Development of a statistical tropical cyclone rainfall forecast model for the Taiwan area

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Abstract

A simple model combining historical tropical cyclone (TC) rainfall climatology and 3-h persistence (CLIPER) has been used in the National Center for Disaster Reduction for rainfall estimation and downstream applications (e.g., calculations of flood and debris flow potential) during TC periods. Despite its simple nature, the CLIPER usually provides a reasonable rainfall pattern in the Taiwan area especially for the westward-moving TCs due to larger number of cases in the climatology database. Based on data during 1989–2002, the correlation coefficient between CLIPER forecasts and observations is about 0.6 in the short forecast range up to 6 h. Equitable threat score with moderate rain threshold (~50 mm) of the CLIPER can be up to about 0.2 for 24-h forecast.

However, CLIPER usually much underestimates the rainfall for TCs with strong intensity/convection, or when the TC track does not belong to the most common ones. Moreover, the rainfall pattern cannot be well captured by CLIPER when the effect of monsoonal flow is strong during TC impact. These limitations of CLIPER greatly reduce its value in disaster mitigation applications. Recently some high-resolution (< 10 km) numerical weather prediction models demonstrated some promising results in quantitative precipitation forecast. However, the skill of these models during their spin-up process (that may take up to 12 h) is usually low, and high-resolution runs of these dynamical models require vast computer resources in real-time application. Therefore, a more generalized statistical TC rainfall forecast model is being developed that not only accounts for climatology and persistence but other factors that may modify the rainfall pattern as well. The statistical model is based on multiple regressions, and additional predictors include the structure parameters of a TC (e.g., size and intensity) and possibly other factors derived from synoptic environment. The relative contribution from these factors to the final forecast can also reveal the essential physical processes determining the rainfall amount and distribution.

Keyword: Typhoon rainfall, climatology-persistence model, generalized linear regression

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 sea and land 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 monsoonal southwesterlies and resulted in large amount of rainfall in the southwest area of Taiwan (Lee et al. 2006). Therefore, improving the skill of rainfall prediction from the short range (1–12 h) up to 3 days becomes a major target for the Taiwan local forecasters and personals in hazard mitigation organizations such as the National Center for Disaster Reduction (NCDR).

This paper describes the design and establishment of the necessary database, and the setup of a simple climatology-persistence TC rainfall model that has been utilized in the NCDR in the past few years. Objective verification of the model is performed based on several skill measures, and characteristics of the model is further explored by stratification of the skill measures according to some related physical parameters including the TC track type, size of the TC and height of the rainfall stations. According to these verification results, the strategy of formulation of a more generalized statistical rainfall model based on several linear regression techniques is discussed.

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2. Characteristics of typhoon rainfall in Taiwan

a. Climatology

Before 1989, the rainfall distribution in Taiwan was measured mainly by the 22 traditional weather stations over the island (Yeh 2002). By 1989, the automatic rain gauge network was completed that made the total number of rain stations to be 371 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 enhanced by orographic lifting. When such an effect is present, the rain amount is often very high and its distribution also greatly affected by topography. Thus the rain stations at the mountain area are important to capture the peak rain rate. Data from these 371 rain stations are updated every ten minutes and they are sent automatically through a radio wireless network into the CWB. NCDR then acquires these real time data from CWB.

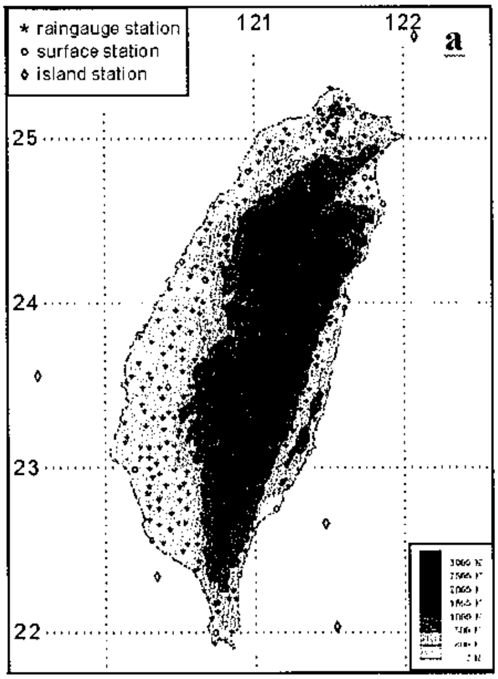

Fig. 1 Locations of the 371 automatic rainfall stations in Taiwan. The contours mark topography with heights 1 km and 2 km respectively.

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 (Lee et al. 2006). The domain used for study is 118°–126°E, 18°–27°N, with grid size 0.5°×0.5° latitude/longitude. When one of the 66 TCs passed through one of the grids in the domain (based on hourly positions interpolated from the best tracks), the rainfall data obtained by the 371 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. 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°×0.5° latitude/longitude grid boxes are further interpolated to 0.1°×0.1° latitude/longitude grid boxes using the Barnes objective analysis (Barnes 1973).

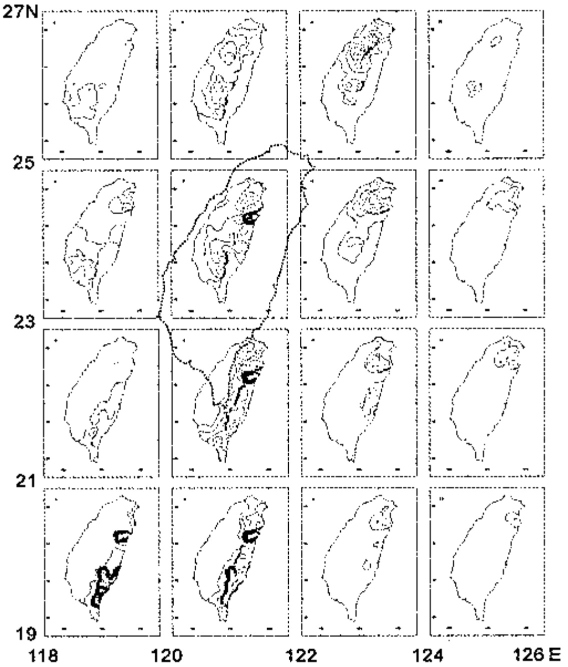

Fig. 2 TC rainfall climatology in the Taiwan area (contours shown are hourly rain rate with interval 2 mm h^{-1}). Each 2°×2° latitude/longitude panel represents the distribution when the TCs are located in that panel relative to the central Taiwan map.

To obtain a simple picture of TC rainfall climatology over Taiwan, the climatological maps within 2°×2° 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. 2). It can be seen that heavy rainfall occurred at the east coast of Taiwan when TCs approached from the south (120°–122°E, 19°–23°N) or southwest (118°–120°E, 19°–21°N). 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 (Lin et al. 2002). However, the CMR also blocked most of the rainfall from the west coast. When a TC made landfall and located in 120°–122°E, 23°–25°N, the rainfall distribution also concentrated on the east. Another situation with heavy TC rainfall was when the TC center located at northeast (122°–124°E, 25°–27°N) of Taiwan. Large amount of rain fell on northwestern Taiwan because the TC circulation impinged directly on the northern part of the CMR.

When the TC center was more to the west, the western side of the CMR also received large amount of rainfall as shown in the panel 120°–122°E, 25 °–27 °N. Comparatively, the rainfall amount would be less severe when the TC center was at other positions relative to the Taiwan island.

b. Monsoon-related Rainfall Patterns

Beside the internal distribution of convections within a TC and Taiwan's topographic influence, the rainfall pattern when a TC affects the Taiwan area is frequently modified by the large-scale monsoonal flow. Sometimes, the rainfall amount and distribution change dramatically that causes much forecast difficulty. For instance, two typical scenarios are much discussed in the Taiwan meteorological community. The first one is the warm, moist southwesterly flow during the summer monsoon period induced by TC circulation especially when the TC center is north of Taiwan. Due to the abundant moisture supply, the rainfall amount can be enhanced substantially. A well-known example that occurred recently is Typhoon Mindulle (2004) that made landfall at the east coat of Taiwan at about 12 UTC 1 July, stayed over land for about 30 h and then moved out to ocean again at about 06 UTC 2 July. When the center of Mindulle was just north of Taiwan, the convergence of its circulation with the monsoonal southwesterlies induced some convection over the southwestern part of Taiwan and brought heavy rain there. When Mindulle moved further northward, its effect to the Taiwan area decreased but strong southwesterlies still persisted. These southwesterlies impinged on the CMR and the orographic-lifting effect caused more torrential rain (Lee et al. 2005). As a consequence, the accumulated rainfall during 2–4 July covered the entire southwestern part of Taiwan as well as some mountainous regions. There were some historical cases of which torrential rain was closely related to the enhanced southwesterlies. Examples are Typhoon Ellen (1959), Agnes (1981), Doug (1994) and Kai-Tak (2000) although the rainfall pattern for the latter two did not resemble that of Typhoon Mindulle due to different synoptic environment. More details can be found in Cheung et al. (2006).

Another scenario occurs during the autumn when the warm, moist TC air mass confronts the cold, dry winter monsoonal flow that produces near frontal rainfall to the area. An example is Typhoon Xangsane (2000) that was located west of the Philippines at the end of October and then passed through the east coast of Taiwan in early November. The high pressure system in mainland China combined with Xangsane's circulation to enhance the northeasterlies in the Taiwan area. Due to the blocking effect of the CMR, the resulted rainfall on 31 October concentrated on the eastern side of the island.

3. A simple climatology-persistence (CLIPER) model

During the impact of a typhoon to the Taiwan area, continuous monitoring and prediction of heavy rainfall is one of the major challenges faced by forecasters and disaster mitigation personnel. Although strong winds associated with typhoons might also bring serious destructions to facilities and cause much economic losses, previous experience shows that flooding and debris flow induced by torrential rainfall are more direct threats to human lives in Taiwan. In real-time situation, an efficient way to perform a rapid estimation of the future rainfall potential is necessary as the information is critical to the disaster response commanders and managers for emergency resources distribution purpose. In particular, reliable rainfall forecasts in the 0-6-h range is extremely important to residence evacuation especially in Taiwan. As mentioned in the introduction, the skill of quantitative precipitation forecast from numerical weather prediction models is improving and besides rainfall these models provide information on other meteorological parameters as well. However, the computer resources required to generate forecasts within a time frame of hours is more than affordable in every disaster mitigation organization. Therefore, a simple statistical model based on the analysis of the spatial patterns of rainfall associated with typhoons is developed.

a. Setup of the Model

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°–126°E and 19°–27°N as in that shown in Fig. 2. The strategy used to construct the rainfall climatology here is based on Lee et al. (2006) and 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. However, 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 likely occur. For example, Lee et al. (2006) showed that the features of TC rainfall in the Taiwan area are closely locked by the topography. Therefore in developing the rainfall CLIPER model for the Taiwan area, the actual climatological rainfall map is used. 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 (i.e., the climatology component of the CLIPER) is obtained.

Next the persistence component of the CLIPER is determined. Various tests on the persistence duration indicate that a 3-h period is optimal to project a reasonable short-range rainfall estimate. Since convective timescale is sometimes as short as an order of 2-3 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. That is, the CLIPER model can be stated mathematically as $\alpha \times$ climatology + $(1-\alpha) \times$ persistence, in which $\alpha = 0.4$ ($\alpha = 0.7$) in the 0-3-h (3-6-h) forecast period and α equals to one otherwise.

b. Case Studies

There were in total seven typhoons that affected Taiwan in 2005, among them Typhoon Haitang, Talim and Longwang were the three with the highest intensity. The three typhoons also had similar tracks: they moved northwestward, made landfall at the east coast of Taiwan and then entered the Taiwan Strait. Due to these similar tracks, their rainfall patterns were also similar, which concentrated at the Yilan county and northern Hualien county, and also the southern central mountain range (Fig. 3). In general, the CLIPER forecasts are able to reproduce the rainfall pattern because it is quite consistent with the climatology pattern when a TC center passes through Taiwan. However, the amount of maximum total rainfall is not well captured in some periods, e.g., in the case of Typhoon Haitang.

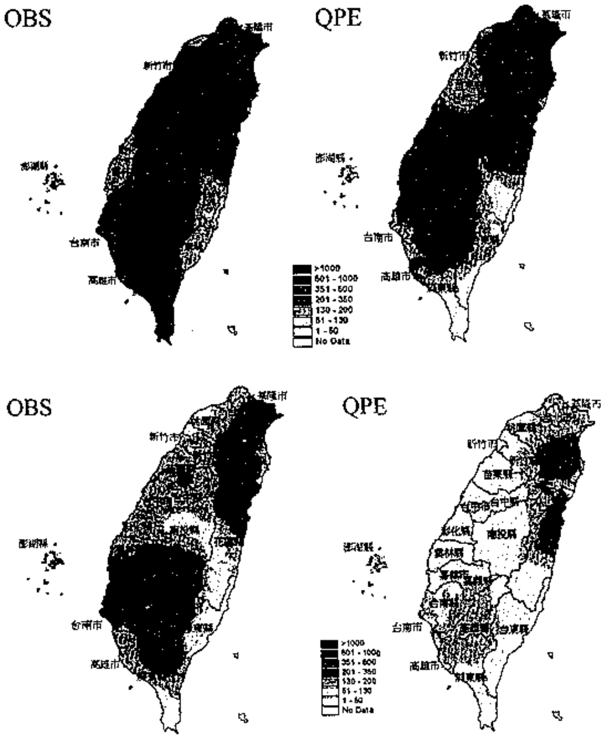

Fig. 3 (to be continued)

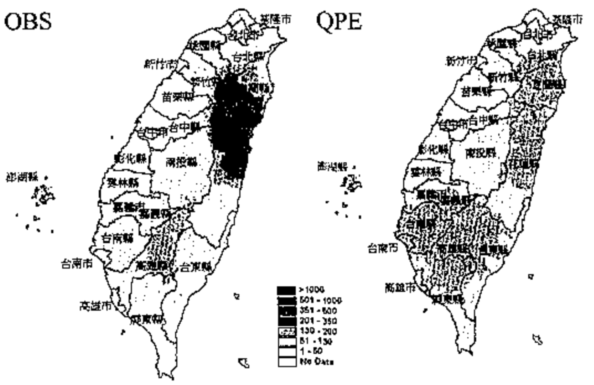

Fig. 3 Observed (OBS) and CLIPER forecast (QPE) accumulated rainfall during the entire typhoon period for Typhoon Haitang (upper panels, 16 July – 20 July), Typhoon Talim (middle panels, 30 Aug – 1 Sep), and Typhoon Longwang (lower panels, 30 Sep – 3 Oct).

4. Skill characteristics of CLIPER

a. Overall Skill

Verification of CLIPER is performed using forecasts starting at times 6 h apart to ensure independency of cases. Within the model database that consists of cases in 1989-2002, correlation coefficient (R^2) 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 in the short range (0.77 for 3-h and 0.68 for 6-h forecasts) and lower RMSE for all time periods (11.4 mm for 3-h and 86.6 mm for 24-h forecasts).

	Dependent Cases (1989–2002)		**Independent Cases (2003–2004)**	
	R^2	**RMSE**	**R^2**	**RMSE**
3-h	0.63	16.0	0.77	11.4
6-h	0.61	26.9	0.68	22.2
24-h	0.50	95.3	0.40	86.6

Table 1 Correlation coefficient (R^2) with observations and root-mean-square error (RMSE) of CLIPER in three different forecast periods for the developmental database in 1989–2002 and the independent cases in 2003–2004.

Equitable threat score (ETS) is also computed to examine the ability of CLIPER to predict rainfall of a certain amount. Four rain thresholds of 50 mm, 130 mm, 200 mm and 350 mm in 24 h are considered according to the definition of different categories of heavy rainfall in the CWB. There are various ways of calculating the ETS in a certain area. If all the 365 rain stations are considered as independent cases in setting up the contingency table for calculating the ETS of 24-h forecast, the values of 0.22, 0.13, 0.08 and 0.04 are obtained for the above mentioned thresholds respectively. The skill indicated by these ETSs is comparable with that of R-CLIPER for Atlantic hurricane rainfall (Marchok et al. 2006).

In order to further explore the temporal variation of CLIPER's skill, the ETSs within 3-h periods up to 24 h are computed (Fig. 4). It can be seen that for all four thresholds, the skill score decreases from the initial value and after about 12 h remains more or less the same. For all time periods, the ETSs for the smaller thresholds are the higher values, and those for the 350-mm threshold fluctuate around its average value of 0.04 after 6 h.

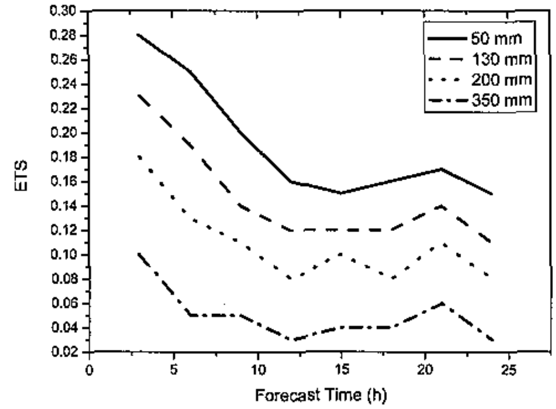

Fig. 4 Time series of ETS for the four thresholds.

bSensitivity to Track Type

Since Taiwan's topography can modify the convection distribution and hence rainfall amount of a TC when it is approaching the island, the dependence of rainfall pattern on different track types is examined. For simplicity, the TC cases during 2003–2004 are classified either as an east-west (EW) oriented type or a south-north (SN) oriented. In the former type, the westward motion of the TC dominates while in the latter type, the northward motion dominates since a TC coming from the north is very rare. An example is Typhoon Nari in 2001. In total there are 27 EW verification cases and 21 SN cases.

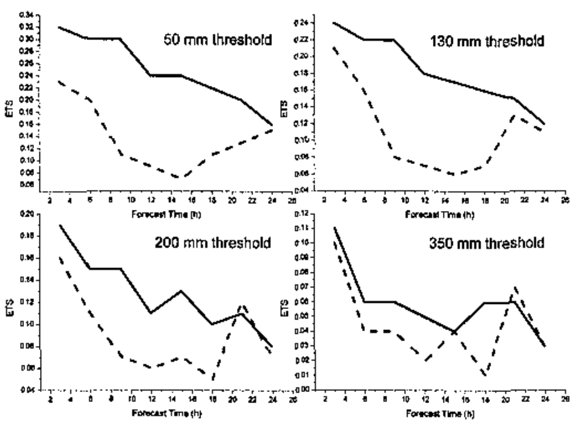

Fig. 5 As in Fig. 4 except for the EW-oriented track type (solid) and the SN-oriented track type (dashed).

For almost all time periods, the EW track type receives higher scores than the SN type especially for the lower rain threshold (Fig. 5). This fact may reveal that the climatology accounts for the rain for the westward moving TCs better than that for the northward moving. An interesting property to note is that whereas the ETS time series for the EW tracks are decreasing similar to those in the non-stratified ones in Fig. 4, those for the SN tracks usually have a minimum around 16–18 h and then rise again. Since the tracks in the SN category are mostly northward moving, this may imply that when the TC center is south of Taiwan during the early forecast periods, there are a lot of factors other than climatology that affect the rainfall pattern and thus reduce the skill. When the TC center moves to north of Taiwan during the later forecast periods, climatology accounts for the rainfall pattern better and thus the ETS increases slightly.

c. Sensitivity to TC Size

Again since the size of Taiwan is similar to the radius of a typical TC, its degree of interaction with TC circulation should depend on the size of the TC. A single convection region in a large TC may already cover the Taiwan area, while the structure of a midget TC may be highly modified by Taiwan's topography when it passes by the island. Therefore, the ETSs are examined under a stratification based on the TC size. The size of a TC is usually indicated by the radius of 30-kt wind (R_{30}) and that of 50-kt wind (R_{50}). In this study, the verification cases are simply categorized into large TCs with $R_{30} >$ 200 km, and small TCs with $R_{30} <$ 200 km according to the CWB best tracks. In total there are 32 large TCs and 16 small TCs during the 2003–2004 period.

For almost all time periods and all four thresholds, the ETSs for the large TCs are higher than those for the small TCs (Fig. 6). Usually the ETS time series for the large TCs drop rapidly in the first 12 h but those for the small ones start at a much lower score. These results may indicate that the rainfall pattern of the midget TCs is highly affected by their direction of approaching the Taiwan area and is not well account for in the climatology. However, these results may also be influenced by the small sample size of the small TCs and are subjected to further confirmation.

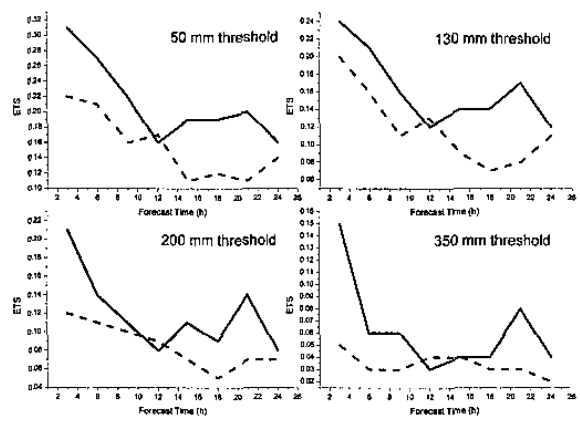

Fig. 6 As in Fig. 4 except for the large (solid) and small (dashed) TCs.

d. Sensitivity to Station Height

A lot of previous studies show that the orographic-lifting effect associated with Taiwan's topography is an important factor in determining the TC rainfall amount and distribution (e.g., Lin et al. 2002). The effect may enhance the rain in mountainous regions exceptionally, and the rain amount is difficult to be captured in statistical models and even dynamical models. Hence, the ETSs of CLIPER for rain stations at different altitudes are examined to see if this is an important factor for improving the model.

Among the 365 main island automatic rain stations in Taiwan, 65 are at a height above 1000 m, 103 are above 500 m, and 165 are above 200 m. In this study, the stations are stratified at an altitude of 500 m so that the numbers of stations in the two categories do not deviate from each other too much. However, the results are similar if the separation is taken at a higher or lower altitude. For the light to moderate rain, the ETSs for the low-altitude stations are clearly higher than those for the high-altitude stations throughout the 24-h forecast period (Fig. 7). This difference is not obvious for the large rain thresholds. Therefore, it can be concluded that it is particularly difficult for CLIPER to forecast rain accurately up in the mountains and this fact has to be considered when trying to improve the current CLIPER.

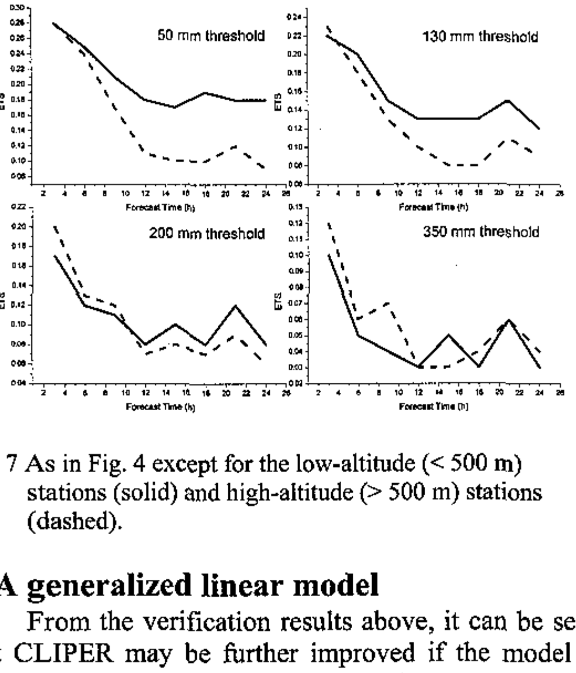

Fig. 7 As in Fig. 4 except for the low-altitude (< 500 m) stations (solid) and high-altitude (> 500 m) stations (dashed).

5. A generalized linear model

From the verification results above, it can be seen that CLIPER may be further improved if the model is able to take into account TC track type, structure (intensity, size, etc) and topography of Taiwan (e.g., height distribution of the rain stations). Therefore, a more generalized statistical model is to be setup based on the current CLIPER, which has the regression form

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon,$$

where y can be treated as the rainfall at a particular station, x_i's the predictors, β's the regression coefficients and ε the error term.

Besides climatology and persistence, the generalized model will include the following predictors: time of occurrence of the TC, position of the TC and its motion vector, structure parameters that include it intensity, surface pressure and R_{30}/R_{50}, and the height of a rain station under consideration. Subsequent research may also include some synoptic parameters (e.g., wind speed in a certain region with respect to the TC) to take into account for potential influence from the monsoonal environment to the rainfall pattern. The above mentioned regression will first be performed for each station individually such that a different set of regression coefficients is available for each station. Certainly, not all these parameters have equal contribution to the skill of the model, and stepwise regression technique will be used to select the most significant factors. In addition, a generalized form of the regression can be used to consider "interaction" effects among the predictors such that a single set of regression coefficients is obtained. The latest progress along this line of research will be reported in the conference.

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