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Typhoon Quantitative Precipitation Forecasts by the 2.5 km CReSS Model in Taiwan: Examples and Role of Topography

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Abstract: In this study, 24 h quantitative precipitation forecasts (QPFs) in Taiwan at the ranges of day 1 (0–24 h), day 2 (24–48 h), and day 3 (48–72 h) by a cloud-resolving model are examined using categorical statistics, targeted mainly for the most-rainy 24 h from 10 typhoon cases between 2010 and 2015, following two earlier studies that evaluated the overall performance for all the typhoons that hit Taiwan from 2010 to 2012 and through 2015. In the selected examples with a peak amount of 322 to 1110 mm, the QPFs by the model (with a grid size of 2.5 km) are shown to be of very high quality for two typhoons (Soulik and Soudelor), and fairly good quality for three cases (Fanapi, Megi, and Fung-Wong) up to day 3 and for four others (Saola, Kong-Rey, Nanmadol, and Tembin) within day 2, respectively. The results are more variable for the one remaining case of Matmo, also impressive on day 1 but degraded at longer ranges. Overall, the quality of the QPFs ranges from excellent to satisfactory for all the typhoons studied as the threat score can achieve 0.2 at thresholds fairly close to the observed peak amount in some typhoons, or at least about half of it in most others. Since the majority of the typhoons produced the greatest rainfall amounts over the mountains in Taiwan due to the topographic effect, in agreement with many previous studies, the QPF skills by the model, often extending into high thresholds, as demonstrated, suggest that heavy rainfall from typhoons in Taiwan is generally of high predictability if and when the model has an adequate resolution.

Keywords: quantitative precipitation forecast; typhoon; rainfall; cloud-resolving model; categorical skill scores; topography; Taiwan



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1. Introduction

Tropical cyclones (TCs), or typhoons in the western North Pacific (WNP), can bring heavy rainfall and cause urban inundation, flash floods, and landslides/mudslides to coastal areas at landfall and islands along their path (e.g., Refs. [1–4]). Due to their hazards, quantitative precipitation forecasts (QPFs) linked to TCs are of great importance and are in heavy demand by society (e.g., Refs. [5–11]). Among those regions threatened by TCs on a regular basis, many possess steep and complex topography that often acts to enhance rainfall and thereby worsen the associated hazards (e.g., Refs. [12–14]). Located along the main typhoon path off the East Asian continent in the WNP, Taiwan is one of such places (cf. Figure 1) and often receives the bulk of its ample annual total rainfall amount (around 3500 mm for the whole island [15]) in the typhoon season [1,2,9,13,16–21].

Traditionally, the skills in typhoon QPFs in Taiwan have been evaluated mainly through categorical statistics based on the 2×2 contingency table (e.g., Refs. [22–24]) since they are straightforward to compute and interpret. As the method is used to verify yes/no events, an event (at a location) is defined as having rainfall reaching a specified

threshold amount (accumulated over a given period) in the case of rainfall (or QPF). With its rows and columns used for observation and prediction (each contains two possibilities of event and no event), respectively, the cells of the 2×2 table are then the numbers of points in four mutually exclusive categories: event in both observation and prediction (hits), event in observation but no event in prediction (misses), event in prediction but no event in observation (false alarms), and no event in both observation and prediction (correct negatives). Then, statistics such as the probability of detection (POD, fraction of hits in all observed events), success ratio (SR, fraction of hits in all predicted events), threat score (TS, fraction of hits in all events either observed or predicted, or both), and bias score (BS, ratio of predicted to observed events) can be calculated to reflect the model skill at that rainfall threshold at the range being verified [22–24]. Overall, except for some known issues to be avoided, such as the double penalty at smaller spatial and temporal scales [25–27], categorical statistics are suitable for the verification of model QPFs, particularly where the hits, i.e., model prediction of rainfall amount to reach a certain threshold at the right location and time period, are essential for hazard prevention and reduction.

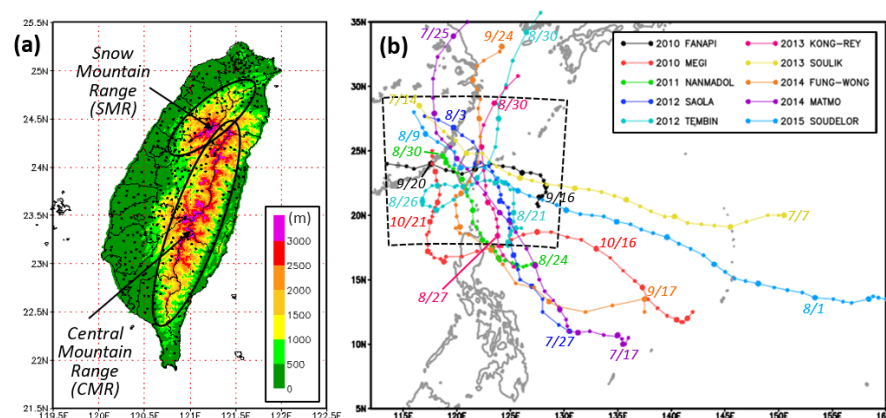


Figure 1. (a) The topography of Taiwan (m, color) and distribution of rain gauges (dots), with the two major mountain ranges (CMR and SMR) labelled. (b) CWB best tracks of the 10 typhoons during 2010–2015 included in this study, with their center positions given every 6 h (at 0000, 0600 UTC, etc., dots, those at 0000 UTC enlarged). The model domain in 2012–2015 is also shown (dashed box).

Using the Cloud-Resolving Storm Simulator (CReSS) [28,29] at a grid size of 2.5 km, Wang [30] (W15 hereafter) reported the performance of its 24 h QPFs in Taiwan at the range of days 1–3 (0–24, 24–48, and 48–72 h) for 15 typhoons between 2010 and 2012. Both using the categorical matrix, the results have been updated to include 29 TCs from 2010 to 2015 recently [31] (W21 hereafter) so that they are stable and robust. Using a cloud-resolving model (CRM) at a high resolution (e.g., Refs. [32,33]), these real-time forecasts exhibited overall TSs, at 350 and 500 mm (per 24 h), of 0.28 and 0.18 on day 1 (0–24 h), 0.25 and 0.16 on day 2, and 0.15 and 0.08 on day 3, respectively. Such values not only show a clear advantage over earlier results in the literature but also compare favorably to those by 5 km models at the same time (e.g., Refs. [5,31,34–37]). Furthermore, when the samples are classified by their event size (observed rainfall amount), a clear tendency of higher TSs for larger events is found [30,31,38,39]. For example, for the largest 5% of events, the corresponding TSs at 350 and 500 mm are 0.39 and 0.25, 0.38 and 0.21, and 0.25 and 0.12 on day 1, 2, and 3, respectively. Thus, not only are the typhoon QPFs improved but the predictability of the more-rainy TCs is also in fact higher (at the same thresholds) in Taiwan. In agreement with some recent studies (e.g., Refs. [9,40,41]), this dependency in categorical statistics on event size is an important property not known before.

In W15 and W21 [30,31], it is demonstrated that the dependency phenomenon still exists even after the rain-area sizes are normalized to remove their influence, and, hence, the model indeed possesses a higher capability in predicting larger TC rainfall events, which are presumably of longer duration, under stronger forcing, with more favorable

conditions, or a combination of these factors (e.g., Refs. [2,3,19,42–44]). Here in this study, it is hypothesized that this dependency of higher TSs for larger rainfall events is mainly due to the topographic effect of Taiwan, as reviewed earlier (e.g., Refs. [12–14], cf. Figure 1a). Through selected examples of typhoons and the QPFs produced for them by the 2.5 km CReSS, we discuss in this article and establish that the mountainous areas of Taiwan typically receive the most rainfall from typhoons and are, therefore, where most of the large events occur. Better illustrated in examples, these are often the regions where the model performs quite well, with relatively high TS values at high thresholds (as compared to smaller, ordinary events). Thus, Taiwan’s topography plays a role to not only enhance rainfall but also make such rainfall more predictable by a CRM, which, obviously, can better resolve both the convection and the topography of the island. This is the aim of the present study.

The remaining part of this paper is arranged as the following. In Section 2, the model, data, and methodology are briefly described. The year-by-year TS results between 2010 and 2015 are shown in Section 3 to provide an overall skill for comparison. Then, in Section 4, the results of several selected examples of typhoons and model forecasts are presented and discussed to demonstrate the relationship mentioned above. Finally, an overall discussion and the conclusions are given in Section 5.

2. Model, Data, and Methodology

2.1. The CReSS Model and Its Forecasts

As a follow-up study of W15 and W21 [30,31], the same version and setup of the CReSS model is used. Thus, only a brief description is given here and the readers are referred to Refs. [30,31] for details. The CReSS model [28,29] is a CRM with a single domain and terrain-following vertical coordinate. In this model, all clouds are treated explicitly through the bulk cold-rain scheme based on Refs. [45–49], with six species: vapor, cloud water, cloud ice, rain, snow, and graupel. Parameterized processes include planetary boundary layer turbulent mixing [28,29,50], as well as surface radiation and momentum and energy fluxes with the use of a substrate model [51–53]. As mentioned, a horizontal grid size of 2.5 km is used with 40 vertical levels, and the model domain has been enlarged since 2012 (Table 1). Using the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) real-time analyses and forecasts [54–56] as initial and boundary conditions (IC/BCs), the CReSS forecasts are routinely made four times a day, with initial times (t_0) at 0000, 0600, 1200, and 1800 UTC (Table 1). Since 2013, the resolution of the GFS data has been increased from every 1.0° to 0.5° . At the bottom, terrain elevation data on a $(1/120)^\circ$ grid (cf. Figure 1a) and the NCEP analyzed sea-surface temperature are also provided.

Table 1. The basic domain and configuration of the 2.5 km CReSS from 2010 to 2015.

Season	2010–2011	2012–2015
Grid spacing (km)	$2.5 \times 2.5 \times 0.2\text{--}0.663$ (0.5) *	
Grid dimension (x, y, z)	$432 \times 360 \times 40$	$600 \times 480 \times 40$
Domain size (km)	$1080 \times 900 \times 20$	$1500 \times 1200 \times 20$
Forecast frequency and range	Every 6 h (at 0000, 0600, 1200, and 1800 UTC) and 72 h (or 78 h)	
IC and BCs	NCEP GFS analyses and forecasts (every 1.0° or 0.5° , 26 levels)	

* The vertical grid spacing of CReSS is uneven and stretched (smallest at bottom), and the averaged value is shown in the parentheses.

2.2. Data and Methodology

The observational data used here are also nearly the same as those in W15 and W21 [30,31] and include the rain-gauge data, best tracks, track type classification, and radar composites, all from the Central Weather Bureau (CWB) of Taiwan. Among them, the gauge data (at 1 h intervals) from around 450 sites [57] (Figure 1a) are used to produce the

observed rain maps and compute the categorical scores to verify QPFs. As in Refs. [30,31], only 24 h QPFs, either 0000–0000 or 1200–1200 UTC, are verified. For each TC selected, one or two 24 h periods with significant rainfall amounts are identified and model QPFs valid for these periods at the range of day 1 (0–24 h), day 2 (24–48 h), and day 3 (48–72 h) covered by the forecasts are examined as needed. Compared to the sample of 99 and 193 24 h segments in W15 and W21 [30,31] that cover the warning periods and are of various event sizes, the present study focuses mainly on the rainiest periods of several selected TCs between 2010 and 2015 and examines only the QPFs targeted for them. Shown in Table 2 and Figure 1b, these selected cases and periods are used as examples as categorical statistics over high thresholds mainly come from events similar to them. They also cover a variety of different track types and have a peak 24 h rainfall of at least near 500 mm, except for Tembin during its second approach (Table 2, cf. Figure 1b). Three TCs studied in W15 and W21 [30,31] are also included but will only be briefly discussed in Section 5. For a few seasons after 2015, relatively few TCs hit Taiwan during the mid-summer.

Table 2. List of the 10 typhoons in this study, including their name and year, CWB track type *, main target period (24 h in length, 0000–0000 or 1200–1200 UTC), and observed peak rainfall amount (mm) over that period. Due to its special track, two target periods are chosen for Tembin (2012). Results of Fanapi (201) and Megi (2010) are taken from W15 [30], and Soulik (2013) from W21 [31].

Name of TC	Track Type *	Main Target Period	Peak Rainfall (mm)
Fanapi (2010)	4	0000 UTC 19 September–1000 UTC 20 September	1110
Megi (2010)	9	0000 UTC 21 October–0000 UTC 22 October	945
Nanmadol (2011)	4	1200 UTC 28 August–1200 UTC 29 August	488
Saola (2012)	2	1200 UTC 1 August–1200 UTC 2 August	889
Tembin (2012)	10	0000 UTC 24 August–0000 UTC 25 August	621
	10	0000 UTC 27 August–0000 UTC 28 August	322
Soulik (2013)	2	1200 UTC 12 July–1200 UTC 13 July	876
Kong-Rey (2013)	6	1200 UTC 28 August–1200 UTC 29 August	706
Matmo (2014)	3	0000 UTC 22 July–0000 UTC 23 July	556
Fung-Wong (2014)	10	1200 UTC 20 September–1200 UTC 21 September	797
Soudelor (2015)	3	1200 UTC 7 August–1200 UTC 8 August	842

* The CWB classifies all typhoons to issue warnings into 10 track types: types 1–5 are westward-moving or northwestward-moving typhoons that pass through Taiwan over the ocean off the northern tip (type 1), through northern, central, and southern part of Taiwan (types 2–4), or off the southern tip (type 5). Types 6 and 7 are northward-moving ones off or along the eastern (type 6) or western coast (type 7). Types 8 and 9 are eastward-moving or northeastward-moving ones off southern Taiwan (type 8), or through the land (type 9). All others belong to type 10 (special track).

2.3. Categorical Score Measures

As reviewed and described in Section 1, the categorical scores based on the 2×2 contingency table [22–24] are used to evaluate the performance of model QPFs in this study.

With the four entries of hits (H), misses (M), false alarms (FA), and corrective negatives (CN), among a total of N verification points ($N = H + M + FA + CN$), the TS and BS to be presented later, following their definition [22–24], can be computed as

$$TS = H / (H + M + FA), \quad (1)$$

and

$$BS = (H + FA) / (H + M), \quad (2)$$

where the observed event points are $O = H + M$, while the predicted event points are $F = H + FA$, respectively. Thus, the TS has a value bounded by 0 and 1, and the higher the better. On the other hand, the BS ($= F/O$ as well) indicates under- or over-prediction by the model when it is below or above unity. Therefore, 1 is the most ideal value for BS, while its range is uneven for under-prediction ($0 \leq BS < 1$) versus over-prediction ($1 < BS \leq N$ in theory). As one can tell from their definition, TS can be no higher than either POD or SR (also, $0 \leq POD, SR \leq 1$) and needs to be shown along with BS and the rainfall maps to more fully grasp the performance of the model QPFs. Thus, TS, BS, and rainfall maps will be used in our examples, and POD and SR will not. As in Refs. [30,31], the model results are interpolated using bi-linear method onto the rain-gauge sites, where the verifications are carried out (i.e., $N \approx 450$ in each forecast), at a set of 15 thresholds from 0.05 to 1000 mm (per 24 h).

In the verification, once the threshold exceeds either the observed or predicted maximum rainfall, there can be no hits and TS must drop to zero. Moreover, as the threshold approaches the peak rainfall (variable among periods), the points involved to compute TS and BS become fewer and fewer (as CN is not used) and the scores can become unstable, especially for the BS if the denominator (i.e., O) is small in the case of over-prediction. Therefore, visual verification of rainfall maps is often necessary to ensure the correct interpretation of results, and the values of observed base rate, i.e., O/N , will also be used later to assist and facilitate interpretation. When the verification is over multiple forecasts, as in W15 and W21 [30,31], the entries need to be combined into a single 2×2 table to ensure the largest sample size (in terms of points) and more stable results. These are some of the properties regarding categorical measures that it is also necessary to be aware of [25–27].

3. The Overall Threat Scores by Year between 2010 and 2015

Before the examples of individual TCs and the QPFs for them are shown, it is worthwhile to give the overall TSs as a function of rainfall threshold for each season of 2010 to 2015 in the samples of W15 and W21 [30,31] for comparison, as presented in Figure 2 for the three different ranges of day 1, 2, and 3. While the TSs generally decrease toward the higher thresholds as expected, they vary to some extent year by year. Moreover, they tend to lower with forecast range (i.e., lead time) at the same threshold as scores on day 1 (0–24 h, Figure 2a) are often higher than those on day 2 (24–48 h, Figure 2b), which, in turn, are higher than those on day 3 (48–72 h, Figure 2c). However, exceptions do exist occasionally. At thresholds of 50, 200, and 500 mm (per 24 h), for instance, the day 1 QPFs have seasonal TSs of about 0.4–0.6, 0.3–0.4, and below ~ 0.32 (Figure 2a), respectively. On day 2, the corresponding values decrease to about 0.35–0.55, 0.2–0.4, and 0.05–0.25, respectively, and further to about 0.25–0.45, 0.1–0.3, and below ~ 0.2 on day 3. Toward the high thresholds (e.g., ≥ 200 mm), the spread of TSs among different years tends to increase somewhat, and those seasons with fewer 24 h segments (given in parentheses), such as 2011 (red) and 2014 (gray), tend to exhibit lower overall TSs (Figure 2). This is because, in the years with fewer TCs to strike Taiwan (and, thus, fewer segments), the chances to have rainier events were also lower and thus the TSs tend not to be as high according to the dependency of event size. That is, this phenomenon is also, to a large degree, dictated by the dependency property found by the authors of Refs. [30,31] and reviewed in Section 1. Later, in Section 4, the TSs from individual model forecasts for a selected typhoon can be compared with the overall scores of the season. At the same time, one should bear in mind that the top events were always the main contributors toward the overall statistics of its season at high thresholds.

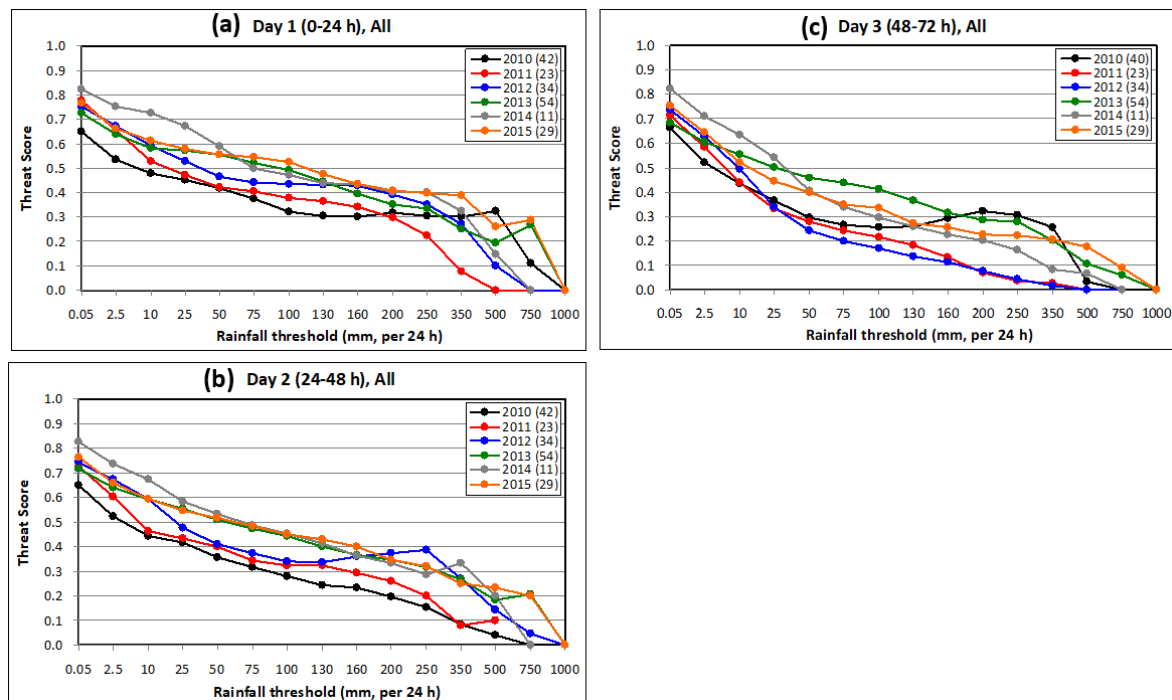


Figure 2. The overall TS of 24 h QPFs for (a) day 1 (0–24 h), (b) day 2 (24–48 h), and (c) day 3 (48–72 h) by the 2.5 km CReSS model in Taiwan as a function of rainfall threshold (mm) from all events in individual seasons between 2010 and 2015 (see insert). The parentheses in insert give the number of 24 h periods included for verification in each season, and they cover the warning periods issued by the CWB for each TC case, as defined in Refs. [30,31].

When all the samples in Figure 2 are combined, the TS curves on days 1–3 would correspond to those for all events (without classification), i.e., identical to those in Figures 6 and 7 of W21 [31]. It is also shown in W21 [31] that the overall BSs between 2010 and 2015 are stable and close to 1 (their Figure 8), except at the two highest thresholds of 750 and 1000 mm ($0.6 \leq BS \leq 3.33$), where the points become very few (only 33 and 3 out of a total of 86016 points from 29 TCs, respectively). Thus, the BSs for individual seasons will not be shown here.

4. Examples of Typhoons and CReSS Forecasts

A few examples of typhoons and CReSS forecasts for them between 2010 and 2015 are shown and discussed in this section. Following the order of presentation, they are from seven cases: Typhoons (TYs) Saola (2012), Fung-Wong (2014), Tembin (2012), Nanmadol (2011), Kong-Rey (2013), and TY Matmo (2014), and Soudelor (2015). Already shown in W15 and W21 [30,31] as examples, three other typhoons of Fanapi (2010), Megi (2010), and Soulik (2013) will not be shown here to avoid redundancy, but their statistics will be included in Section 5 to enhance the representativeness of our study. Together, the above 10 TCs account for most of the rainier typhoons between 2010 and 2015, as well as a variety of different track types (cf. Figure 1b, Table 2). For each case, the model-predicted distributions of rainfall over Taiwan will be compared with the observations for the selected 24 h periods, and the corresponding TS and BS are shown and discussed. For some, the predicted TC track and rainfall structure will also be verified against the best track and radar observations, preferably at a longer lead time (during day 2 or day 3).

4.1. Typhoon Saola (2012)

The first TC example to be presented is TY Saola (2012), which was by far the rainiest and most hazardous typhoon to strike Taiwan in the 2012 season. The main reason was its slow moving speed (e.g., Refs. [9,42,44,58,59]) as it approached northern Taiwan from the

southeast at only about 10 km h^{-1} (cf. Figure 1b). In Figure 3, reflectivity composites from land-based radar in Taiwan for TY Saola at two selected times are shown, at 1000 UTC 1 (Figure 3a) and 1000 UTC 2 August (Figure 3c), and the slow translation speed of the storm can be clearly depicted. Here, in the reflectivity composites, note that the radar's field of view becomes increasingly limited farther away from Taiwan at longer distances. The forecasts made by the CReSS model initialized at 1200 UTC 31 July and valid at the same times ($t = 22$ and 46 h) are shown in Figure 3b,d for comparison. In Figure 3b, it is seen that Saola was a large storm and it approached Taiwan with an equally slow speed but more apparent wobbling motion at the center in the model. At this time, when the storm center was east of Taiwan, the main rainfall area was mainly over northeastern Taiwan in both the radar observation and the model (Figure 3a,b). Afterwards, TY Saola turned west to almost make landfall near 24° N at eastern Taiwan and made a small loop and turned north (Figure 3c). In the model, the storm exhibits a similar behavior but at a higher latitude (by about 1°); therefore, the looping takes place in northeastern Taiwan instead (Figure 3d). At 1000 UTC 2 August, when Saola's center was just off the northern tip of Taiwan, the rain was in western Taiwan, over the windward side of SMR and CMR and the Taiwan Strait (Figure 3c). In the model, the TC center is slightly too far east (by about 50 km) at the same time, but a similar rainfall pattern in Taiwan is produced (Figure 3d).

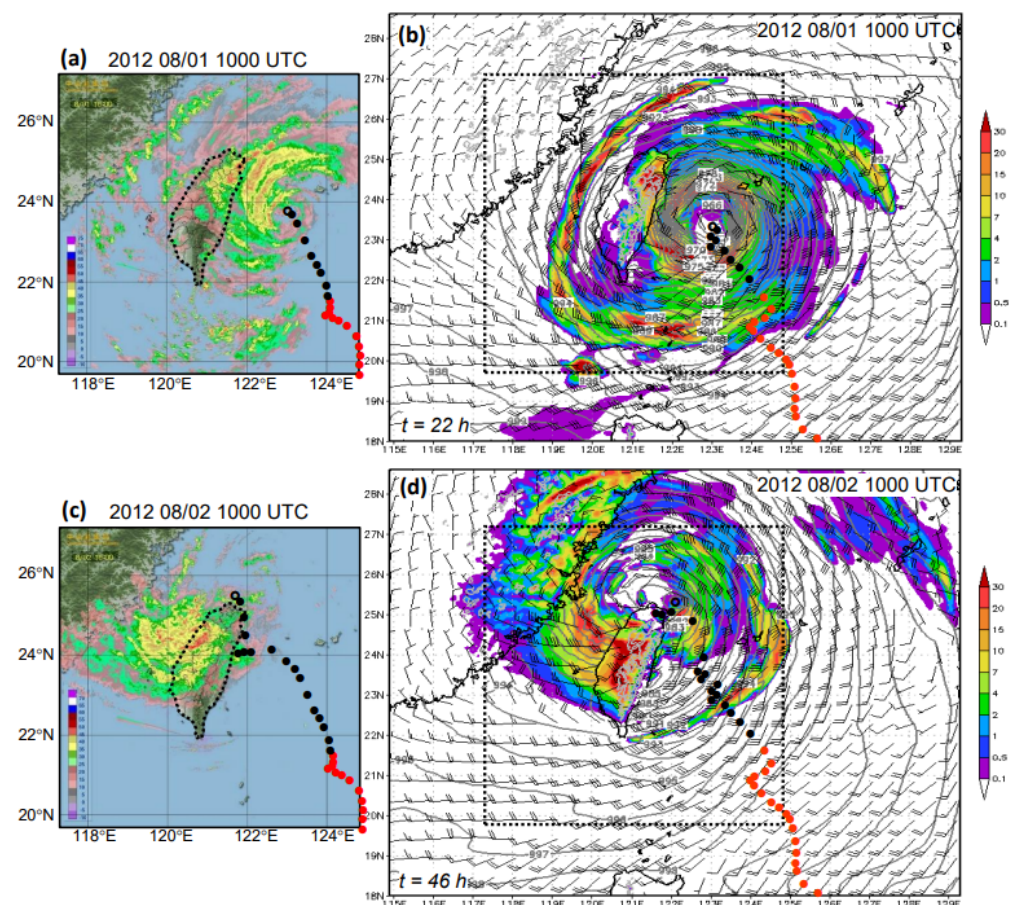


Figure 3. (a) Radar VMI reflectivity composite (dBZ, scale on top, every 5 dBZ from -10 to 75 dBZ) at 1000 UTC 1 August (provided by the CWB) and (b) CReSS forecast (t_0 at 1200 UTC 31 July) of sea-level pressure (hPa, every 1 hPa, over ocean only), surface wind (kts, barbs) at 10-m height, terrain elevation (gray contours at 1 and 2 km, over land only), and 1 h rainfall (mm, color, scale to the right) valid at the same time as (a). (c,d) As in (a,b) but for radar reflectivity at 1000 UTC 2 August and CReSS forecast valid at the same time as (c). The current typhoon center is marked by an open dot, and the earlier positions every 3 h (at 0000, 0300 UTC, etc.) by solid dots (in red prior to 1200 UTC 31 July). The dotted box in (b,d) corresponds to the region of radar plots.

The 24 h rainfall distributions in Taiwan from rain gauges for three periods starting from 1200 UTC of 30 and 31 July and 1 August are presented in Figure 4 (left column). In the first two segments, the observed rainfall was mainly in northeastern and eastern Taiwan, with peak amounts near the northern end of the CMR (Figures 1a and 4a,e) as the prevailing wind from the TC was northeasterly (cf. Figure 3b). When Saola moved closer to landfall after 1200 UTC 1 August, the rainfall in Taiwan increased dramatically, with a 24 h peak amount of 889 mm again at the northern end of the CMR (Figure 4i), and the prevailing winds gradually turned into northwesterly and westerly (cf. Figure 3b,d) such that the western part of the island also received much rainfall. During the next 24 h period, the rainfall in Taiwan reduced significantly (not shown) as Saola moved away and made landfall in China (Figure 1b). Clearly, this storm produced the most rainfall during the 24 h period from 1200 UTC 1 to 1200 UTC 2 August (Figure 4i), so the model's QPFs valid for this period at different lead times are our main focus.

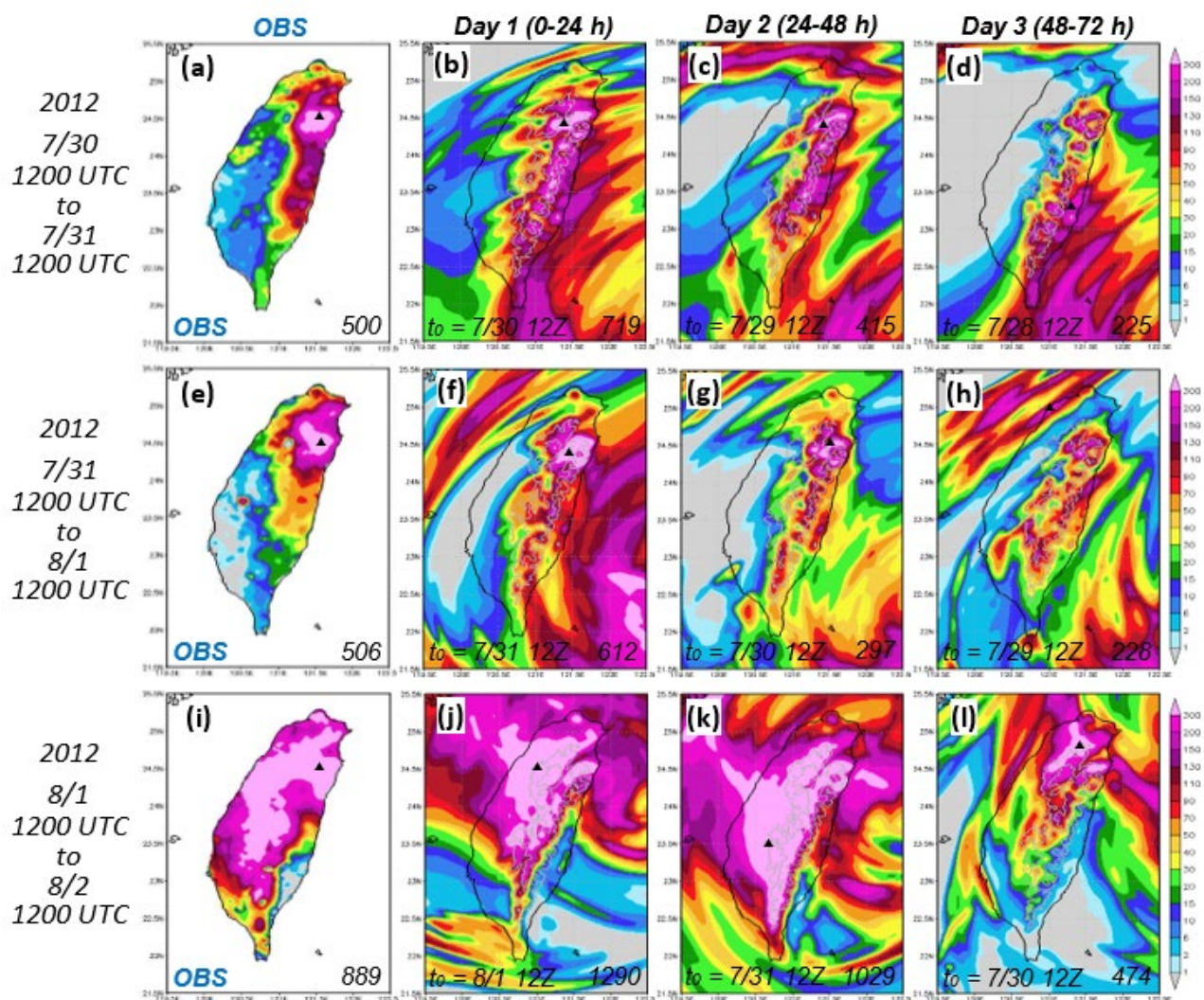


Figure 4. (a) Observed 24 h rainfall distribution (mm) over Taiwan starting from 1200 UTC of 30 July 2012, and CReSS 24 h QPFs (all targeted for the same period) made at 1200 UTC of (b) 30 July (day 1, 0–24 h), (c) 29 July (day 2, 24–48 h), and (d) 28 July (day 3, 48–72 h), respectively, during TY Saola (2012). (e–h) and (i–l) as in (a–d), except for observed and predicted rainfall for the 24 h period starting from (e–f) 1200 UTC of 31 July and (i–l) 1200 UTC of 1 August, respectively. The observed or predicted peak rainfall amount (mm, lower right), its location (triangle), and t_0 of forecast (lower left, columns 2–4 only) are all labeled. For the peak rainfall in QPFs, results are obtained after spatial interpolation onto locations of gauge sites. The color scales (to the right) are identical for all panels.

Columns 2–4 in Figure 4 show the predicted 24 h rainfall valid for the same period as the observation on the same row but at different ranges of day 1 (0–24 h), day 2 (24–48 h), and day 3 (48–72 h), respectively. Thus, the farther to the right, the earlier was the t_0 of the forecast. In other words, the day 1 to day 3 QPFs made by the same run (with the same t_0) are placed diagonally, from upper-left to lower-right. Therefore, the 24 h QPFs on days 1 and 2 made by the run in Figure 3 are depicted in Figure 4f,k, respectively, both of fairly good quality by visual inspection with some minor track errors described earlier. For Saola, the rainfall forecasts made for the three 24 h periods shown in each row of Figure 4 are all reasonably good within day 2, often with peak rainfall close to the observed spot. However, the quality of the QPFs for Saola was degraded to some extent at a longer range on day 3 and typically exhibited under-prediction. In these situations, the track of the TC deviated more to the east and farther away from Taiwan, thus resulting in too little rainfall over the island. For example, the forecast made at 1200 UTC 30 July produced decent QPFs on day 1 (Figure 4b) and day 2 (Figure 4g) but not enough rainfall on day 3 targeted for the rainiest 24 h of Saola (Figure 4l) as the storm center stayed about 150 km offshore (figure not shown). As the lead time decreased, such track errors also reduced so that the predicted rainfall in Taiwan increased in both runs starting at 1200 UTC 31 July (on day 2, Figure 4k) and 1200 UTC 1 August (on day 1, Figure 4j), with even slight over-prediction. While the overall rainfall patterns were reasonable in these two forecasts, location error in peak rainfall still existed. Nonetheless, a local rainfall center remained at the northern end of the CMR in both runs (Figure 4j,k). The above-mentioned location errors were apparently less for the two earlier target periods despite the lower rainfall amounts (Figure 4a–h) when the prevailing low-level wind directions associated with TY Saola were more stable in the model.

In Figure 5, the TS and BS from three individual runs with t_0 at 1200 UTC of 30 July to 1 August, at 15 thresholds from 0.05 to 1000 mm, are presented. In the earliest run (on 30 July), its 0–24 QPF is very good, hitting TS = 1 at 250 mm where the base rate (O/N) is only 0.9% (Figure 5a). Here, the BS must also be unity because $M = FA = 0$, while $H > 0$. The 24–48 h QPF from the same run is also reasonably good despite some under prediction (Figure 5b). The day 3 QPF targeted for the rainiest period, however, is less ideal, as mentioned and discussed earlier, with TSs dipping below 0.2 before 160 mm and further to zero at 500 mm almost linearly due to the rather serious under-forecasting (TC being too far away). Affected by this major event of TY Saola, the overall TSs for the day 3 QPFs at high thresholds in the 2012 season are only slightly better (cf. Figure 2c, blue curve). On the other hand, in the next run, the day 1 QPF for the period starting at 1200 UTC 31 July was rather impressive, with the TS hitting 1 at 500 mm where O/N approaches zero (but TS only near 0.2 at 200 mm), while its day 2 QPF, valid for the rainiest period, also exhibits high TS values across the low and middle thresholds and remains above 0.2 at 500 mm (Figure 5c). These TS values (as well as some of the better ones mentioned above) are at times much higher than the overall seasonal values (cf. Figure 2a,b, blue). At both ranges, the BSs are close to unity and quite good (Figure 5d). In the final forecast (Figure 5e), the day 1 QPF targeted the rainiest period and, again, was very good in TS values, which are quite close to those on day 2 in the run 24 h earlier (cf. Figure 5c), and the BS values in this later run are even better by comparison and stay very close to 1 up to 500 mm (Figure 5f). Nevertheless, the lead time of this run was reduced. At a longer range not yet mentioned in Figure 5, the QPFs were made for periods starting at 1200 UTC 2 August or later when the rainfall was diminishing, so they are less important and, thus, not discussed further. Overall, for the rainiest 24 h period from TY Saola (2012), one can see that rainfall amounts above 300 mm mainly occur in the mountainous regions of Taiwan (cf. Figure 4i–k), and the model QPFs can be verified to be reasonably good within 2 days, with TS near 0.2 at 500 mm, but not on day 3 where the track errors are larger.

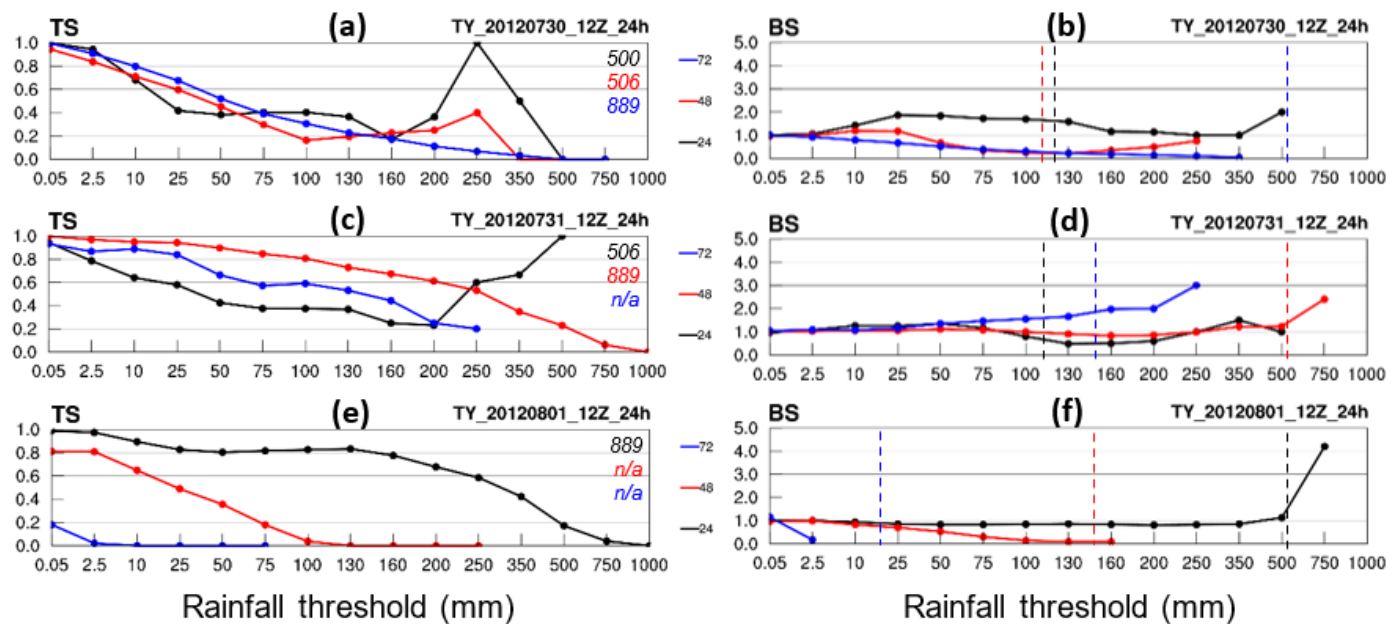


Figure 5. (a) TS and (b) BS of CReSS 24 h QPFs for day 1 (black), day 2 (red), and day 3 (blue) from the forecast made at 1200 UTC 30 July 2012 during TY Saola (2012) as a function of threshold (mm) (c–f). As in (a,b), except from the forecasts made at (c,d) 1200 UTC 31 July and (e,f) 1200 UTC 1 August, respectively. On days 1–3, the observed maximum 24 h rainfall values (mm, rounded to integer) are given at the upper-right corner of TS plots, and the observed base rate (O/N) at 10% are also marked (vertical dashed lines) in BS plots using the corresponding color.

4.2. Typhoon Fung-Wong (2014)

The second typhoon selected is TY Fung-Wong (2014). In Figure 6a,c, radar reflectivity composites at 0100 and 1800 UTC 21 September 2014 are shown, together with the best track up to those times. Classified to have a special track of type 10 (cf. Table 2), Fung-Wong approached the southern tip of Taiwan from the south also very slowly at about 11 km h^{-1} , and it turned to move toward the east just before landfall (Figure 6a). After a brief landfall of its center across Hengchun Peninsula in the southernmost part of Taiwan, TY Fung-Wong accelerated and moved north off the eastern coast and then just missed the northeastern tip of the island at around 1500 UTC 21 September (Figure 6c) before moving farther north. The TC rainfall structure was initially quite symmetric and covered a wider area at radii of roughly 50 to 150 km (Figure 6a) but became increasingly distorted and gradually weakened as it moved north and away (Figure 6c).

In the CReSS run with t_0 at 1200 UTC 18 September 2014, the simulated Fung-Wong also approached Taiwan from the south quite slowly near the beginning of the third day ($t = 51 \text{ h}$), as shown in Figure 6b, but this took place in the model about 10 h too early compared to the observation (cf. Figure 6a). Then, the storm also moved north at a faster pace off Taiwan's eastern shore. After 0000 UTC 21 September, a secondary center developed off the northwestern coast in the model (Figure 6d) and quickly became the primary center and moved northward. Thus, a discontinuous track occurred in the model in contrast to the continuous track in the observation. Nevertheless, when the model TC moved past 26° N at $t = 71 \text{ h}$ (Figure 6d), it was about 7 h too early, so the timing error somewhat reduced. Overall, besides the stage near departure, the route of the TC in the prediction was not too different from the observation but with a considerable timing error of being too early by roughly 7 to 10 h. Since the storm was very slow during its approach, as with Saola, the environmental steering flow must be weak to give a potential for larger track errors. Due to this timing error, the track error was about 200 to 250 km during day 3 in Figure 6, considerably larger than that in Figure 3 for TY Saola (2012) by comparison.

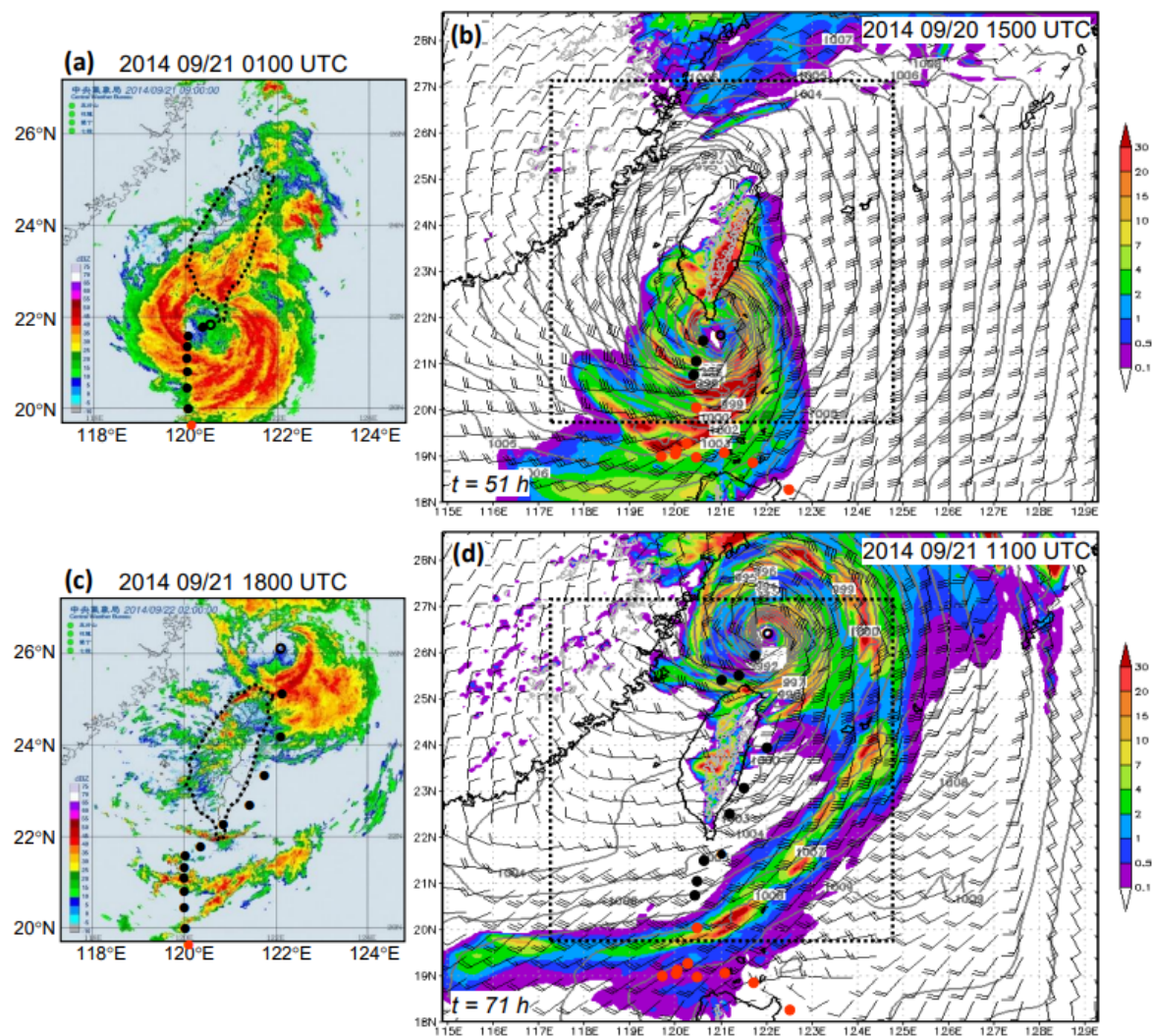


Figure 6. As in Figure 3, except for radar reflectivity (dBZ) at (a) 0100 and (c) 1800 UTC 21 September and CReSS model forecast (t_0 at 1200 UTC 18 September) valid at (b) 1800 UTC 20 and (d) 1100 UTC 21 September 2014. The current typhoon center is marked by an open dot, and earlier positions (every 3 h) by solid dots (in red prior to 0600 UTC 20 September).

Despite the timing error, however, when the model storm moved to a location in relation to Taiwan similar to the observed as those pairs shown in Figure 6, the rainfall patterns produced are similar. When TY Fung-Wong was near the southern tip of Taiwan, its circulation developed an oval shape with the long axis in a northwest–southeast orientation, and the rainfall in Taiwan was mainly along the eastern side and over the southwestern plains (Figure 6a). Likewise, when the TC moved to the north of Taiwan in Figure 6c, the model rainfall also weakened with a rainband along the northwestern coast in Figure 6d. Thus, it appears again that the model can capture the major rainfall characteristics of TY Fung-Wong (2014) and in Taiwan to a reasonable degree, when the storm moved to a similar location as in the observation, even though the timing was not right.

The observed 24 h rainfall distributions over Taiwan from 1200 UTC 19 to 1200 UTC 22 September (Figure 7, left column) reveal that the rainfall from TY Fung-Wong (2014) was the most over the 24 h period from 1200 UTC 20 to 1200 UTC 21 September (Figure 7e), with heavy rainfall along the eastern part of the island and a peak amount of 797 mm near the base of Hengchun Peninsula and along the ridge of southern CMR. This took place when Fung-Wong was approaching Taiwan slowly and moving northward to about 24° N

(figure omitted). In the following 24 h, the storm had moved past 24° N, and thus the rainfall area shifted to northern Taiwan but with a reduced amount (Figure 7i).

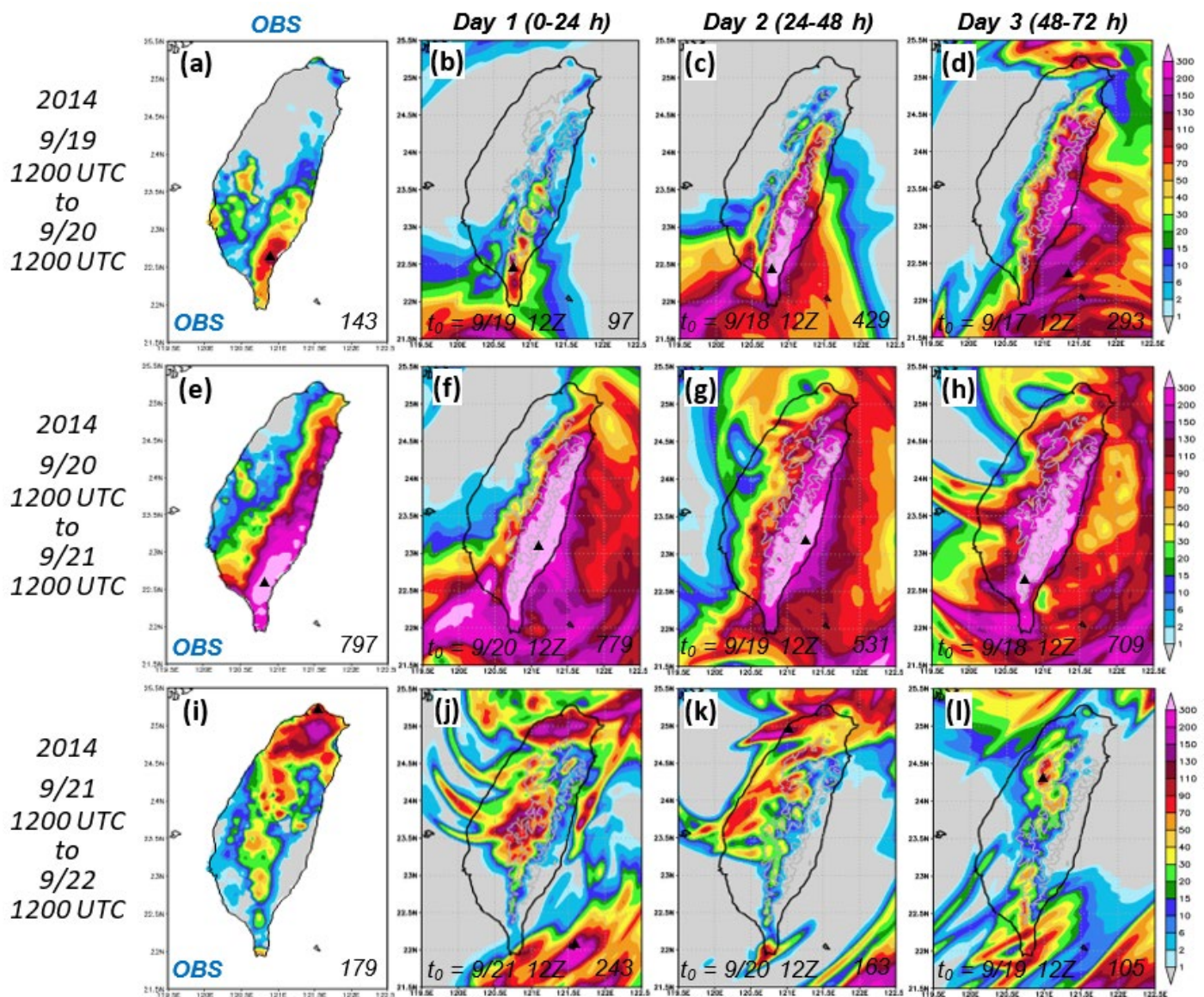


Figure 7. As in Figure 4, except for the rainfall distribution (mm) in observation (first column) and CReSS QPFs at ranges of days 1–3 (second to fourth column), valid for the 24 h period starting from 1200 UTC of (a–d) 19 September, (e–h) 20 September, and (i–l) 21 September, respectively, during TY Fung-Wong (2014).

In columns 2–4 of Figure 7, the daily rainfall forecasts at different ranges but valid for the same 24 h period as the observation on the same row during TY Fung-Wong (2014) are shown. In the experiment starting at 1200 UTC of 18 September, i.e., the one shown in Figure 6, the model predicted reasonable rainfall patterns on days 2 to 3 but with some over-forecast in rainfall area and amount (Figure 7c,h). Given the early arrival of the TC (by about 10 h), some over-prediction is perhaps not surprising and even somewhat expected. The predicted peak amount on day 3 was 709 mm and lower than the observation but at the right location (Figure 7h). Owing to the topographic effect, the two later runs with t_0 at 1200 UTC of 19 and 20 September both also produced the most rainfall over southeastern Taiwan during the correct 24 h period (starting from 1200 UTC 20 September). However, the one starting on 19 September (Figure 7b,g,l), on day 2, over-predicted the area but

under-predicted the peak amount at 531 mm (Figure 7g). This discrepancy in peak rainfall was corrected to some extent in the run 24 h later, which had a maximum amount of 779 mm on day 1 (Figure 7f). This run also better captured the rainfall in northern Taiwan on day 2 (Figure 7k). Overall, visual inspection suggests that the QPFs by CReSS for TY Fung-Wong (2014) were reasonable, even though timing errors existed in at least some of its forecasts. In this example, one can see why a relatively longer accumulation period of 24 h is chosen here as in W15 and W21 [30,31] since it can remedy part of the issue of “double penalty” [25–27] even on day 3, at least in time if not in space. Of course, another reason for choosing 24 h was that the bulk of the rainfall brought by typhoons in Taiwan, typically over 24 to 36 h, is our primary concern for evaluation.

In Figure 8 (left column), the TSs of 24 h QPFs from the above three runs are shown, and, again, those targeted at the most-rainy 24 h (from 1200 UTC 20 to 1200 UTC 21 September) exhibit the highest scores. For the run at 1200 UTC 18 September (cf. Figures 6 and 7c,h), the most-rainy segment was day 3 and the TS is 0.4 at 100 mm and above 0.35 at 500 mm (where $O/N = 0.6\%$, Figure 8a) due to the correct prediction in peak rainfall location (cf. Figure 7c,h). For the two later runs, it was day 2 (Figure 8c) and day 1 (Figure 8e), respectively, and those TSs can reach 0.5 at 130 mm and at least 0.2 at 350 mm (where $O/N = 1.8\%$). All these TS values mentioned are better than the overall values in 2014 at the same range (cf. Figure 2, gray curves). The TSs of the QPFs for other days, however, while they might be comparable at low thresholds, are not as high across the middle thresholds and typically decrease to zero or nearly so before 130 mm, worse than the seasonal scores. In most cases, the BSs (Figure 8, right column) are also more ideal when targeted at the most-rainy day, but they do indicate over-prediction across the thresholds to a various degree, consistent with Figure 7. This over-prediction was the least serious on day 2 as the BSs never exceed 2 (red, Figure 8d) and slightly more severe on day 3 (blue, Figure 8d), with a BS below 2.5. On day 1, the over-prediction occurred only at thresholds of about 160 to 350 mm, with the highest BS near 3.6 (black, Figure 8f). For other days when rainfall was less or limited in area size, the BSs can go much higher or dip below 0.5 more easily. In summary, for TY Fung-Wong (2014), the TS values of 0.2 to 0.35 at 500 mm are quite impressive on days 1 and 3 in Figure 8a,b,e,f considering that the observed base rate was less than 1% of Taiwan at this threshold.

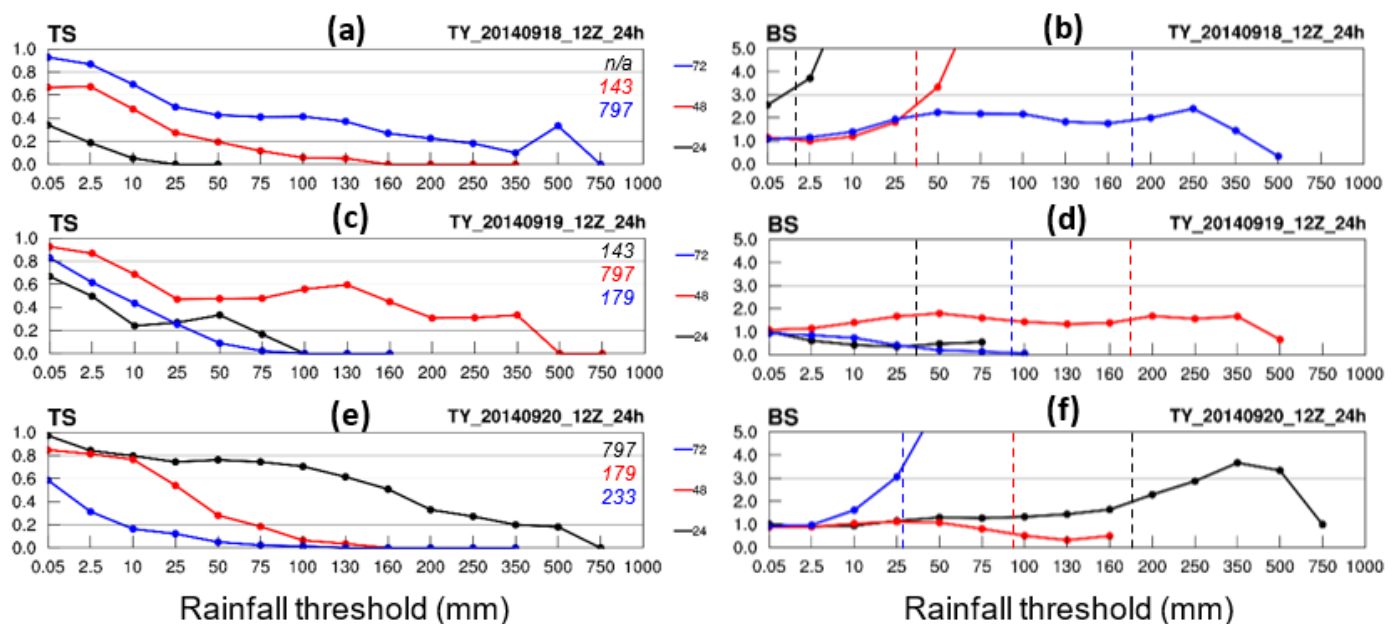


Figure 8. As in Figure 5, except for TS and BS of CReSS 24 h QPFs from the forecast made at 1200 UTC of (a,b) 18, (c,d) 19, and (e,f) 20 September, respectively, during TY Fung-Wong (2014).

4.3. Typhoon Tembin (2012)

The next example is TY Tembin (2012), relatively small in size but with a rather interesting track to strike Taiwan twice (cf. Figure 1b). This case and TY Saola are both included in Refs. [59,60], so its evolution is only briefly described here. Moving northward initially at a safe distance (Figure 1b), TY Tembin made a sudden turn toward Taiwan after 1200 UTC 21 August and, subsequently, penetrated Hengchun Peninsula near 0000 UTC 14 August. After it entered the Taiwan Strait and was over the northern South China Sea (SCS), it made a loop and turned back to move toward Taiwan again and almost made a second landfall on the island near 1800 UTC 27 August due to the surge of southwesterly flow induced by TY Bolaven that was much larger and more intense [59,61]. Thus, in the observation, Tembin produced rainfall in Taiwan on all three days of 23–24 (Figure 9a,e) and 27 August (Figure 9i). As the storm was lingering near the southern tip of Taiwan, the prevailing wind from central to southern Taiwan was mostly from the east, and thus the major rainfall areas were all on the eastern half (or southeastern quadrant) of the island.

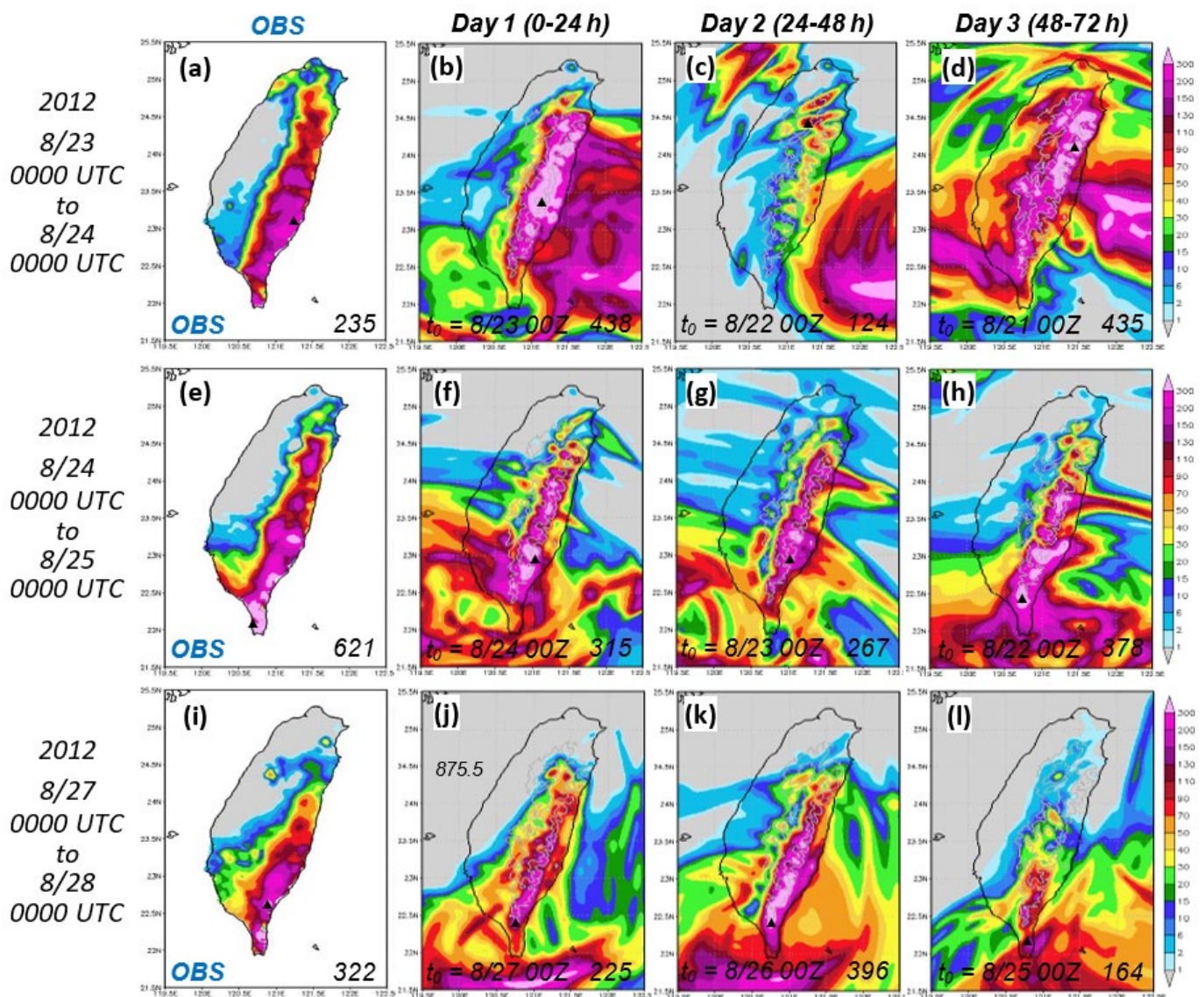


Figure 9. As in Figure 7, except for the rainfall distribution (mm) in observation and CReSS QPFs at ranges of days 1–3, valid for the 24 h period starting from 0000 UTC of (a–d) 23 August, (e–h) 24 August, and (i–l) 27 August, respectively, during TY Tembin (2012).

For 23 August, when Tembin was approaching southern Taiwan for the first time, the QPFs appear to be the best on day 1, followed by day 3, and the least ideal on day 2 (Figure 9b–d) through visual inspection, with some over-prediction in rainfall in the better two and under-prediction on day 2. Closer inspection revealed that such a difference is mainly because the TC approached Taiwan too slowly and too late in the run starting on 22 August, causing the rainfall to occur mostly over the ocean off southeastern Taiwan (cf. Figure 9c) rather than over land (details not shown).

For 24 August, when the storm was to the southwest of Taiwan in the southern Taiwan Strait, the peak amount (621 mm), located in Hengchun Peninsula, was in fact the highest among the three days (Figure 9e). For this day, the predicted rainfall occurred mainly in eastern Taiwan (as those for 23 August) at all three ranges, with rain-area sizes seemingly comparable to the observation (Figure 9f–h). While none of them adequately captured the heavy rainfall in Hengchun Peninsula, the day 3 forecast (with t_0 at 0000 UTC 22 August) performed the best, as revealed by the TS curve (0.43 at 160 mm, Figure 10a), with BS values close to 1 up to 250 mm before dropping lower (Figure 10b). Between the day 2 and day 1 QPFs for 24 August, the day 2 forecast was better over the threshold range of 10 to 130 mm (with TSs around 0.3–0.7), but the day 1 forecast had slightly higher TSs (~0.2) at 160 to 200 mm (Figure 10a). Nonetheless, at higher thresholds of 350 and 500 mm, all three runs had under-prediction with no hits (and, thus, TS = 0). Overall, the day 3 forecast performed the best for 24 August despite its lead time being the longest.

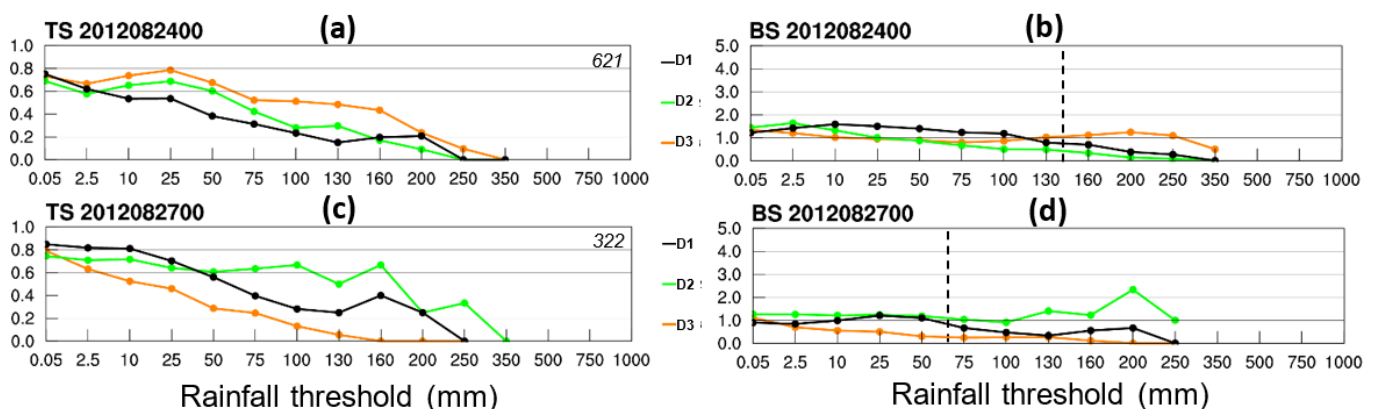


Figure 10. Similar to Figure 5, except for TS and BS of CReSS QPFs from the three forecasts made at 0000 UTC of (a,b) 22–24 August (at ranges of days 1–3) but all targeted for 24 August (0000–2400 UTC), and of (c,d) 25–27 August but all targeted for 27 August, respectively, during TY Tembin (2012). For the 24 h target period, the observed maximum rainfall (mm, rounded to integer, in TS plots) and base rate (O/N) at 10% (vertical dashed line, in BS plots) are both given.

As Tembin moved close to southern Taiwan for the second time (cf. Figure 1b) on 27 August, the observation shows a rainfall pattern over the southeastern quadrant of the island, with a peak amount of 322 mm (Figure 9i). This pattern was predicted most successfully on day 2, followed by day 1, and then day 3 with considerable under-forecast (Figure 9j–l). Such differences in the quality of QPFs are well reflected by the TS values in Figure 10c, which exhibits TSs of 0.33 at 250 mm on day 2, 0.40 at 160 mm on day 1, but only 0.13 at 100 mm on day 3 with more serious under-prediction (Figure 10d). As the observed peak rainfall was 322 mm, a TS of 0.33 at 250 mm is considered very good. However, over-prediction also exists on day 2 and leads to a lowered TS of 0.25 at 200 mm.

4.4. Typhoons Nanmadol (2011), Kong-Rey (2013), Matmo (2014), and Soudelor (2015)

Four other TCs, including TYs Nanmadol (2011), Kong-Rey (2013), Matmo (2014), and Soudelor (2015), are also briefly examined in this subsection (cf. Table 2), each for the QPFs targeted for the most-rainy 24 h period of the storm. The first of them, TY Nanmadol (2011), approached Taiwan from the south-southwest and moved across the southwestern

plains of the island (track type 4). Influenced mainly by the TC circulation from the east, the main rainfall regions from Nanmadol between 1200 UTC 28 and 1200 UTC 29 August were over the eastern half and southwestern plains (Figure 11a). Targeted for this period, the QPFs were reasonable on days 1 and 2 but less ideal on day 3 (Figure 11b–d). On day 1, the peak rainfall is predicted correctly in location but too much in value. Nonetheless, the TSs are ≥ 0.2 up to 350 mm (where O/N is only 0.9%) with good BS values across all the thresholds (Figure 12a,b). On day 2, the TSs are also quite good and only slightly lower, although the over-prediction was more serious toward the high thresholds. On day 3 at the longest range, the TSs can only reach 0.2 at and below 130 mm, mainly because the heavy rainfall was displaced north in the QPFs since the BSs remain at 0.65 to 0.96 up to 250 mm (Figure 12a,b). Overall, for the most-rainy 24 h target period of Nanmadol, the QPFs on days 1–3 can reach a TS of 0.2 at 350, 250, and 130 mm, respectively. At these thresholds, the base rate O/N in the observation was less than 1%, less than 3%, and about 19% following the order.

The next case is TY Kong-Rey (2013), which had a rainfall pattern atypical for its track (type 6) due to the strong influence of the southwesterly monsoon [62]. This typhoon was also studied in Ref. [59], but the 2.5 km 3-day CReSS forecasts for it have not been examined. While the storm moved northward off the eastern coast of Taiwan and never made landfall, the rainfall over the 24 h target period (starting from 1200 UTC 28 August) was mainly over the western part of the island, with a peak amount of 706 mm again along the southern CMR near the base of Hengchun Peninsula (Figure 11e). Such a rainfall pattern was very different from those of Fung-Wong (cf. Figure 7e) or Tembin (cf. Figure 9i) on its second passage despite the similarities in tracks (cf. Figure 1b) and peak rainfall location. Clearly, even though much of the rainfall was from southwesterly flow associated with Kong-Rey in this case, the distribution pattern was, nevertheless, still heavily influenced by the topography of southern Taiwan. As in the simulation [62], the QPFs by the CReSS model can capture the rainfall pattern at all three ranges of days 1–3, even though there is considerable under-prediction at the longer range on day 3 (Figure 11f–h). Among the three runs, the day 2 QPF performed the best and has the highest TSs toward the high thresholds, reaching 0.31 at 350 mm (Figure 12c), and slightly better than the seasonal value (cf. Figure 2b). At a shorter range, the day 1 QPF was, to some degree, worse in TS values, but, apparently, the overall rainfall area was shifted more inland toward the mountains. Finally, the day 3 QPFs has under-forecasting (Figure 12d) and only reaches TS = 0.19 at 130 mm.

The third typhoon in this subsection is TY Matmo (2014), which penetrated central Taiwan with a type-3 track (cf. Figure 1b). It was distributed mainly over the eastern part of the island and along the mountain ridges, with a peak amount of 556 mm over the northern section of the CMR (Figure 11i). This rainfall pattern of Matmo was captured quite well on day 1, with some over-prediction in the peak amount. While the BS curve shows that the over-prediction was slight overall, the TSs of this run can reach 0.64 at 250 mm and 0.2 at 500 mm (Figure 12e,f), which is only 56 mm below the observed peak value. On day 2, there was under-prediction and the TSs from this run can only reach 0.2 at thresholds of 130 mm and below. The under-prediction was even more severe on day 3 as the lead time increased, and the TS cannot reach 0.2 at thresholds of 75 mm and above (Figure 12e,f).

The final case here is TY Soudelor (2015), which was also very rainy and the most destructive typhoon in 2015, as it devastated the Wulai area, a popular destination for tourists in northern Taiwan known for its hot springs. Since the storm moved across central Taiwan following a path almost due west (cf. Figure 1b), the rainfall was concentrated over the northeastern and southwestern quadrants of the island, with a 24 h peak value of 842 mm over its target period from 1200 UTC 7 to 1200 UTC 8 August (Figure 11m). At the three ranges, the QPFs for this target period were all quite good and reasonable (Figure 11n–p). At the very high threshold of 750 mm, the TS values are 0.33, 0.25, and 0.11 on day 1, 2, and 3, respectively, indicating some gradual improvement as the lead time shortened (Figure 12g). On day 1, however, the peak value in the QPF occurs in southern

Taiwan as it exceeds the one in the northeastern quadrant (Figure 11n). The BS curves for the three runs, on the other hand, are, in general, very good and similar across the low and middle thresholds but also show some slight improvements (decreased over-prediction) with time at thresholds of 500 mm and above (Figure 12h). At 500 and 750 mm, the values of O/N were only 2.4% and 0.2%, respectively, so that a TS up to 0.33 at 750 mm reflects very good skill in the model to predict the heavy rainfall close to the peak amount with accuracy. Such a performance in TS at all three ranges is also better than the seasonal values in 2015 (cf. Figure 2), which are much contributed by the results of Soudelor.

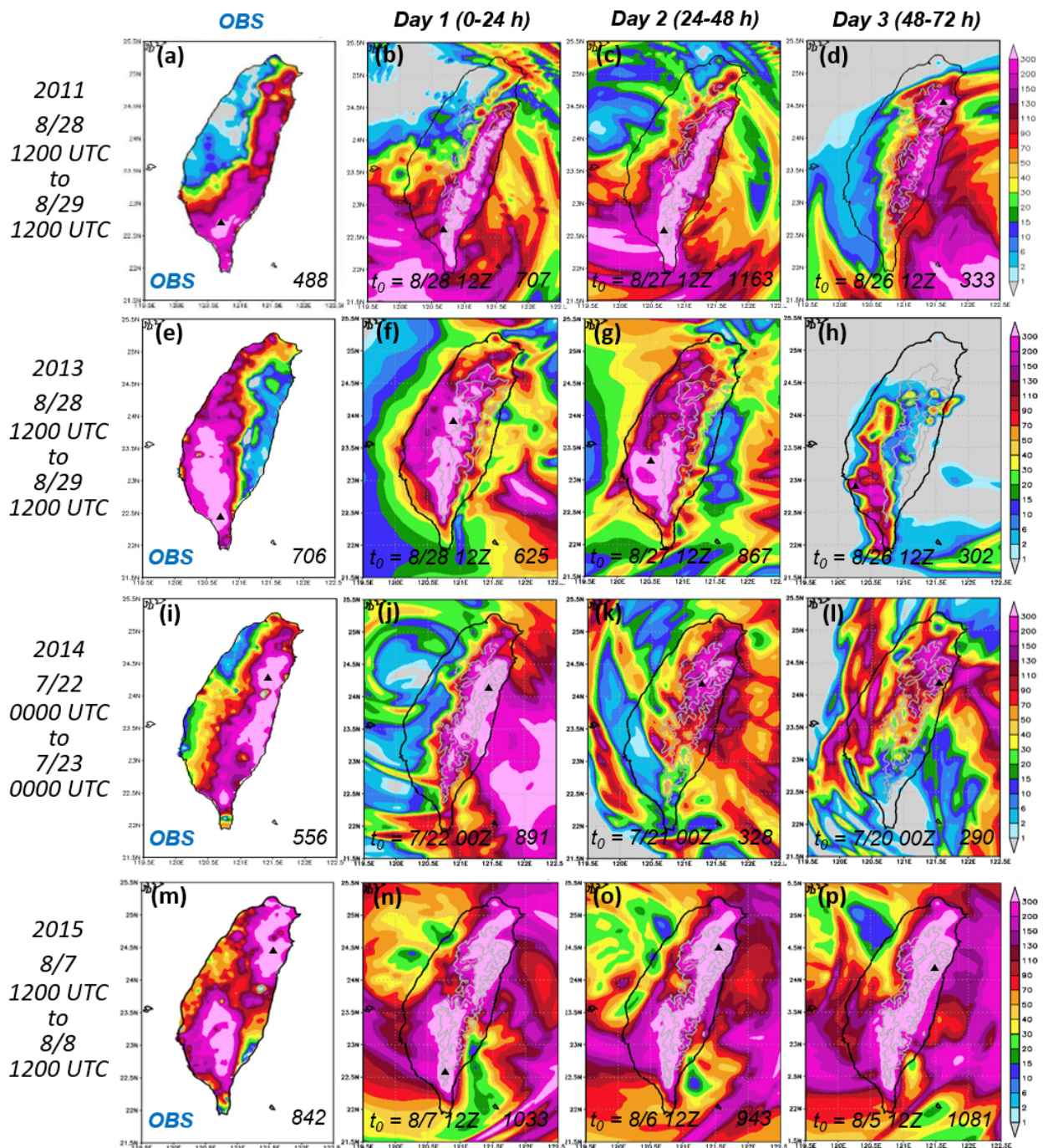


Figure 11. As in Figure 7, except for the rainfall distribution (mm) in observation and CReSS QPFs at ranges of days 1–3, valid for the 24 h period starting from (a–d) 1200 UTC 28 August 2011 during TY Nanmadol, (e–h) 1200 UTC 28 August 2013 during TY Kong-Rey, (i–l) 0000 UTC 22 July 2014 during TY Matmo, and (m–p) 1200 UTC 7 August 2015 during TY Soudelor, respectively.

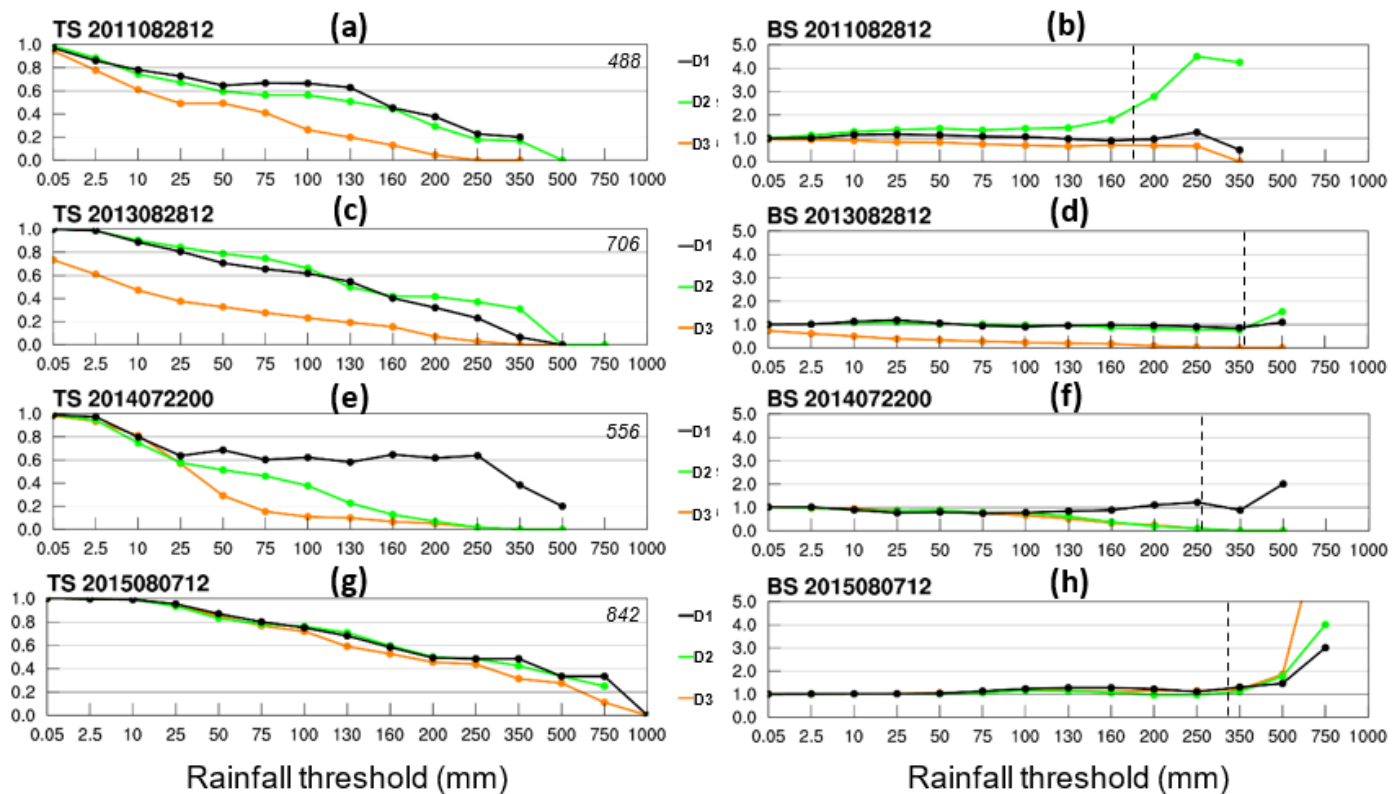


Figure 12. As in Figure 10, except for TS and BS of 24 h, QPFs made at (a,b) 1200 UTC of 26–28 August but all targeted for the period of 1200 UTC 28 to 1200 UTC 29 August during TY Nanmadol (2011), (c,d) 1200 UTC of 26–28 August but all targeted for the period of 1200 UTC 28 to 1200 UTC 29 August during TY Kong-Rey (2013), (e,f) 0000 UTC of 20–22 July but all targeted for 22 July (0000–2400 UTC) during TY Matmo (2014), and (g,h) 1200 UTC of 5–7 August but all targeted for the period of 1200 UTC 7 to 1200 UTC 8 August during TY Soudelor (2015), respectively. The observed maximum rainfall (mm, rounded to integer) and base rate (O/N) at 10% (vertical dashed line) for the target period are both given.

5. Discussion and Conclusions

In this study, 24 h QPFs in Taiwan at three ranges of day 1 (0–24 h), day 2 (24–48 h), and day 3 (48–72 h) by the 2.5 km CReSS model initialized at either 0000 or 1200 UTC are examined using the categorical skill matrix for seven typhoons between 2011 and 2015, mainly targeted for the rainiest 24 h period for each. As a follow-up study of Ref. [30] that verified the overall skill of 24 h QPFs for all 15 typhoons at the same ranges up to day 3 between 2010 and 2012, and Ref. [31], which further expanded the statistics to include 14 more TCs from 2013 to 2015 (with a total of 29 events), the present work mainly uses selected examples and intends to demonstrate the following: (1) at a cloud-resolving grid size of 2.5 km, the model performs well in QPFs at the short range for the selected typhoons in Taiwan; (2) typically, the majority of the TCs produced most of the rainfall over the mountainous areas in Taiwan due to the topographic effect (forced uplifting) of the island; and (3) the good QPF skills by the model can often extend into high thresholds and, therefore, indicate that the heavy rainfall from typhoons is highly predictable in Taiwan (with high predictability) when the model has an adequate resolution. These above points are the aims of the study.

For the rainiest 24 h of the seven typhoons presented in Section 4, the model QPFs perform quite well at the short range, as discussed. On day 1 (0–24 h) and day 2 (24–48 h), for example, the predicted rainfall patterns are at least reasonably similar to the observation through visual inspection for all seven typhoons of Saola (Figure 4i–k), Fung-Wong

(Figure 7e–g), Tembin (Figure 9e–g,i–l), Nanmadol (Figure 11a–c), Kong-Rey (Figure 11e–g), Matmo (Figure 11i–k), and Soudelor (Figure 11m–o), perhaps with the only exception in Matmo on day 2 (Figure 11k). Even on day 3, the same can be said for TYs Fung-Wong (Figure 7e,h), Tembin (for 24 August, Figure 9e,h), and Soudelor (Figure 11m,p). However, the above assessment is subjective and somewhat arbitrary. To summarize the results in Section 4 using the objective measure of the TS, Table 3 is constructed below to show the highest rainfall threshold to reach the TSs of 0.2 and 0.5 in the three ranges, for those rainiest periods listed in Table 2, using linear interpolation from Figures 5, 8, 10 and 12 as needed. For $TS = 0.2$, it means that, on average, the area of H reaches $1/3$ of those of both O and F , assuming $BS = 1$. Similarly, $TS = 0.5$ means that H reaches $2/3$ of both O and F so that H equals $M + FA$ in size. In Table 3, TYs Fanapi (2010), Megi (2010), and Soulik (2013) are also included [30,31], all very rainy with a peak amount of at least 876 mm.

Table 3. Highest rainfall threshold (mm, per 24 h) to reach TS values of 0.2 and 0.5 at the three ranges of day 1 (0–24 h), day 2 (24–48 h), and day 3 (48–72 h), respectively, from the QPFs for the selected target period of the 10 typhoons (cf. Table 2) in this study. Estimates through linear interpolation are used as necessary, and the source of figure (abbreviated as “F”) or reference are also given. Results of Fanapi (201) and Megi (2010) are taken from Ref. [30] and Soulik (2013) from Ref. [31]. Bold faces denote the highest threshold for the given TS among the three ranges, and parentheses indicate extrema in percent of peak rainfall.

Name of Typhoon	Observed Peak Rainfall (mm)	TS ≥ 0.2			TS ≥ 0.5			Source
		Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	
Fanapi (2010)	1110	720	290	440	290	180	320	[30]
Megi (2010)	945	700	440	470	(600)	190	390	[30]
Nanmadol (2011)	488	350	240	130	150	135	50	F12a
Saola (2012)	889	490	540	145	305	270	55	F5
Tembin (2012)	621	(200)	155	210	(30)	(65)	115	F10a
	322	210	290	85	60	(175)	15	F10c
Soulik (2013)	876	870	(870)	(870)	400	390	(380)	[31]
Kong-Rey (2013)	706	265	405	125	140	130	(8)	F12c
Matmo (2014)	556	500	(135)	(65)	300	55	30	F12e
Fung-Wong (2014)	797	350	410	600	160	150	25	F8
Soudelor (2015)	842	(840)	800	615	195	200	175	F12g
Percent range of peak	min.	32.2	24.3	11.7	4.8	10.5	1.1	
	max.	99.8	99.3	99.3	63.5	54.3	43.4	

In Table 3, one can see that, on day 1, a TS of 0.2 can be reached at a threshold approaching the observed peak amount for Soulik and Soudelor, at a very high threshold for Fanapi, Megi, and Matmo, and at a threshold at least close to half of the observed peak amount for Nanmadol, Saola, Tembin (for 27 August), and Fung-Wong (left half). While interpreting such TS results, one should bear in mind that the TS must go to zero once the observed peak amount is exceeded. On day 2, the same of good to excellent performance in TS is true for essentially all the typhoons, except for perhaps Fanapi, Tembin (for 24 August), and Matmo. On day 3, the results of TS are still excellent for Soulik, Fung-Wong, and Soudelor, and quite satisfactory for Fanapi, Megi, and Tembin (for 24 August), while the track errors tend to become larger for the other TCs. Nonetheless, the QPFs are still very good for more than half of the typhoons (six out of the eleven periods being examined, Tembin accounting for two).

For the TS value of 0.5, of course, this would occur at a lower threshold in individual forecasts for the TC cases (as compared to that with $TS = 0.2$). In the seasonal scores shown in Figure 2, the threshold of $TS = 0.5$ typically occurs between 10 and 130 mm on day 1, 5–75 mm on day 2, and about 5–30 mm on day 3 among the seasons included. In individual

forecasts for specific typhoons, this can occur at a much higher threshold (Table 3, right half). For example, on day 1, TS reaches 0.5 at around 600 mm for Megi, and this is very impressive. The same TS value also occurs at a fairly high threshold (near or above 300 mm) for Fanapi, Saola, Soulik, and Matmo, and ≥ 150 mm for Nanmadol, Fung-Wong, and Soudelor. On day 2, the TSs are also satisfactory at a relatively high threshold for Soulik, Saola, Tembin (for 27 August), Soudelor, Megi, Fanapi, Fung-Wong, Nanmadol, and Kong-Rey. On day 3, the same can be said for Soulik, Megi, Fanapi, Tembin (for 24 August), and Soudelor. Even for Saola and Nanmadol, where TS = 0.5 takes place at around 50 mm, this threshold is already considerably higher than the seasonal value. For interpretation, one should also be aware that these thresholds with TS hitting 0.5 are from the same forecasts as TS = 0.2 discussed above and in Section 4 and Refs. [30,31], and most of them have already been visually verified to have a decent quality. Overall, many of the forecasts listed in Table 3 have a good to excellent skill in QPFs through categorical statistics, although case-to-case variations certainly exist. Moreover, on many occasions, despite longer ranges, the day 2 or day 3 QPFs perform better than those in day 1 in Table 3 (bold faces). This indicates that, in the forecasts of TC rainfall in Taiwan, some factors other than the lead time (or forecast range) are more important (at least in a CRM), namely an accurate TC structure and evolution and a realistic topography of Taiwan.

The strong controlling effect exerted by the topography of Taiwan on the amount and spatial distribution of TC rainfall over the island has been well studied and documented in the literature, for both long-term characteristics [2,16,19,21] and individual events (e.g., Ref. [1]), such as TY Morakot (2009) [3,9,13,18,27,44]. Other potential factors, such as a moisture-laden environment of Taiwan (surrounded by oceans), may also contribute to TC rainfall but are generally less important. In the examples presented and discussed in this study, the topographic effects have also been demonstrated. Typically, most rainfall occurs over the windward slopes or along the ridges of the steep mountains of CMR and SMR, as shown in Figures 4, 7, 9 and 11 as well as in W15 and W21 [30,31]. As shown in Section 4 and Table 3, such TC rainfall over the mountains is quite predictable in general since the TS values can often reach 0.2 at very high thresholds not much lower than the observed peak amount at the short range (within 72 h) for many typhoons (Table 3). Among the TCs studied herein, the QPFs are particularly impressive at all three ranges for Soulik (2013) and Soudelor (2015), and of very good quality for Fanapi, Megi, and Fung-Wong up to day 3, and for Saola, Kong-Rey, Nanmadol, and Tembin (for 27 August) up to day 2. For the rainfall on 24 August for Tembin (2012), the day 3 QPF performs the best, and those at the two shorter ranges also produce good rainfall patterns (Figure 9e–h). Finally, for Matmo (2014), the day 1 QPF is also very impressive, but those at longer ranges are not as ideal (Figure 11i–l). Overall, the quality of the QPFs ranges from excellent to satisfactory for the majority of the typhoons included in this study, and only a few cases are less than ideal at some of the ranges. Thus, the good QPF skills by the CReSS model can often extend into high thresholds and indicate that the heavy TC rainfall is highly predictable in Taiwan, and the third and final point mentioned above is also demonstrated.

While the QPFs of heavy rainfall from TCs and their verifications receive more and more attention under the potential impact of climate change of increased severity (e.g., Refs. [63–69]), this issue is beyond the scope of the present work. Moreover, our results are obtained using examples of deterministic forecasts, so their uncertainty and sensitivity (beyond variations among different cases and forecasts) are not addressed, but some related studies using an ensemble approach are available (e.g., Refs. [18,59,70–72]). Finally, it is expected that TC QPFs in other regions with steep topography similar to Taiwan (e.g., Refs. [12,14]) should also exhibit more rainfall and a higher predictability using categorical statistics, but this remains to be verified in future studies.

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