Correlating the Transport of Precipitable Water Vapor with Rainfall in a Complex Orographic Environment Before, During and After a Typhoon: Case Study of Typhoon Morakot

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Abstract

On August 7, 2009 typhoon Morakot struck Taiwan producing 1504 mm of rain in a 24-hour period, making it the second largest rainfall event recorded. The flooding and landslides associated with Morakot claimed more than 700 lives and caused major damage in Taiwan. In-situ observations of precipitable water vapor (PWV) from 82 GPS stations and 450 rain gauges operated by the Taiwanese Central Weather Bureau (CWB) captured the significant features of this storm as it struck the island nation. Forecasts of this storm made using the Advanced Weather Research Forecast model (WRF-ARW) failed to resolve heavy localized rainfall associated with Taiwan's complex topography and had subtle. This research compared model generated PWV and rainfall to in-situ data to evaluate the performance of the WRF-ARW during the passage of Morakot. The vast distribution of GPS provided reliable PWV estimations which proved useful in verifying model PWV in complex terrain. Coupling of GPS PWV and rain gauge stations also helped diagnose the mesoscale structure of the rain around the Central Mountain Region (CMR) of Taiwan. This study provides a better understanding of how complex terrain influences heavy localized precipitation and PWV distribution before, during and after typhoon Morakot. It is hypothesized that a finer resolution terrain model and modified precipitation parameterizations could improve the WRF-ARW rainfall prediction.
1. Introduction

On August 7, 2009 1530 UTC Typhoon Morakot made landfall in Taiwan as a category 2 typhoon according to the Saffir-Simpson scale. Over the next twenty four hours 1504 mm of rainfall fell over Taiwan breaking the 50 year record. After 96 hours Typhoon Morakot caused an estimated $3.3 billion in damages with over 700 casualties. The Saffir-Simpson scale rates hurricane/typhoon damage based on wind strength and not on potential rainfall damages so the people of Taiwan underestimated the potential destruction of this moderate strength typhoon and were caught off guard. In addition, the Advanced Weather Research Forecast Model (WRF-ARW) failed to forecast adequate rainfall amounts and misrepresented the storm track (Fig.1). Greenwald (1991), IPCC (1992) stressed the importance of proper analysis of PWV because the phase change from water vapor to rain can significantly impact vertical stability, radiational energy balance of the earth-atmosphere system, and storm structure and evolution as noted in Businger et al. (1994). Errors in model PWV and terrain resolution are thought to be two potential sources of error in WRF-ARW model performance for this storm. A better understanding of the errors associated with both model PWV and terrain resolution can be used to improve future forecasts which can improve risk management decisions to reduce costs and loss of lives. Our research project used ground-base GPS stations to measure and correlate PWV distribution before, during, and after the typhoon with gauged rainfall amounts in order to identify the geographical areas most influenced by the passing of a typhoon. In situ model terrain and model rainfall error were also compared and analyzed. The topographic effects of Typhoon Morakot will be outlined in section 1 a., section 2 b. will discuss the inner workings of the WRF-ARW model, section 1 c. will discuss the physics behind ground-base GPS, section 2
summarizes methodology while section 3 reveals results, section 4 is the discussion, and section 5.

Figure 1. The figure on the left shows the storm track forecast courtesy of the Naval Research Laboratory in Monterey, California (NRL). On the left is the storm forecast (noted in pink) as of August 6, 2009 at 0000Z. On the right is the observed landing (noted in black color) of typhoon Morakot for August 7, 2009 1800Z. Filled in circles are observed winds more than 63 knots unfilled circles are observed winds between 34-63 knots.

a. The Complex Orographic Environment

Taiwan has a unique environment in that it is a heavily mountainous island centered on the Tropic of Cancer. The southern sector of Taiwan experiences warm temperature year round while the northern sector tends to have more seasonal conditions. The Central Mountain Range (CMR) is the dominant mountain range in Taiwan extending from the
southeast sector to the (CMR) is the dominant mountain range in Taiwan extending from the southeast sector to the northeast creating a very steep eastern coast. Taiwan’s mountainous ranges account for about 2/3.

Figure 2. On the left, a map of Taiwan with color coded horizontal lines depicts the location of the cross-section for the figure on the right which shows elevation as a function of longitude.
f the total 36,000 km² area of Taiwan. There are an estimated 200 peaks with heights above 3,000 m, the highest peak standing at 3,952 m (Fig.2). Mountains are notorious for creating microclimates and for Taiwan that is not far from the truth. Chiayi County experienced the most rainfall, 1504 mm in 24 hours and is located on the northwest facing slopes of the CMR.

Mountainous regions create a barrier for tropical cyclones altering their track, weakening their intensity and frequently shielding the leeside (or opposite slope) of a mountain from the impinging tropical storm as noted by Chang (1982); Wang (1980); Foster et al. al (2000). A storm with relatively low central pressure tends to be horizontally advected to the north of the mountainous regions in a cyclonic, clockwise, manner. This diversion creates a leeside low-level circulation similar to the reaction of Typhoon Morakot and the CMR. A relatively weaker cyclone will have a stronger mean maximum wind but will often pass over the mountainous region. Typhoon Morakot hit in a more southerly position then what was forecasted at WRF-ARW and the track was forced over the mountainous region. In addition Chan et al. (2009) determined that the track and structure of typhoon Morakot as asymmetric and concluded the inherent vortex motion and surface friction initiated by air sinking due to differential convergence caused a deviation in the typhoons storm track. Chang (1982) finds that the intensity or convection to sustain the intensity, latent heat by cumulus convection plays an important role in cyclone’s reaction to the topography.

When a parcel of air is lifted over a mountain range, the air mass cools according to the dry adiabatic lapse rate until it reaches the dew point temperature, or point of condensation. Further lifting will cool the air parcel at the saturated adiabatic lapse rate, with water vapor
condensing into liquid water and releasing its latent heat into the atmosphere. As the air mass cools to the dew point, or point of condensation, latent heat is released causing instability, when an air parcel finds itself warming then the surrounding environment. Unstable air tends to rise creating vertical motion which often forms cumulus clouds, cumulus convection, which is associated with rain. With this concept in mind, the north-facing slopes have a small vertical gradient from west to east then east to west. If you were to think of how cold fronts work, cold air mass pushing warm air mass, the warm air mass rises quickly which causing rapid cooling and often short rain period. This is related to orographic lift, along the eastern coast of Taiwan as typhoon Morakot approaches. High concentrations of PWV are forced over the CMR causing rapid cooling, and quick rain showers, however west of the CMR rain showers lasted for days. Before Typhoon Morakot hit Taiwan there was a constant northwesterly and southwesterly wind flow that collided with the northwest facing slopes. This wet air mass was forced by orographic lifting into the upper atmosphere where it cooled and produced rain. Research done by Fang et al (2008), Chan et al (2009), and Kuo et al (2010) described Typhoon Morakot as asymmetric, meaning the storm structure had a flux of moisture concentration between the northern circulation of the storm and the southern circulation of the storm where it had the most moisture. The storm structure plus the storm track, concentrated the PWV transport in the southern sector of Taiwan which also increases potential rainfall.

b. The numerical model

The Morakot case study will utilize the Advanced Weather Prediction model WRF - ARW because it has physical parameters including: terrain representation, vertical coordinate,
advection scheme, and boundary conditions (Shamrock and Dudhia, 2010). This model is used in now-casting, real-time and short-term forecasting for the general public and specializes in mesoscale meteorological phenomena such as typhoons. The WRF-ARW was recently used to simulate for 0000 UTC August 6, 2009 through 0000 UTC August 10, 2009, when Morakot dissipated over China. The WRF-ARW model was run at both 12-km and 4-km resolution for our research. This model run included PWV and rainfall point data that was geo-referenced to the same location as the ground-base GPS stations provide by the Central Weather Bureau of Taiwan (CWB). We normalized our model PWV data by taking the difference between initial time frame (0000 UTC August 6, 2009), which included all the GPS geo-referenced stations in Taiwan and all 32 other time frame at a 3-hour interval to normalize the PWV for this particular event. The normalization method will show the development of PWV at each ground-based station as Typhoon Morakot progresses through Taiwan. This model also incorporates key physical parameters such as cumulus parameterization, estimation of latent heating due to PWV convergence, which was initiated by Kuo (1974) and utilized by Chang (1982).

c. Ground-base GPS

Pre-ground base GPS model forecast only had three ways in which to observe PWV fields, satellites, rawinsondes, and surface stations. Rawinsonde is the only one of the three which can retrieve a full vertical PWV reading routinely. The drawbacks of rawinsondes include poor temporal variation, only launched twice daily at 0000 UTC and 12 UTC, high cost, failure to consistently retrieve the full vertical profile and drift heavily in the horizontal (Smith et al 2006; Turner et al. 2003). Surface observations of PWV favor well in lower atmosphere
however it is very difficult to correlate the surface PWV with higher altitude PWV. Satellite infrared sounder data can give PWV from the tops of stratiform cloud layers and satellite microwave sounders must be used over large bodies of water to avoid noise in the data caused by land Smith et al. (2006). Ground-base GPS stations are very compact and the widespread distribution in virtually any terrain allows for a more consistent and accurate representation of the 3-D PWV field both vertical and horizontally.

Ground-based GPS stations have a dual-frequency antenna with a receiver box where data is collected and sent to a super computer for data analysis Businger et al.(1996). Bevis et al. (1992, 1994); Rocken et al. (1993, 1995), Duan et al. (1996) observed that PWV can be derived from GPS signals if the GPS receiver is accurately geo-referenced, the ionospheric delay has been accounted for and there is adequate observations of surface temperatures. As noted in Businger et al. (1996) the importance of accurately geo-referenced stations allows for the PWV to be measured by the wet delay or the delay of microwave radiation to the ground-based GPS station receiver which is proportional to the amount of water vapor in that column of air. Hydrogen bonds between water molecules and ice reduces dipole movement thus PWV readings do not interfere with other phases of water readings. PWV has a permanent dipole moment which causes a unique delay in the penetration of electromagnetic radiation, resulting from an asymmetric charge distribution in the water molecule Businger et al. (1996). Processing time of ground-base GPS PWV is every 30 minutes and has high accuracy comparable to radiometer estimates. The fast processing time and accuracy initiated research that incorporated GPS-PWV initializations in forecast models in 1997 (Smith et al., 2006). From 1997 to 2004 positive impacts in forecasts were observed as ground-base GPS network increased from 20 to over 300.

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GPS-PWV were incorporated in the operational Rapid Update Cycle in 2005 and then in the North American Mesoscale (NAM) model in 2006 after observed improvements in CAPE forecasts (Smith et al., 2006).

2. Methods

To answers our scientific question on why Typhoon Morakot, a category 2 storm, produced so much rainfall, our research team correlated the affects of topography microclimates in Taiwan with gauged rainfall amounts, similar to the work of Fang et al. (2010). Topological effects due to passing tropical storms are drawn from research of Fang and Kuo (2010), (Smith, 2000), Foster (2003), (Gutman, 2004) and Chang (1982). At 3-hour intervals we tested the model relative humidity forecast error with and without assimilations of GPS observations. We assumed the density of ground-based GPS stations provided the best interpolation of the 3D PWV fields and distribution which acted as a control. To begin we first took the climatological PWV record for the month of August, 2008 and computed the average for each ground-base GPS station. We then subtracted the average PWV from the first time-step in our research study, August 6, 2009.

\[
\text{average} = \frac{\sum_{k=1}^{n} x_k}{n}
\]

*Equation 1. Average summation where \( n \) denotes the number of days in August, 2008 and \( x_k \) denotes the average PWV for the \( n_k \) day.*

Our research required time-series plots of selected ground-based GPS stations (fig. 4). The goal was to select stations upstream and downstream of the southerly monsoon flow to see how winds...
coupled with elevation distributed PWV. Stations selected were based on elevation (m), and complete PWV (mm) data sets for the time-period in question.

In our comparison of the ground-based GPS with the WRF-ARW we had to take into consideration time differences between ground-based GPS and WRF (ARW). Ground-based GPS reading are taken every half-hour starting on 0015 UTC. WRF (ARW) model readings begin on the hour 0000 UTC every 3-hours. For this study we treated the ground-based GPS PWV readings at 0015 UTC as 0000 UTC to compare with the model run after taking into consideration the 10 minute downloading time. Model rainfall was also adjusted from 3 hour increments to hourly by dividing the 3hr accumulated rainfall by 3 to get evenly distributed hourly model increments. Simple algebra between WRF-ARW and ground-based GPS height differences (Fig. 3) gave us an indication that we needed to normalize our time series graphs. We accomplished this by subtracting the initial time step, 2008.218.00 (August 6, 2009 0000 UTC), for each time series. The initial model time-step was subtracted by all 32 3-hour steps in our research period and the initial ground-based GPS time-step was subtracted by each of the 1-hour time steps. This algebraic manipulation gives us the time evolution of PWV at each station, meaning we are not comparing absolute PWV ground-based GPS data and model data.
Another series of algebraic manipulation between west and east coast station ground-based and model PWV gave us the time-evolution of a selected west coast station relative to its east coast neighbor. These station comparisons are selected based on line of latitude and points of interest. For this study we chose six stations to represent the west and east coast in the upper northern sector, mid-sector, and southern sector of Taiwan. We also selected two high range stations in the CMR and their neighboring west and east coast stations to determine if PWV was transported around or over the CMR.

3. Results
In our analysis of the climatological record we saw the PWV distribution was abnormally high before, during and after typhoon Morakot compared to the same time one year earlier as depicted in (Fig.4). The first time step, 2009.218.00, is noted by yyyy.doy.hr, year, day of year and Z hour. We saw that PWV distribution was especially large in the south-western sector of Taiwan and in a smaller section in the northeastern sector. On the leeward side of CMR in the northwestern sector PWV noticeable smaller than its neighboring northeastern sector. The opposite is true for the southern sector. The southwestern sector experiences the most PWV distribution compared to its neighboring southeastern sector. When the typhoon makes landfall (Fig.4 b) PWV increases and is concentrated around point of contact ~ 22°N latitude but retains unbalanced distribution as seen in (Fig.4 a. As the storm passes over Taiwan in a northeastern track PWV is concentrated over the northwestern sector comparatively to the entire eastern coast of Taiwan however there is still signs of above normal PWV. A time series of the passage of Typhoon Morakot allowed us to make a selective decision on particular ground-base GPS stations that are representative of geographical location due to the CMR, the worst hit area (HA)(southwest sector), elevation, and typhoon Morakot. Each station has a time series chart with PWV (mm) and rainfall (mm) as a function of time. Figure 5 shows a map of Taiwan where the red circles indicate the location of the selected ground-based GPS stations for our time evolution analysis.
Figure 4. Difference of the average PWV for the month of August, 2008 (mm) measured ground-base GPS PWV: from upper left clockwise a) August 6, 2009 0000 Z, before b) August 7, 2009 2100 Z, during c) August 10, 2009 0000 Z, after typhoon Morakot.
The stations selected to represent the northern sector of Taiwan include WANL, PAOS, LTUN, mid-sector stations include: DNAN, GUKN, ALIS, TATA, JSUI and southern-sector stations include: TUNS, DCHU, JLUT. An analysis of the northern sectors' time evolution of PWV supports the idea that PWV distribution preceding Typhoon Morakot is concentrated in the northeastern sector of Taiwan as the general circulation before and during as Typhoon Morakot approaches Taiwan.

4. 4. Discussion

Our findings from the Typhoon Morakot case are similar to the findings of other scientific research which investigates the physical meteorological impacts of tropical storms as they propagate over mountainous islands notably Chang (1982), Fang and Kuo (2010), and Foster et al. (2003). The abnormally large PWV distribution over Taiwan before, during and after Typhoon Morakot (Fig. 4) provided an abundance of water vapor which served as the source of moisture that eventually lead to high rainfall amounts and flooding. The storm track observed is similar to research done by Chang (1982) where the storm was moderately weak and struck Taiwan in a more south-central location than forecasted. This forced the storm to pass over the CMR where low level winds diverged around the CMR creating impinging northwesterly and southwesterly winds on the northwestern
facing slopes. The asymmetric structure of the storm was similar to previous case studies by Foster (2003), Chang (1982), Fang and Kuo (2010) with higher PWV in the southern sector of Taiwan before, during and after the tropical storm.

Some inconsistencies or data error may be due to the spatial and temporal resolution of the model and absolute data was lost in translation due to many interpolations and equipment damage as the typhoon propagated over Taiwan. The climatologically record of ground-base GPS is inconsistent as new stations are assembled every year as others die out, and our climatology accounts for one month of August 2008. However our comparative analysis of the ground-base GPS proved beneficial in correlating PWV and rainfall model error due to terrain in the WRF-ARW. The model consistently missed areas which resembled orographic and rain shadow effect, where the wind-ward side of a mountain range experienced moisture convergence and rainfall due to adiabatic cooling, rising air, and adiabatic heating, sinking air on the lee-ward side which is associated with decrease in water vapor and rain showers. The selected stations served to represent the microclimates of Taiwan and proved to show varying PWV and rainfall amounts. Stations in higher elevations had the most model error compared to lower elevations. In order to reduce model inconsistency one proposal is to simulate the WRF-ARW at a higher spatial and temporal resolution so the model can capture the true topography of Taiwan and smaller hourly increments will allow for more detail of the evolution of the model rain and PWV. Also a more consistent data set from each of the ground-base GPS stations could improve to our climatological records by increasing distribution and modifying the equipment to withstand harsh elements.
**Figure 5.** WRF-ARW PWV is shown in red, ground-base GPS PWV is shown in green, Gauged rainfall is light grey, and WRF-ARW rainfall is in dark grey, rainfall amounts are on the right of the graph, PWV amounts around left of the graph. Both PWV and rainfall amounts are in (mm). The model rainfall is at 3 hour intervals (do not match time line). Gauged rainfall is every hour. Ground-base GPS is every 30min.
5. Conclusion

Our study determined that the environment before Typhoon Morakot was above normal according to climatological records before, during and after Typhoon Morakot. At the beginning of our research period there was more PWV located in the northeastern and southwestern sections of Taiwan due to the general circulation of Typhoon Morakot, counter clockwise and inward, where moisture convergence and the mountainous island provided vertical motion which induced rainfall. After Typhoon Morakot left the WRF-ARW did not capture this effect for the western slopes of Taiwan as the circulation switched to more dominate northwesterly and southwesterly flow when the heaviest rains occurred. However, the model PWV forecast had subtle differences yet still captured the relative variation of PWV time evolution.

Our research suggests a higher special resolution of 3 km or 1 km resolution could help reduce the rainfall forecast error because the true elevation of Taiwan will be carefully included in the precipitation parameterizations. Also, a higher temporal resolution of the WRF-ARW model could give more point data to compare with the rain-gauges. Future work for this study may include a full comparison of all 32 members of the WRF-ARW model to improve our understanding of each of the algorithm’s role in determining the forecast before, during and after other typhoons which propagate over Taiwan.

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