapping analysis was made in combination with CORS/PWV (Figure 13-15). Based on the data analysis of the three regions, it was found that the variation of CORS/PWV was significantly correlated with the actual rainfall, which was very obvious in the case of extreme weather and heavy precipitation. Rainfall mostly occurred near the peak or valley value of PWV, and generally, the greater the PWV change rate, the greater the precipitation, and the better the coincidence between the PWV change rate and precipitation.
As the most violent typhoon, when Typhoon Hato landed in Guangdong, its formed air mass had affected Guangxi already, so significant change of CORS/PWV in Nanning and Wuzhou close to the typhoon landing place had occurred on August 20, especially in Nanning, with the average daily rate of more than 20 mm/d on August 20 and 21, and greater than 30 mm/d on August 22, and the whole changing process was mainly completed within 12 hours. The CORS/PWV values in the three regions had reached the peak of the same month after two days of drastic changes before the typhoon invaded Guangxi on August 23, which had accumulated sufficient water vapor for the torrential rain on August 23 and 24.

From the perspective of topographic factors, Wuzhou was the first place invaded by the typhoon; therefore, heavy rainfall came first in Wuzhou on August 21, 2017 and ended first too; the CORS/PWV in Wuzhou decreased significantly and rainfall decreased after 12:00 on August 21. With the drastic change of PWV, heavy rainfall occurred in Nanning on August 22, with the hourly rainfall exceeding 15mm and the average daily rainfall exceeding 100mm, which belonged to the category of heavy rainstorm. The high-intensity rainfall lasted until the end of August 24. In Baise, rainfall began after August 24, with the average daily rainfall reaching 65mm, and the duration of only one day.

Among the three regions, Nanning showed the highest intensity and longest duration of rainfall, which was mainly because Nanning was on the path of the typhoon, and the typhoon intensity was not weakened too much when passing over Nanning. Wuzhou was far from the path of typhoon, and the typhoon in Baise was weakened to a tropical storm; in addition, the influence of terrain caused water-vapor diversion in such two mountainous regions, so it was unable to form high-intensity precipitation like that in plain area. Therefore, the intensity and duration of rainfall in the two regions were relatively weaker and less affected.

To sum up, a lot of factors can affect rainfall, and it is very complicated to make quantitative analysis. Among them, the formation of weak rainfalls shows greater randomness, and poor correlation with water vapor; the occurrence of heavy rainfalls is mainly concentrated in the peak or valley value of CORS/PWV. Whenever the CORS/PWV value changes sharply and the daily change rate exceeds 20mm/d, the probability of heavy rainfall will increase rapidly. This is because the CORS/PWV does not show simple direct ratio with the actual precipitation, the total water vapor content in the atmosphere measured by CORS/PWV is not sensitive to the cloud liquid water, and the water vapor gradient value, water vapor convergence and divergence, weather system and etc. also have significant influence on the size and duration of rainfall [11], so it is essential to make an overall consideration of mean value, peak size, increasing range and other conditions. [12]. Therefore, the sudden variation of CORS/PWV can play a certain role in predicting rainfall.
4. Conclusions
Based on the analysis of CORS station data and corresponding radiosonde data in time series and various accuracy indexes in the three regions along the path of Typhoon Hato before and after it passed over Guangxi, the following conclusions are concluded:

(1) CORS/PWV and Radio/PWV showed good consistency in both overall trend and peak point in spite of the large data difference between the both at a few time points; the worst correlation with the radiosonde data in high-altitude mountain areas could be seen, but the best correlation with that in the low-altitude plains.

(2) The PWV calculated with Inverse Distance weighted (IDW) showed high consistency and correlation with Radio/PWV, which had better analysis accuracy RMS, smaller PWV difference, and higher correlation coefficient R compared with the directly reverse-calculated PWV with CORS data. The introduction of IDW greatly weakened the gross error in the inversion calculation of PWV with CORS data, and improved the calculation accuracy to 50% above.

(3) Both the directly obtained CORS/PWV data and the optimized IDW/PWV maintained highly consistent with Radio/PWV in the overall trend, and the sudden change in the peak value of PWV could maintain a good corresponding relation with the extreme weather variations and torrential rains in practical application, which indicated the short-term variation in the CORS/PWV and optimized PWV was of high reference value to extreme weather monitoring and forecasting.

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