JPNT 4(2), 87-95 (2015)
http://dx.doi.org/10.11003/JPNT.2015.4.2.087

JPNT Journal of Positioning, Navigation, and Timing

Analysis of Temporal and Spatial Variation of Precipitable Water Vapor According to Path of Typhoon EWINIAR using GPS Permanent Stations

Jihye Won[1†], Dusik Kim[2]

[1]Jipyong Space Inc., Incheon 402-751, Korea
[2]Department of Geoinformatic Engineering, Inha University, Incheon 402-751, Korea

ABSTRACT

In this study, the temporal and spatial variation in precipitable water vapor (PWV) was analyzed for typhoon Ewiniar which had made landfall in the Korean peninsula in 2006. To make a contour map of PWV, zenith total delay (ZTD) was calculated using about 60 GPS permanent stations in Korea, and the pressure and temperature data of nearby AWS stations were interpolated and applied to the equation for calculating the PWV. While Typhoon Ewiniar was migrating north from the southern coast to the eastern coast of Korea, the PWV migrated showing a spatial distribution similar to that of rainfall. Also, the fluctuating pattern of the normalized PWV was analyzed, and the moving speed of the PWV was estimated using the delay time of the increase/decrease pattern in the eight-test stations. The result indicated that the moving speed of the PWV was about 35 km/h, which was similar to the average moving speed of the typhoon (38.9 km/h).

Keywords: EWINIAR, GPS, precipitable water vapor, rainfall, normalized PWV

1. INTRODUCTION

In recent years, severe droughts and floods have frequently occurred due to climate change, and these phenomena are expected to increase in the future. According to the fourth assessment report of the Intergovernmental Panel on Climate Change (Solomon 2007), the average temperature of the Earth would increase by up to 4.0℃ and the sea level would rise by 58 cm by 2100; and tropical cyclones (typhoons) have shown stronger intensity and longer duration since the mid-1970s. It was mentioned that this is closely related with the increase in the sea surface temperature of tropical regions (Oh et al. 2011). If the temperature of the Earth's surface increases, the supply of heat energy that is used as the power source of typhoons and the increase of the water vapor over tropical ocean are promoted, and thus the intensity and occurrence frequency of typhoons increase due to global warming. Webster et al. (2005) and Emanuel (2005) emphasized the increase in the risk of typhoons due to global warming, and Kerr (2005) forewarned the occurrence of a typhoon that is stronger than Hurricane Katrina. In Korea, the National Institute of Meteorological Research analyzed the trend in typhoons, and predicted that the number of summer typhoons would increase by 35.6% when the CO_2 concentration doubles, and the maximum wind speed and duration of typhoons would also increase in a warm climate (Park et al. 2013).

According to these studies, Korea is a region where rainfall is expected to increase due to typhoons in the future, and the damage and casualties due to floods are expected to increase since rainfall is concentrated in the summer season. However, it is difficult to reproduce precipitation occurrence in the current condition based on the modeling of the global circulation model and the regional circulation model depending on the climate change scenario (Park et al. 2013); and a supercomputer with a fast computational capacity is used for accurate forecast of precipitation, but

Received May 12, 2015 **Revised** May 18, 2015 **Accepted** May 19, 2015
†**Corresponding Author**
E-mail: jihyewon.82@gmail.com
Tel: +82-32-873-4305 Fax: +82-2-6455-4305

http://www.gnss.or.kr Print ISSN: 2288-8187 Online ISSN: 2289-0866

the uncertainty of estimated precipitation and weather forecast still exists.

To establish an emergency action plan for floods, probable maximum precipitation (PMP), which defines the magnitude of extreme rain storm, should be accurately predicted. The PMP is obtained through multiplying the rainfall of major observed heavy rain by a moisture maximizing rate. The moisture maximizing rate is defined as the ratio of probable maximum rainfall to observed rainfall. However, it is difficult to directly obtain probable maximum rainfall, and thus a meteorological factor called precipitable water vapor (PWV) is used. In the end, PWV is the most important factor for the estimation of a moisture maximizing rate (Park et al. 2013).

PWV expresses the amount of water vapor in the vertical column of the atmosphere as the depth of water, and representative ground-based observation equipment includes radiosonde observation, microwave radiometer (MWR), and global positioning system (GPS). A radiosonde is the most widely used upper air observation equipment. An observation instrument is attached to a balloon and is flown into the atmosphere, and the meteorological information observed at each altitude is transmitted to the ground. A radiosonde can directly observe the meteorological information of the upper atmosphere, but continuous observation is difficult because one observation costs about 4 million won and only two to four observations are carried out per day. MWR is equipment that measures PWV by measuring the radiation energy of the atmosphere. MWR can measure the vertical structure of the atmosphere in real time. However, it cannot measure the variation in PWV during the occurrence of meteorological phenomena such as a typhoon because abnormal values are obtained when there is heavy rain or snow. On the other hand, GPS is capable of 24-hour continuous observation regardless of weather phenomena. Thus, it has been widely used in the United States, Europe, and Japan; and the observation of PWV using GPS has also gradually increased in Korea.

According to the result of previous studies (Ha et al. 2007, Kim et al. 2010, Sohn et al. 2013), the PWV obtained from GPS was precise at a 1~3 mm level compared to the values obtained from a radiosonde or MWR. Therefore, if PWV is calculated using all the GPS permanent stations distributed over the Korean peninsula, continuous observation can be obtained at a high spatial resolution; and based on this, the temporal/spatial variation of PWV can be examined. In Korea, Song & Yun (2006) analyzed the temporal and spatial variation of GPS PWV in the area affected by typhoon Ewiniar, and compared the contour map of the PWV with the water vapor image taken by the Multi-functional Transport Satellite, which is a meteorological satellite, and the constant maximum composite image taken by ground-based radar. However, in the previous study, only 22 permanent GPS stations were used, and comparison with actual rainfall was rather insufficient.

For detailed analysis of the temporal and spatial variation of the PWV during the occurrence of typhoon Ewiniar, the PWV was calculated for 60 GPS permanent stations, and this was compared with the rainfall information obtained from AWS stations. Also, to analyze the migration of the typhoon and the resultant variation in PWV, the moving speeds of the PWV and the typhoon were calculated and compared.

2. PWV CALCULATION BASED ON GPS

When passing through the atmosphere, GPS signals are refracted and delayed by hydrostatic gases and water vapor. A hydrostatic delay, which accounts for 90% of the tropospheric error, has a physically stable distribution, and can be accurately predicted using pressure; but a wet delay, which accounts for 10% of the tropospheric error, varies significantly depending on the metrological condition, and thus accurate correction is difficult. However, if the value for a wet delay is estimated as an unknown in high-precision data processing, PWV can be accurately calculated based on this.

The signal delay due to the troposphere can be expressed as the delay in the zenith direction, as shown in Eq. (1). In this regard, zenith total delay (ZTD) is expressed as the sum of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD).

$$ZTD=ZHD+ZWD \tag{1}$$

In GPS data processing, ZTD can be defined using a priori hydrostatic delay (AHD), a priori wet delay (AWD), and zenith delay correction (ZDC); and their relationship is shown in Eq. (2).

$$ZTD=AHD+AWD+ZDC \tag{2}$$

AHD is a function of altitude (h); it was calculated using Eq. (3) (Webb & Zumberge 1993). For AWD, 0.1 m was applied, similar to previous studies (Ha et al. 2005, Kim et al. 2012).

$$AHD=2.29951e^{-0.000116h} \tag{3}$$

In GPS data processing, ZDC is estimated as an unknown,

http://dx.doi.org/10.11003/JPNT.2015.4.2.087

and ZTD can then be accurately calculated. In this regard, if ZHD is accurately calculated using pressure information, ZWD can be calculated by subtracting the ZHD from the ZTD, based on the relationship in Eq. (1). In the present study, ZHD was calculated using Eq. (4), which is the Saastamoinen model (Saastamoinen 1972).

$$ZHD = \frac{(2.2779 \pm 0.0024)P_s}{1 - 0.00266\cos 2\phi - 0.00028h} \tag{4}$$

where ϕ is the latitude of the station, h is the altitude (km), and P_s is the surface pressure (hPa). The ZWD can be converted to the PWV as shown in Eq. (5).

$$\mathrm{PWV} = \frac{\mathrm{ZWD}}{\rho R_v \left[\frac{k_3}{T_m} + k_2'\right]} \tag{5}$$

where ρ is the density of water (998.00897 [kg/m^3]), and R_v is the specific volume of water vapor (4.165 × 10^2 [J/kg•K]). and k'_2 are k_3 refractivity, and 17±10 [K/hPa] and (3.776±0.004)×10^5 [K^2/hPa] were applied, respectively (Davis et al. 1985). T_m is the mean temperature [K]; and in the present study, the HP model which is the mean temperature equation for Korea developed in 2008 was used (Ha & Park 2008). The HP model equation can be expressed as Eq. (6).

$$T_m = 0.884\, T_s + 23.4 \tag{6}$$

where T_s is the surface temperature for the station [K]. Therefore, to calculate PWV using GPS, the pressure and temperature information of the GPS station is required for Eqs. (4) and (6). However, most GPS permanent stations in Korea have no meteorological sensors, and thus the pressure and temperature information collected from nearby AWS stations needs to be used via interpolation.

Kim et al. (2010) suggested an interpolation method for pressure and temperature based on reverse sea level correction and altitude correction; and found that the pressure showed the root mean square error (RMSE) 0.97 hPa and the temperature showed the RMSE 2.18℃ by analyzing about three-month data. The study has shown that the effect of interpolation error on the calculation of PWV is not large (0.3 mm level). Therefore, in the present study, temperature values were calculated using a proportional expression where the temperature decreases by 0.5℃ per 100 m increase in the altitude, and pressure values were calculated by converting the AWS pressure information into the values at the locations of the GPS stations based on reverse sea level correction, following the method suggested by Kim et al. (2010).

3. RESEARCH SUBJECT AND DATA

3.1 Typhoon Ewiniar

Typhoon Ewiniar was the third typhoon in 2006. It was formed 1,010 km southwest of Guam, the United States at 03:00, July 1 (UTC), and gradually developed while moving northwest (Fig. 1). Then, it weakened to a central pressure of 975 hPa and a maximum wind speed of 31 m/s, which is intensity 'medium', on the sea about 120 km south of Mokpo, and the Korean peninsula was indirectly affected by the typhoon from July 8 due to the effect of the westerlies from China. The typhoon made landfall in the coast of Jindo-gun, Jeollanam-do on July 10, and dissipated near Hongcheon-gun, Gangwon-do at around 13:00, July 10. In Korea, a seasonal rain front stayed between Jeju and the southern region from early July, 2006, and there was a lot of precipitation centering on Jeju Island and the southern region. Then, there was a lot

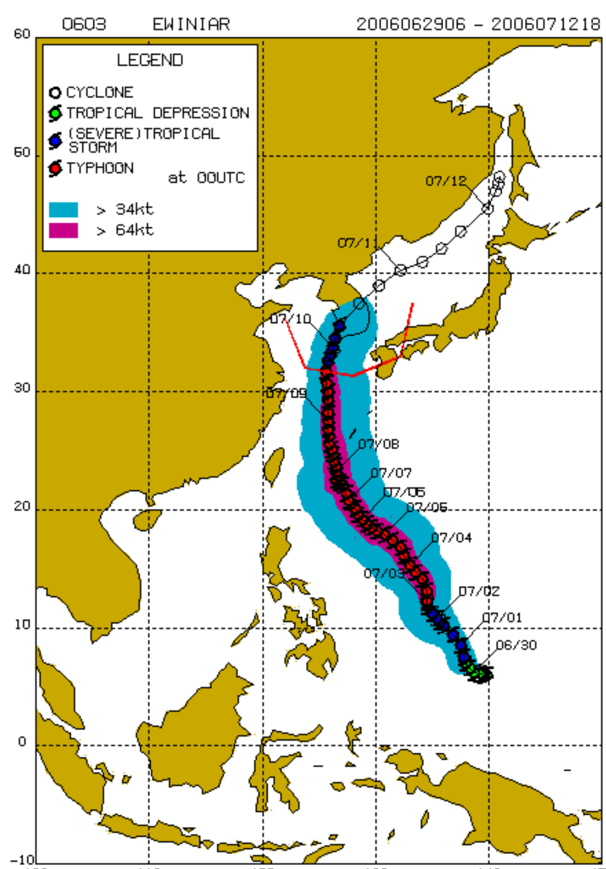

Fig. 1. EWINIAR's moving path.

of rain due to the trough developed on the seasonal rain front and the direct effect of typhoon Ewiniar, causing 655 victims and a total of nine casualties (death and missing) on a national scale.

3.2 GPS Observation Data

In 2006, a total of 84 stations were operated in Korea, but PWV was calculated for 60 stations where data could be secured from July 7 (DOY: 188) to July 12 (DOY: 193) when the Korean peninsula was affected by the typhoon. Fig. 2 shows the locations of the permanent stations operated by Korea Astronomy and Space Science Institute (KASI), Korea Hydrographic and Oceanographic Administration (KHOA), DGNSS Central Office (DCO), and National Geographic Information Institute (NGII) in 2006. Also, in Fig. 2, the locations of a total of eight stations were numbered. These represent the target stations at each latitude for estimating the moving speed of the PWV. Table 1 summarizes the location information of the eight stations marked in the Fig. 2. In this study, the GIPSY5.0 software developed by jet propulsion laboratory (JPL) was used to process the GPS observation data, and 10-minute interval ZTD was estimated using the precise ephemeris provided by JPL, which was then used for the calculation of PWV.

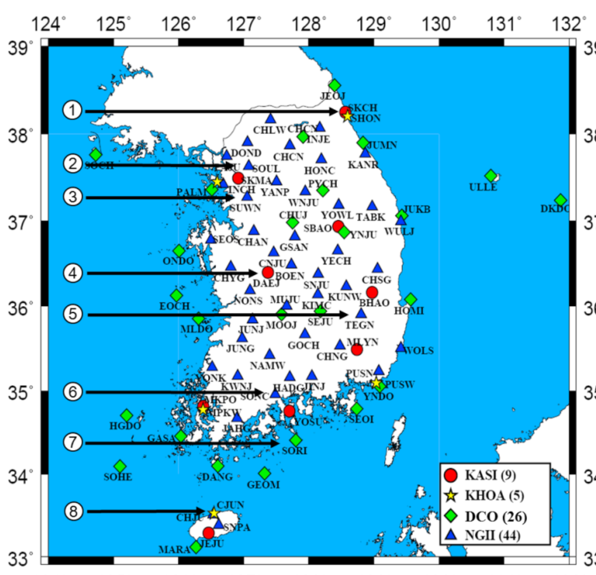

Fig. 2. Location of GPS permanent stations in Korea.

Table 1. Information of 8 GPS stations used in calculation of velocity.

No	Site	Lat (°N)	Lon (°E)	No	Site	Lat (°N)	Lon (°E)
1	SKCH	38.2509	128.5647	5	TEGN	35.9063	128.8020
2	SOUL	37.6297	127.0797	6	SONC	34.9575	127.4861
3	SUWN	37.2755	127.0542	7	SORI	34.4119	127.8010
4	DAEJ	36.3994	127.3745	8	CHJU	33.5139	126.5298

3.3 Meteorological Observation Data

The meteorological observation data were collected from 460 AWS stations in Korea, and the pressure and temperature information are converted the values at the GPS stations using reverse sea level correction and altitude interpolation. The pressure and temperature information at the GPS station was interpolated using three AWS stations that are closest to the GPS station, respectively. And an average value was used by applying the inverse distance weighted method, which resolved the problem of meteorological data omission due to the missing data of AWS. Also, in order to make a contour map, the cumulative hourly rainfall information collected from the AWS stations; and based on this, the temporal and spatial variation in rainfall depending on the elapsed time of the typhoon was compared with the temporal and spatial variation in PWV.

4. VARIATION OF PWV IN THE AREA AFFECTED BY THE TYPHOON

4.1 Comparison with the Rainfall Contour Map

PWV is a factor for expressing the amount of water vapor in the atmosphere, and is used as an index for estimating potential rainfall. For PWV to be converted to rainfall, various meteorological conditions should be satisfied; and it is not that 100% of the amount is converted to rainfall even though the meteorological conditions are satisfied. Thus, there is a limitation in the direct comparison of PWV and rainfall. However, PWV actually represents the introduction of water vapor that could be converted to rainfall, and the direct comparison of PWV and rainfall has been occasionally performed in the meteorological research field. However, there has been no study in which PWV was calculated for the entire Korean Peninsula at a dense spatial resolution during a typhoon period and this was spatially compared with rainfall. In several previous studies, the time series of PWV calculated for less than 10 permanent stations was directly compared with rainfall, but the temporal and spatial variation could not be examined since a contour map was not used (Song & Yun 2006, Ha et al. 2007).

To compare PWV and rainfall in areas affected by a typhoon, it is important to first analyze the variations for

http://dx.doi.org/10.11003/JPNT.2015.4.2.087

the same period. The GPS PWV is calculated at 10-minute intervals, while AWS provides values that have been accumulated for one hour. The physical and temporal meanings of the two values are different, and thus it is virtually impossible to compare the two values in an equivalent condition. Therefore, in this study, an average value of the PWV observed for one hour was calculated as a representative value, and this was compared with the one-hour cumulative rainfall. For example, when data from 00:00 to 01:00 were used for the analysis, they were expressed as the values at 00:30. Fig. 3 shows the contour maps of the one-hour average PWV and the one-hour cumulative rainfall, respectively, calculated for about 60 GPS permanent stations. The figure shows the values at three-hour intervals from 18:30, July 9 (DOY: 190), which was just before the Korean peninsula was directly affected by the typhoon, to 09:30, July 10 (DOY: 191). A total of six sets of contour maps were made depending on the time interval (T1~T6), where the PWV contour maps were shown on the top and the cumulative rainfall contour maps at the bottom. Also, the center location of the typhoon was marked on the PWV contour map in Fig. 3 (T1) so that the moving path of the typhoon could be examined. Table 2 summarizes the detailed information depending on the moving path of the typhoon.

Typhoon Ewiniar first made landfall in Jeju Island, migrated north, and dissipated in Hongcheon, Gangwon-do. According to the rainfall contour map in Fig. 3, the pattern of rainfall occurrence area was consistent with the typhoon moving. First, the rainfall in Jeju and the southern coast significantly increased; and as time passed, there was a lot of rain in Gyeongsang-do, the Yeongdong region, and Gangwon-do. When the PWV contour map was compared together, detailed distribution was different, but the overall moving pattern was consistent with the moving pattern of the rainfall. Also, the PWV was maintained at a 40~50 mm level even when there was no rain, and it increased up to a 70 mm level in areas with rain. On the other hand, the rainfall ranged from 0 mm to 50 mm when compared with the case without rain. In addition, the rainfall showed a locally more sporadic pattern than the PWV. This indicates that for PWV to be converted to rainfall, complicated and diverse conditions need to be considered at the same time.

Table 2. Track of Typhoon EWINIAR on Jul 10, 2006.

No	Time [UTC]	Lat [˚N]	Lon [˚E]	Distance from (a) [km]
(a)	00:00	33.8	126.2	-
(b)	03:00	34.5	126.4	79.8
(c)	06:00	35.6	126.8	127.4
(d)	12:00	37.5	128.5	260.0

4.2 Calculation of the Moving Speed of the PWV

To temporally and spatially analyze the variation of PWV in areas affected by the typhoon, the PWV time series are calculated using about 60 GPS permanent stations were shown in Fig. 4 depending on the latitude. On the left side of Fig. 4, the time series of the PWV were presented by classifying the coordinates of the stations at 1˚ latitude intervals; and on the right side, the individual time series of the PWV were presented by selecting eight stations that represent each latitude. According to the left graph in Fig. 4, the shapes of the PWV time series for the stations located within the same latitude seem to be generally similar. In addition, the values changed steeply depending on the (a) indirect influence, (b) direct influence, and (c) dissipation of the typhoon, and the times for the occurrence of the maximum and minimum values were slightly delayed depending on the latitude.

According to Fig. 4 (left), in the low-latitude region (33˚-34˚), the PWV increased steeply in the early stage of typhoon formation (a) and the size was maintained; while there was no significant rise as the latitude increased. It is thought that typhoon Ewiniar affected the low-latitude region in the early stage of formation (a), and then gradually increased the PWV in the high-latitude region (37˚-38˚) as the typhoon migrated north. This phenomenon is represented by the delay of the time for the occurrence of the maximum PWV with time, and the general shape of the time series seems to be maintained. To compare the times for the occurrence of the maximum and minimum values of the time series depending on the latitude, the PWV was normalized using Eq. (7).

$$N_{pq} = \frac{I_p(t_q) - \mu_p}{\sigma_p} \quad (7)$$

where N_{pq} is the normalized PWV, $I_p(t_q)$ is the PWV value at the q-th time calculated at the p-th station, μ_p is the mean, and σ_p is the standard deviation. Fig. 5 shows the PWV of the eight stations normalized by Eq. (7). The left side of the figure shows the original time series. As shown in the figure, the time for the increase in PWV was delayed as the latitude increased.

For the normalized PWV calculated at the eight stations, the signal delay time was measured by performing a cross-correlation analysis based on the CHJU station. The values after the correction of the delay time were shown in Fig. 5 (right). After the correction of the delay time, the times for

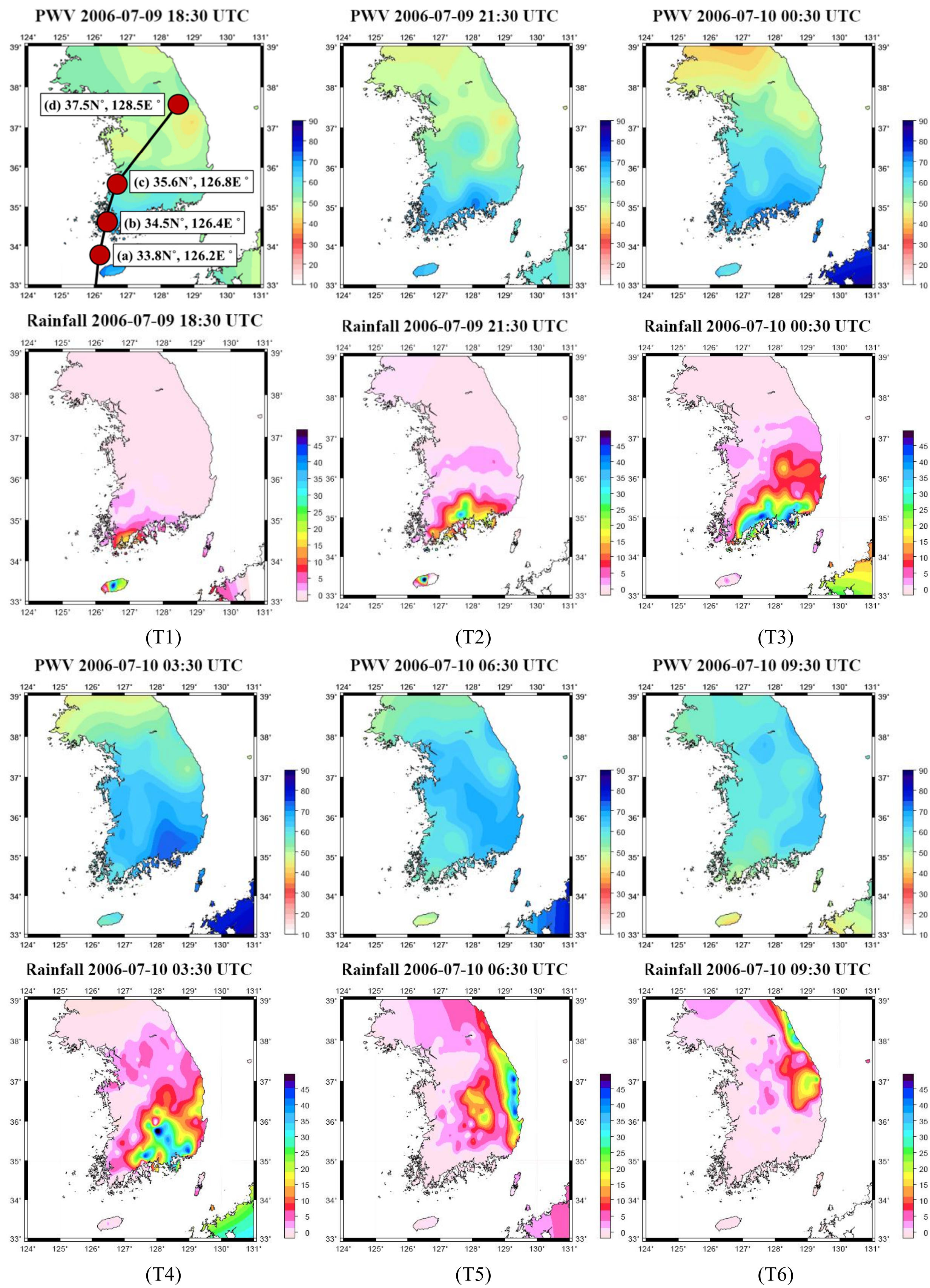

Fig. 3. Comparison of the one-hour average PWV and the cumulative rainfall in areas affected by Typhoon EWINIAR (unit: mm).

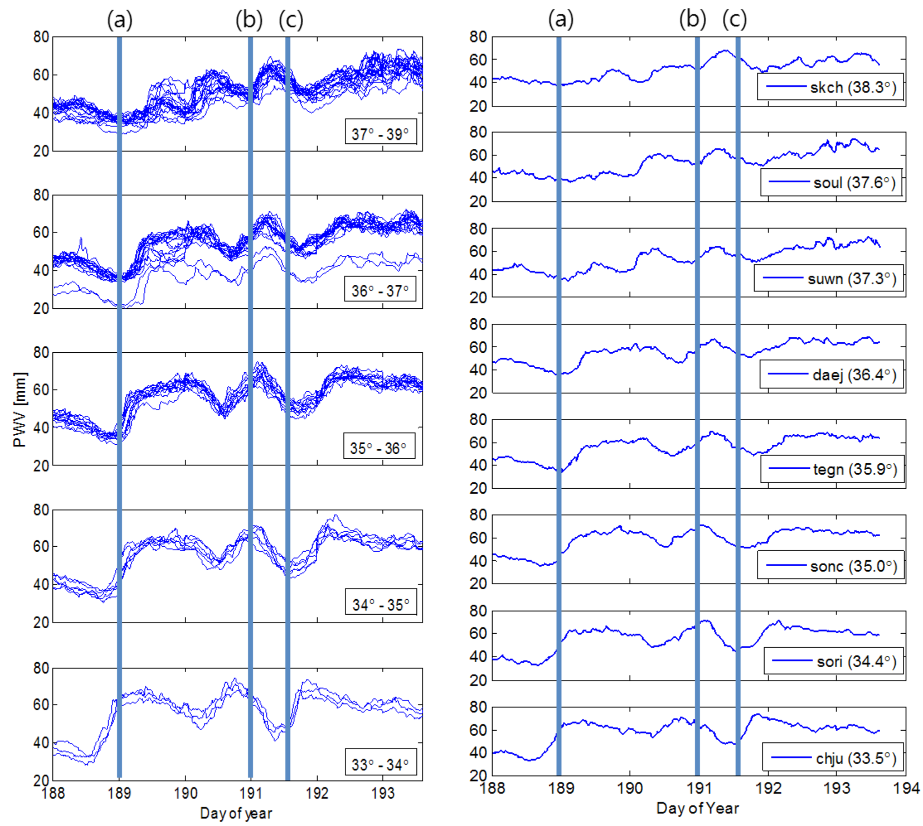

Fig. 4. Time series of the PWV depending on the latitude (left) and the time series of the PWV for the eight representative stations (right).

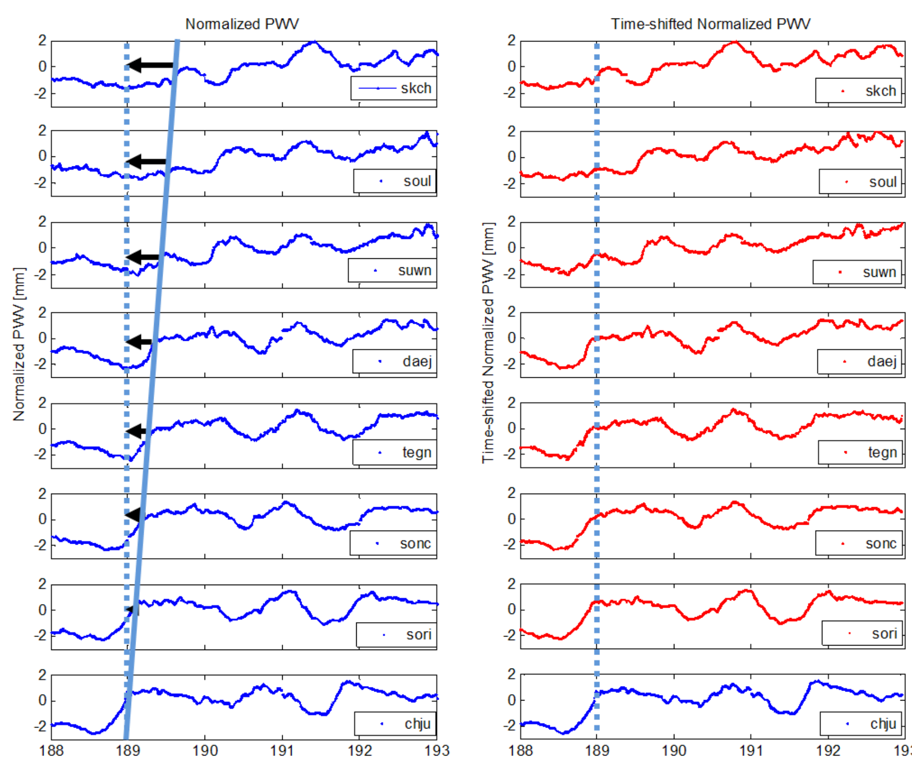

Fig. 5. Normalized original PWV time series (left) and the time series after the correction of the delay time (right).

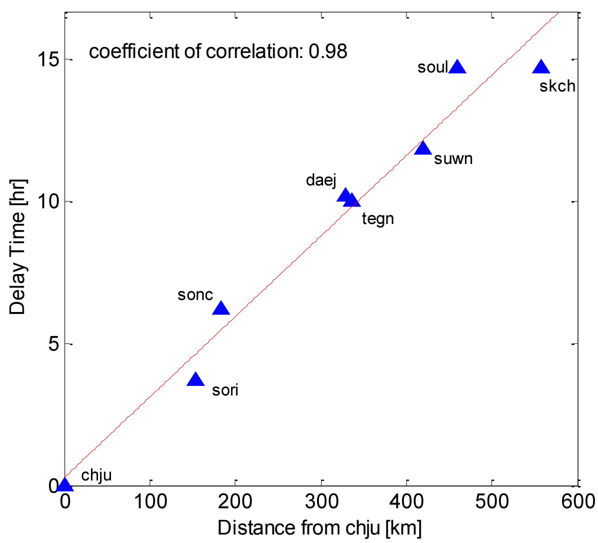

Fig. 6. Correlation between the baseline distance of the station and the delay time of the PWV.

the oscillation of the time series were mostly consistent. The baseline distance was calculated based on the CHJU station, and its correlation with the delay time was analyzed, as shown in Fig. 6. The correlation coefficient between the baseline distance of the reference station and the delay time was very high (0.98). When the moving speed of the PWV was estimated based on the above relationship, it was about 35 km/h. To compare the moving speed of the PWV with the moving speed of typhoon Ewiniar that had made landfall in the Korean peninsula, the moving speed of the typhoon was estimated based on the center location and observation time of typhoon Ewiniar announced by the Typhoon Research Center (Table 2). The calculation of the speed using the center location and observation time of typhoon Ewiniar from 00:00 to 12:00, July 10, 2006 indicated that it was 26.6 km/h between (a) and (b) in Fig. 3 (T1), 42.5 km/h between (b) and (c), and 43.3 km/h between (c) and (d). The moving speeds of the typhoon in each section were different from the moving speed of the PWV, but the average speed for the entire moving path [between (a) and (d) in Fig. 3 (T1)] was 38.9 km/h, which was similar to the moving speed of the PWV.

5. SUMMARY AND CONCLUSION

In this study, high-resolution contour maps of the PWV calculated from about 60 GPS stations were generated for the first time in Korea. By comparing them with rainfall contour maps, it was found that the moving paths of the PWV and the rainfall depending on the migration of a typhoon were similar. However, the distribution of the PWV was generally smooth, but the distribution of the rainfall was locally sporadic and showed a large variation. This indicates that various meteorological elements other than the inflow of PWV had large effects on the formation of rain. In addition, the increase and decrease in the PWV depending on the northward migration of the typhoon were analyzed based on the time series of the normalized PWV. The moving speed of the PWV was estimated by observing the delay time of the increase/decrease pattern for the PWV at each station. The result indicated that the moving speed of the PWV was about 35 km/h, which was similar to the average moving speed of typhoon Ewiniar (38.9 km/h).

ACKNOWLEDGMENTS

This research was supported by a grant from “Development of GNSS based Transportation Infrastructure Technology” funded by Ministry of Land, Infrastructure and Transport of Korean government.

REFERENCES

Davis, J. L., Herring, T. A., Shapiro, I. I., Rogers, A. E. E., & Elgered, G. 1985, Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length, Radio Science, 20, 1593-1607. http://dx.doi.org/10.1029/RS020i006p01593

Emanuel, K. 2005, Increasing destructiveness of trophical cyclones over the past 30 years, Nature, 436, 686-688. http://dx.doi.org/10.1038/nature03906

Ha, J. & Park, K.-D. 2008, Comparison of local mean temperature equations for GPS-based precipitable water vapor determination, Journal of Astronomy and Space Sciences, 25, 425-434. http://dx.doi.org/10.5140/JASS.2008.25.4.425

Ha, J., Park, K.-D., Chang, K.-H., & Yang, H.-Y. 2007, Precision validation of GPS precipitable water vapor via comparison with MWR measurements, Atmosphere, 17, 291-298

Ha, J., Park, K.-D., Park, P.-H., & Park, J.-U. 2005, Analysis of error sources in determination of tropospheric slant wet delay using GPS, Journal of the Korean Meteorological Society, 41, 337-346. http://www.dbpia.co.kr/Journal/ArticleDetail/773677

Kerr, R. A. 2005, Is Katrina a harbinger of still more powerful hurricanes?, Atmospheric Science, 309, 1807. http://dx.doi.org/10.1126/science.309.5742.1807

Kim, D. S., Won, J. H., Kim, H. I., Kim, K. H., & Park, K. D. 2010, Accuracy analysis of GPS-derived precipitable water vapor according to interpolation methods of meteorological data, Journal of Korea Spatial Information Society, 18, 33-41

Kim, D., Won, J., Son, E. S., & Park, K. D. 2012, Generation of grid maps of GPS signal delays in the troposphere and analysis of relative point positioning accuracy enhancement, Journal of Korean Navigation and Port Research, 36, 825-832. http://dx.doi.org/10.5394/KINPR.2012.36.10.825

Oh, J. H., Suh, K. D., & Kim, Y. O. 2011, Trend Analyses of Intensity and Duration of Typhoon That Influenced the Korean Peninsula during Past 60 Years, Journal of the Korean Society of Civil Engineers, 31,121-128

Park, M., Park, M., Kim, S., & Joo, J. 2013, Extreme storm estimation by climate change using precipitable water, Journal of the Korean Society of Hazard Mitigation, 13, 121-127. http://dx.doi.org/10.9798/KOSHAM.2013.13.1.121

Saastamoinen, J. 1972, Atmospheric Correction for Troposphere and Stratosphere in Radio Ranging of Satellites, In: Transactions-American Geophysical Union, vol. 52 (Washington, D.C: American Geophysical Union)

Sohn, D. H., Park, K. D., & Kim, Y. H. 2013, Determination of precipitable water vapor from combined GPS/GLONASS measurements and its accuracy validation, Journal of the Korean Society for Geospatial Information System, 21, 95-100. http://dx.doi.org/10.7319/kogsis.2013.21.4.095

Solomon, S. (Ed.). 2007, Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC, vol. 4 (Cambridge: Cambridge University Press)

Song, D. S. & Yun, H. S. 2006, Analysis of GPS precipitable wataer vapor variation ;during the influence of a typhoon EWINIAR, Journal of the Korean Society of Civil Engineers, 26, 1033-1041

Webb, F. H. & Zumberge, J. F. 1993, An introduction to GIPSY/OASIS-II (Pasadena, CA: JPL Publ.)

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. 2005, Changes in tropical cyclone number, duration, and intensity in a warming environment, Science, 309, 1844-1846. http://dx.doi.org/10.1126/science.1116448

Jihye Won received Ph.D. degree in Geoinformatic Engineering from Inha University, and she is currently at Research Institute of Jipyong Space Inc. Her research interests include GNSS PPP-RTK data processing algorithm and modeling of the GNSS error sources.

Dusik Kim received M.S. degree from the Geoinformatic Engineering at the Inha University, and he is currently at Inha University as a Ph.D. candidate. His research interests include GNSS Geodesy, Meteorology, Seismology and Ionosphere modeling.