16A.7 A TROPICAL CYCLONE RAINFALL CLIMATOLOGY-PERSISTENCE MODEL FOR THE TAIWAN AREA

Kevin K. W. Cheung [1*], Li-Rung Huang[1] and Cheng-Shang Lee[2]
[1]*National Science and Technology Center for Disaster Reduction, Taiwan*
[2]*Department of Atmospheric Sciences, National Taiwan University*

1. Introduction

Impact from typhoons or tropical cyclones (TCs) is one of the major natural hazards to the coastal cities in Southeast Asia and in particular to Taiwan. According to the records of issuing typhoon warnings from the Central Weather Bureau (CWB) of Taiwan in the period 1961−2004, an average number of nearly five TCs affected Taiwan every year and nearly two would make landfall. About 74% of these TCs occurred during July−September. Very often, damages and human-life losses were brought by the torrential rainfall from these TCs that caused flooding and debris flow. Sometimes, the difficulty in forecasting rainfall associated with TCs was further increased by the fact that heavy rainfall would be brought by monsoonal flows enhanced or modified by the TC circulation. A recent example is Typhoon Mindulle (2004) that was accompanied by strong Asian summer monsoon southwesterlies and resulted in large amount of rainfall in the southwest area of Taiwan (Lee et al. 2005). Therefore, improving the skill of rainfall prediction from the short range (1–3 h) up to 3 days becomes a major target for the Taiwan local forecasters and personals in hazard mitigation organizations.

Although a lot of effort has been spent on understanding and predicting the physical processes when a TC makes landfall (including precipitation), it is generally recognized that the progress in improving TC intensity forecast and quantitative precipitation forecast has been slow. Recent studies indicate that some high-resolution (as fine as ~2 km) dynamical model simulations are capable of capturing roughly the rainfall pattern for scales as small as the Taiwan island (e.g., Wu et al. 2002; Chiao and Lin 2003). However, the maximum accumulated rainfall was usually either much underestimated or overestimated that reduces greatly the value of these numerical products in hazard mitigation applications. Before the skill of dynamical models is improved to an acceptable level for operational applications, forecasters usually rely on various statistical models for rainfall estimation and issuing warnings. The fact that the distribution of convections and rainfall in TCs has certain characteristic patterns both when they were in open oceans and when making landfall allows the application of statistical descriptions and predictions based on climatology. These statistical models also serve as skill references in developing new rainfall prediction techniques based on dynamical models.

[*] *Corresponding author address:* Kevin K. W. Cheung, National Center for Disaster Reduction, Taipei 106, Taiwan ROC; email: cheung@ncdr.nat.gov.tw

2. The Rainfall Observational Network in Taiwan

Before 1989, the rainfall distribution in Taiwan was measured by only the 22 traditional weather stations over the island. By 1989, the automatic rain gauge network was completed that made the total number of rain stations to be 371 (365 on the main island) including several off-coast island stations (Fig. 1). As can be seen in the figure, the rain stations are quite uniformly distributed in the plain area but are less dense in the central mountain range (CMR). However, the torrential rain occurred over the CMR was frequently affected by orographic lifting and when such a forcing is present, the rainfall distribution follows approximately the topography. Thus the rain stations at the mountain area are mainly responsible for capturing the peak rain rate. Data from these 371 rain stations are updated every ten minutes and they are sent automatically through wires into the CWB and the National Center for Disaster Reduction (NCDR).

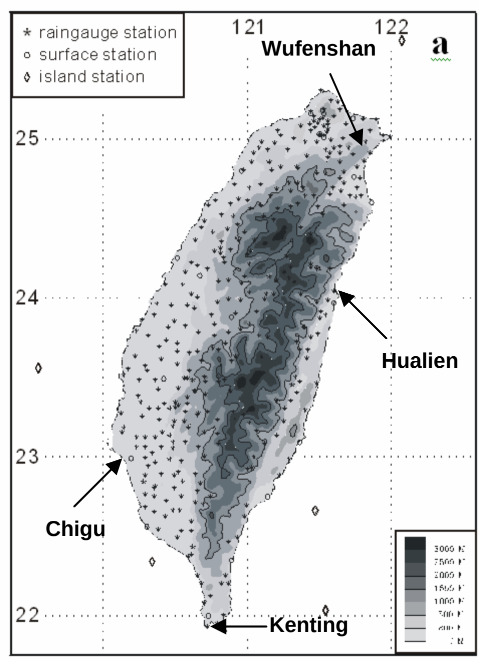

Fig. 1 Locations of the 371 automatic rainfall stations in Taiwan and the four cities with Doppler radar stations. The contours mark topography with heights 1 km and 2 km respectively.

Certainly, for hazard mitigation purpose high-resolution rainfall data is needed to estimate the potential of flooding and debris flow in local areas. Therefore, a Doppler radar network was setup in Taiwan and finished in 2001. The network consists of four Doppler radars that approximately cover each of the four respective directions. A software system called the Quantitative Precipitation Estimation and Segregation Using Multiple Sensors (QPESUMS) adapted from the U.S. National Severe Storms Laboratory integrates reflectivity data from the four radars and performs rainfall estimation based on a particular reflectivity-rainfall relationship tuned for the Taiwan area. The QPESUMS radar data is also updated every ten minutes.

3. TC Rainfall Climatology

The spatial characteristics of TC rainfall is studied by first setting up a climatology based on the sixty-six TCs that affected Taiwan during 1989−2002. The domain used for study is 118^o−126^oE, 18^o−27^oN, with grid size $0.5^o \times 0.5^o$ latitude/longitude. When one of the 66 TCs passed through one of the grids in the domain (based on their best tracks), the rainfall data obtained by the 365 main-island rain gauges are recorded. Thus after examining all 66 TC cases, statistics on the average, maximum and minimum rainfall, standard deviation and the number of TCs passed through each grid box and for each rain gauge are obtained. In other words, for each rain gauge there is a map of rainfall describing the climatology of that particular station when a TC is situated at different position in the domain (Fig. 2). In order to refine the rainfall map so that rainfall estimation for localized regions in Taiwan can be provided, the climatology within the $0.5^o \times 0.5^o$ grid boxes are further interpolated to $0.1^o \times 0.1^o$ latitude/longitude grid boxes using the Barnes objective analysis.

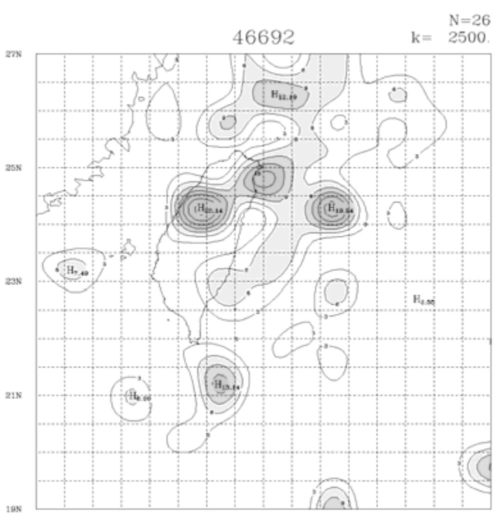

Fig. 2 Computation domain and rainfall climatology map for the Taipei station (46692) after a Barnes objective analysis to a fine $0.1^o \times 0.1^o$ latitude/longitude grid.

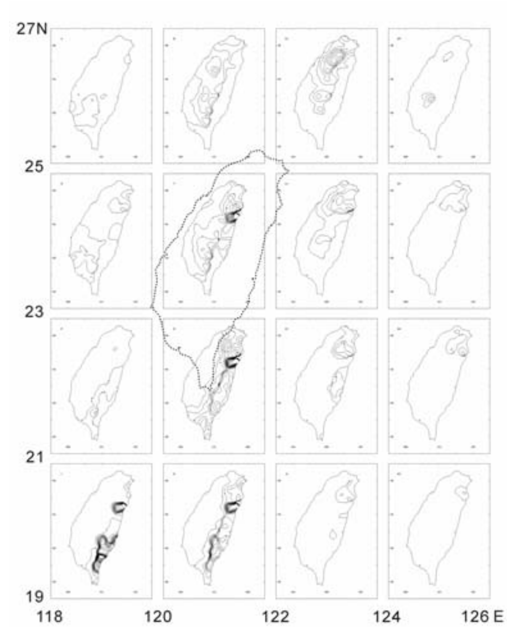

Fig. 3 TC rainfall climatology in the Taiwan area (hourly rain rate, interval: 2 mm h^{-1}). Each panel represents the distribution when the TCs located in that panel relative to the central Taiwan map.

To obtain a simple picture of TC rainfall climatology over Taiwan, the climatological maps within $2^o \times 2^o$ latitude/longitude grids of the original domain are averaged and the resulted maps are placed according to the relative position of the involved TCs to the Taiwan island (Fig. 3). It can be seen that heavy rainfall occurred at the east coast of Taiwan when TCs approached from the south or southwest. In this situation, the eastern side of the CMR was under impact from the TC circulation and orographic lifting effect would enhance the rainfall there. However, the CMR also blocked most of the rainfall from the west coast. Another situation when heavy TC rainfall occurred is when the TC center located at north or northeast of Taiwan. Large amount of rain fell on northeast Taiwan because the TC circulation impinged directly on the northern part of the CMR. If the TC center is more to the west or the TC size is large, the western side of the CMR would also receive large amount of rainfall. Comparatively, the rainfall amount would be less severe when the TC center is at other positions relative to the Taiwan island.

4. Temporal Patterns

Besides the accumulated rainfall amount, the temporal profile is also important in understanding the characteristics of rainfall brought by TCs. For this purpose, the hourly rain rate recorded at each of the 365 stations in Taiwan (i.e., the 5 off-coast island stations are neglected in this analysis) during the 66 TC impacts are averaged. Since the time period of each TC affecting Taiwan (when the CWB typhoon warning was raised) is different, this time period and the associated rain rate are first normalized to 100 time units before averaging. Then the 365 average rainfall time series are input to a hierarchical clustering analysis with the correlation coefficient between two time series as their distance measure. Basically similar clusters result when using the single-linkage, complete-linkage or the average-distance-within-clusters methods, the final results are based on the last one. When the correlative coefficient between two clusters drops to about 0.6, six clusters remain that are physically meaningful when considering the locations of the cluster members. The number of members for the six clusters is respectively 52, 117, 5, 33, 96, 62.

The six rain profiles obtained by the clustering analysis show two typical characteristic temporal patterns of TC rainfall affecting Taiwan (Fig. 4). One with a peak rain rate at an earlier time within the TC impact period (cluster 4 and cluster 5), and the other one with the peak rain rate near the end of the TC period (clusters 1, 2 and 6). Moreover, the peak rain rate in the former pattern is much higher. Detailed comparison between clusters 4 and 5 also reveals that cluster 4 contains another peak rain rate early in the period (around 20 normalized units). Cluster 3 is not shown in the figure because of its small member number and its profile consists of a single peak at the beginning of the entire time period (to be explained later).

Examination of the location of the station members within each cluster shows that they are also grouped in the physical space (Fig. 5). Clusters 1 and 2 account for the rainfall profiles at the plain areas west of the CMR. Cluster 3 has only 5 members and they are all located at high altitudes (see topography in Fig. 1). Orographic lifting effect plays a crucial role for the large rainfall amount recorded in these stations and therefore these 5 members are not combined into other clusters during the analysis. Clusters 4 and 5 possess similar temporal profiles, and they respectively account for the rainfall patterns at the east coast and northeastern part of Taiwan. Finally, members in cluster 6 all concentrate at the southwestern side of Taiwan. Generally speaking, the temporal rainfall profiles classified according to the clustering analysis procedure are indeed consistent with the track types of TCs affecting Taiwan. Most of the TCs approached from the east or from the south (those formed in the South China Sea or recurved from the Philippines) and the east coast of Taiwan is the first region to receive heavy rainfall, which explains the first peak rain rate in the profile of cluster 4. As most of the TCs in the WNP travel northwestward, those approaching the Taiwan area would bring rain then to the northeastern Taiwan where the cluster-5 members situate. The peak rain rate for the members in clusters 1, 2 and 6 all occur later when the landfalling TCs pass through the CMR of Taiwan or when the northward traveling TCs move to higher latitudes.

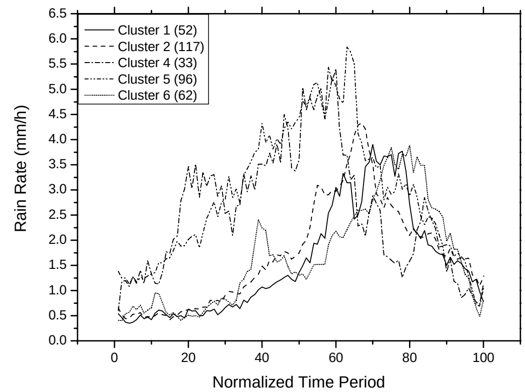

Fig. 4 Five of the six rainfall temporal series (normalized to 100 time units) obtained from a hierarchical clustering analysis of the 365 rain gauge data during 1989–2002. Number in parentheses gives number of members in each of the clusters.

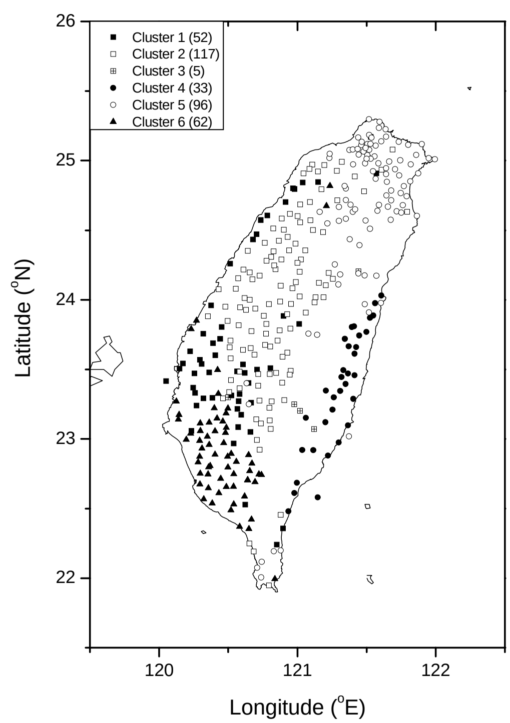

Fig. 5 Geographic locations of rain gauge members of the six clusters.

5. Model Setup

The CLIPER model is a simple weighed combination of TC rainfall climatology and persistence for estimating rainfall in the future. The model domain is 118^{o}–126^{o}E and 19^{o}–27^{o}N as in that shown in Fig. 2. The strategy used to construct the rainfall climatology here is different from that in Marks et al. (2002) that developed the R-CLIPER for Atlantic TCs. The latest version of R-CLIPER utilizes rain estimates from the Tropical Rain Measurement Mission (TRMM) microwave imager (TMI) and derives storm-centered mean rain rate distribution stratified for different TC intensities. This mean rain rate distribution is azimuthally symmetrical, and when accumulated rain amount is computed along the forecast TC track, the rainfall distribution is also symmetrical with respect to the track. When a typhoon is approaching the Taiwan Island, its structure and convection distribution will be greatly affected by Taiwan's topography and highly asymmetric rainfall distribution will probably result. Therefore in developing the rainfall CLIPER model for the Taiwan area, the actual climatological rainfall map is used instead of an azimuthally symmetrical distribution as in Marks et al. (2002). Whenever an official forecast track from the CWB is issued, it is first spatially interpolated such that hourly positions are available. Then the rainfall database for each of the 365 stations is looked up in turn to obtain the climatology value for a particular TC center position. When this rain amount is accumulated along the forecast TC track, the rain distribution within a certain forecast period is obtained.

Next the persistence component of the CLIPER is determined. Tests on the persistence duration indicate that a 3-h period is adequate to project a reasonable short-range rainfall estimate. Since convective timescale is sometimes as short as an order of 1-3 h, application of a longer persistence amount even degrades some of the forecasts. Thus the 3-h persistence duration is applied to all of the 365 rain stations. Then experiments are performed to determine the relative contributions from climatology and persistence in the final rainfall prediction. Evaluation is based on pattern correlation (correlation coefficient computed for all stations) in 3-h periods up to 24 h. It is found that the optimal pattern correlation is realized when the ratio of climatology to persistence is 4/6 (7/3) in the 0-3-h (3-6-h) time period, and then only climatology is used after 6 h.

6. Model Performance

Within the model database that consists of cases in 1989-2002, correlation coefficient (*R*) between CLIPER's forecasts (using the official CWB forecast tracks) and observations at all the 365 rain gauges ranges from 0.63 for 3-h accumulated rainfall to 0.5 for 24-h period (Table 1). The corresponding root-mean-square error (RMSE) ranges from 16.0 mm to 95.3 mm, indicating that the simple combination of climatology and persistence does provide reasonable estimates of rainfall pattern and amount in the short range. The verification for the independent cases in 2003-2004 actually indicates slightly higher correlation coefficient within 6 h and lower RMSE for all time periods.

Equitable threat score (ETS) is also computed to examine the ability of CLIPER to predict rainfall of a certain amount. The ETS averaged over all stations for a threshold of 50 mm/day is about 0.24 in the 0-6-h period and drops gradually with increasing lead time (Table 2). The ETS for 24-h rainfall forecast with the same threshold is about 0.13. These ETS values decrease substantially for higher rainfall thresholds (e.g., the CWB heavy rainfall categories of 130, 200 and 350 mm/day), indicating that CLIPER is unable to estimate the super heavy rainfall amount. However, these verification results are quite dependent on TC tracks. If the forecast tracks are perfect (i.e., using the best tracks as inputs to CLIPER), the ETS in the 24-h period for 50 mm/day threshold increases to 0.22. The ETS's in other verification periods also increase substantially, indicating that good TC track forecasts are indeed essential for even a statistical model based on climatology like CLIPER.

	Dept. Cases (1989–2002)		**Indept. Cases (2003–2004)**	
	R	RMSE	*R*	RMSE
3-h Acc. Rainfall	0.63	16.0	0.77	11.4
6-h Acc. Rainfall	0.61	26.9	0.68	22.2
24-h Acc. Rainfall	0.50	95.3	0.40	86.6

Table 1 Correlation coefficient (R) and root-mean-square error (RMSE) of the 3-, 6- and 24-h CLIPER forecasts for the dependent and independent cases, respectively.

50-mm threshold			
00-06 h	**06-12 h**	**12-18 h**	**18-24 h**
0.24 (0.20)	0.12 (0.17)	0.087 (0.17)	0.064 (0.19)
0.19 (0.21)		0.086 (0.20)	
0.13 (0.22)			
130-mm threshold			
0.15 (0.16)	0.052 (0.13)	0.049 (0.12)	0.025 (0.14)
0.11 (0.14)		0.035 (0.13)	
0.064 (0.12)			
200-mm threshold			
0.11 (0.12)	0.030 (0.087)	0.028 (0.076)	0.014 (0.097)
0.068 (0.099)		0.016 (0.075)	
0.032 (0.047)			
350-mm threshold			
0.045 (0.05)	0.010 (0.022)	0.0088 (0.015)	0.0048 (0.030)
0.024 (0.029)		0.0029 (0.020)	
0.0081 (0.0035)			

Table 2 Average equitable threat score (ETS) of CLIPER for four thresholds and different verification periods. The first score in each period is that using forecast TC track while the score in parentheses is that using best track as input.

Moreover, it is also found that the ETC's for individual stations have similar geographic distribution for different forecast periods. The scores for northwest Taiwan are consistently higher than those in south and southwestern Taiwan. While the dynamical processes affecting rainfall in the southwestern part of Taiwan are complicated (e.g., influence from monsoonal flow and sharp orographic gradient), this geographic distribution of ETC may imply that the predictability of TC rainfall in different parts in Taiwan is different.

Examination of the bias scores indicates that CLIPER's forecasts have no serious bias throughout the 24-h forecast period for rainfall threshold near or below 100 mm (Table 3). However, for the super heavy rainfall thresholds of 200 mm and 350 mm, the bias toward underestimation is obvious. Nevertheless, this model forecast bias is also due partially to error in track forecast. If best track is used as input to CLIPER, the bias is corrected to a large extent especially for the large rainfall thresholds.

<table>
<tr><th colspan="4">50-mm threshold</th></tr>
<tr><th>00-06 h</th><th>06-12 h</th><th>12-18 h</th><th>18-24 h</th></tr>
<tr><td>0.84
(0.84)</td><td>0.96
(1.12)</td><td>0.94
(1.18)</td><td>1.12
(1.29)</td></tr>
<tr><td colspan="2">0.85
(0.94)</td><td colspan="2">0.93
(1.16)</td></tr>
<tr><td colspan="4">0.75
(0.99)</td></tr>
<tr><th colspan="4">130-mm threshold</th></tr>
<tr><td>0.46
(0.50)</td><td>0.60
(0.81)</td><td>0.66
(0.98)</td><td>0.79
(1.04)</td></tr>
<tr><td colspan="2">0.48
(0.56)</td><td colspan="2">0.63
(0.82)</td></tr>
<tr><td colspan="4">0.48
(0.63)</td></tr>
<tr><th colspan="4">200-mm threshold</th></tr>
<tr><td>0.33
(0.37)</td><td>0.46
(0.56)</td><td>0.52
(0.73)</td><td>0.59
(0.76)</td></tr>
<tr><td colspan="2">0.36
(0.37)</td><td colspan="2">0.46
(0.59)</td></tr>
<tr><td colspan="4">0.29
(0.34)</td></tr>
<tr><th colspan="4">350-mm threshold</th></tr>
<tr><td>0.14
(0.16)</td><td>0.23
(0.17)</td><td>0.36
(0.28)</td><td>0.32
(0.37)</td></tr>
<tr><td colspan="2">0.13
(0.10)</td><td colspan="2">0.21
(0.19)</td></tr>
<tr><td colspan="4">0.076
(0.052)</td></tr>
</table>

Table 3 As in Table 2 except for the bias score.

7. Summary

In this study, the characteristics of TC rainfall in the Taiwan area are first examined through its climatology and statistical analyses of the temporal variation of rainfall during TC impacts. Then a simple TC rainfall climatology-persistence (CLIPER) model is established for the Taiwan area. Its skill is found to be moderate for light rainfall threshold but decreases substantially for heavy rainfall events. However, the skill scores are much improved by using best tracks as input to the model, showing it is quite sensitive to track errors. In the near future, the TC rainfall CLIPER will be further improved by taking into account more TC structural parameters and environmental conditions.

Acknowledgements

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