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Opportunity for Early Warnings of Typhoon Lekima from Two Global Ensemble Model Forecasts of Formation with 7-Day Intensities along Medium-Range Tracks

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Received: 30 September 2020; Accepted: 24 October 2020; Published: 27 October 2020

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Abstract: Typhoon Lekima (2019) with its heavy rains and floods is an excellent example of the need to provide the earliest possible warnings of the formation, intensification, and subsequent track before a typhoon makes landfall along a densely populated coast. To demonstrate an opportunity to provide early (10 days in advance) warnings of the threat of Typhoon Lekima, the ensemble models from the European Centre for Medium-Range Weather Forecasts and the National Centers for Environmental Predictions have been used to provide time-to-formation timing and positions along the weighted-mean vector motion track forecasts. In addition, the seven-day intensity forecasts after the formation using a weighted analog intensity prediction technique are provided. A detailed description of one European Center ensemble forecast is provided to describe the methodology for estimating the formation time and generating the intensity forecasts. Validation summary tables of the formation timing and position errors, and the intensity errors versus the Joint Typhoon Warning Center intensities, are presented. The availability of these ensemble forecasts would have been an opportunity to issue alerts/watches/warnings of Lekima even seven days in advance of when Lekima became a Tropical Storm. These ensemble forecasts also represent an opportunity to extend support on the 5–15 day timescale for the decision-making processes of water resource management and hydrological operations.

Keywords: tropical cyclone formation; track forecasts; intensity forecasts; early hydrological warnings

1. Introduction

The formation of Typhoon (TY) Lekima in the far western North Pacific, its rapid intensification into a Super-Typhoon as it approached Ishigaki-jima and Miyako-jima of the Ryuku Islands, and then its landfall on the densely populated East China coast make Lekima an excellent example of the great threat from landfalling tropical cyclones. Fortunately, an eyewall replacement cycle led to a weakening to a Category 2 typhoon prior to landfall in Zhejiang late on 9 August 2019, and the slow translation of Lekima gave more time for disaster preparedness activities (en.wikipedia.org/wiki/Typhoon-Lekima). Indeed, more than 800,000 people were successfully evacuated from Zhejiang (bbc.com/news/world-asia-china-49303877), and 250,000 people from Shanghai, or the death toll of 56 people in mainland China could have been worse. Nevertheless, 2.7 million homes lost power and there was great damage. More than half of the deaths in China occurred in the city of Wenzhou when the heavy rainfall during landfall caused a landslide to form a natural dam that led to a rapid pooling of water before the dam then collapsed and people could not escape the downstream flood.

In such cases as TY Lekima that form relatively close to densely populated islands or coastal areas, it is essential that the formation (either 25 kt or 35 kt depending on the warning center definition) timing and position be known as early as possible. Furthermore, it is essential to know the likely storm category at peak intensity. That is, will this tropical disturbance only reach tropical depression (TD, 25 kt according to the Joint Typhoon Warning Center) stage and not attain Tropical Storm (TS, 35 kt) stage so that no wind damage or high storm surge is to be expected? Or with the large areas of the western North Pacific with sea-surface temperatures much higher than the minimum 26 °C for tropical cyclone (TC) formation, will a pre-TC circulation in a numerical weather prediction model become a typhoon, and perhaps a Super-Typhoon like Lekima? If so, the most critical question becomes the future track of that pre-TC circulation, but the track uncertainty is also important and the global ensemble models provide that track spread information.

Although the Japan Meteorological Agency was the official World Meteorological Organization warning center tasked for naming Lekima, in this study the Joint Typhoon Warning Center working best track (WBT) file will be used. That is, the time-to-formation (T2F) of Lekima as a tropical depression (T2F(25)) is considered to be 00 UTC 4 August near 16.1° N, 131.6° E and as a Tropical Storm (T2F(35)) is 12 UTC 4 August near 17.6° N, 131.2° E, and the peak intensity of 130 kt is considered to have occurred at 06 UTC 8 August. Note that the Japan Meteorological Agency, or other warning centers such as the China Meteorological Administration, will have different formation times and positions because their maximum wind speed definitions have different averaging times than the one-minute average of the Joint Typhoon Warning Center. Similarly, the peak intensity for Lekima will be different from the other warning centers.

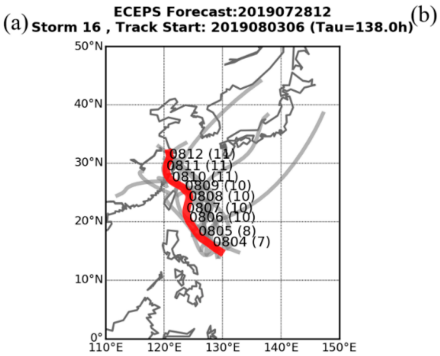
The objective of this study is to demonstrate the opportunity for early detection of the pre-Lekima circulation in two global ensemble models, and then the T2F and the intensity evolution along the predicted track. The two ensemble models are the 15-day European Center for Medium-range Weather Forecasts ensemble (ECEPS) and the 16-day National Centers for Environmental Prediction Global Ensemble Forecast System (NCEP GEFS). Only a brief description of the methodology will be given in Section 2 as a detailed description is available in Elsberry et al. (2020) [1]. The methodology will be explained using as an example the first ECEPS detection of the pre-Lekima circulation, its track forecast, and how the T2F (25) and T2F (35) are calculated. One of the key elements is the use of the weighted-mean vector motion technique [2–4] to create the ensemble storm track forecasts along which the T2F times and positions will be estimated. In addition, the combined weighted-analog intensity pacific prediction technique of Tsai and Elsberry [5–8] is calculated along that track forecast so the timing and position of the peak intensity are provided. In Section 3, the ECEPS and GEFS forecasts will be compared 24 h later and 48 h later. Validation summary tables of the formation timing and position errors, and the intensity errors, will be presented in Section 4. The applicability of these medium-range ensemble forecasts of pre-TY Lekima for support of decision-making processes of water resource management and hydrological operations will be discussed in Section 5. Finally, a summary and concluding thoughts will be given in Section 6.

2. Methodology

Most centers provide the ensemble mean track forecasts by using a simple mean of the tracks from all the available ensemble members. However, a slow along-track bias will be found if equal weight is given to an ensemble member that significantly deviates from the mean track. In the weighted-mean vector motion (WMVM) track calculation [2,3], an ensemble storm is initiated if individual ensemble member tracks starting within a 180 km radius and with similar 12-h vector motions. A weighting factor is given to the next 12-h motion vector by using the inverse distance from its origin point to the WMVM position. Thus an ensemble member is given a small weight if its track deviates from the WMVM track. As compared to a simple mean track, the WMVM track forecast has a smaller along-track motion error.

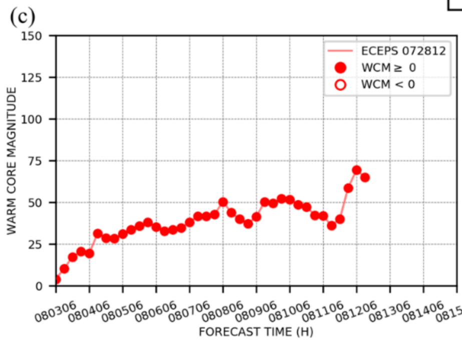
Note the objective in this study is not to try to establish any advantage of the ensemble model track forecast over a single model track forecast such as the ensemble control (which is one of the 51 ECEPS or 21 GEFS members), or the corresponding deterministic model that has higher horizontal resolution, but these single model track forecasts are only one realization of the solution of the dynamics and thermodynamics. The reason an ensemble model is employed is there is uncertainty in the track, in the environmental effects versus the internal effects on the vortex structure, and uncertainty in the deep convective heating from the mesoscale convection down to scale of the individual convective towers. The same weighted-mean approach with the same weighting factors will be used to calculate the most likely values of the predicted variables (e.g., ensemble member intensity) along the WMVM track forecast.

In the first ECEPS forecast from 072812 (12 UTC 28 July 2019), the WMVM forecast track (Figure 1a, red line) for pre-TY Lekima starts at 080306 (model forecast time Tau = 138 h) at 14.9° N, 129.6° E with just 3 of a possible 51 members (Figure 1b, first line). Later the number of members increases to a maximum of 11 members (fourth column in Figure 1b, and numbers in parentheses along the track in Figure 1a). Note that the 3 member tracks that deviate far to the northeast (gray lines in Figure 1a) of the WMVM track would have severely degraded a simple ensemble mean track, but they have little effect on the WMVM track forecast that correctly predicts landfall near Zhejiang around 10 August.



(b)

Datetime	Lat(N)	Long(E)	Num. of Members
080306	14.9°	129.6°	3
080312	15.1°	129.4°	6
080318	15.4°	128.9°	6
080400	15.8°	128.3°	7
080406	16.3°	127.7°	7
080412	16.8°	127.0°	8
080418	17.2°	126.4°	8
080500	17.7°	125.9°	8
080506	18.3°	125.5°	8
080512	18.9°	125.0°	9
080518	19.5°	124.6°	9
080600	20.1°	124.3°	10
080606	20.5°	124.1°	10
080612	20.9°	124.0°	10
080618	21.2°	123.8°	10
080700	21.6°	123.8°	10
080706	22.1°	123.8°	10
080712	22.6°	123.9°	10
080718	23.1°	124.1°	10
080800	23.6°	124.2°	10
080806	24.2°	124.3°	10
080812	24.6°	124.3°	10
080818	25.0°	124.1°	10
080900	25.4°	123.6°	10
080906	25.9°	123.2°	9
080912	26.3°	122.5°	9
080918	26.6°	121.8°	10
081000	26.9°	121.4°	11
081006	27.3°	120.9°	11



(d)

Datetime	WCM	ECEPS Intensity (kt)
080306	4.0	19
080312	10.3	20
080318	17.3	23
080400	20.7	24
080406	19.3	26
080412	31.3	25
080418	28.7	29
080500	28.3	28
080506	31.0	30
080512	33.7	28
080518	35.8	29
080600	38.0	28
080606	35.3	28
080612	32.7	29
080618	33.7	30
080700	34.7	29
080706	38.2	30
080712	41.7	31
080718	41.7	32
080800	42.7	32
080806	50.3	31
080812	44.0	30
080818	40.0	31
080900	37.3	34
080906	41.3	33
080912	50.3	34
080918	49.3	34
081000	52.3	33
081006	51.7	29

ECEPS	Members		Storm Start			Storm End			Warm Core Mag		Likely Storm Cat.	T2F(25)	T2F(35)		WAIP Ending Time		
	Start	Max	Time	Lat(N)	Long(E)	Time	Lat(N)	Long(E)	Start Mag.	WCM Max.		ECEPS (22.51)	WCM(25)	WCM(30)	ECEPS (22.51)	WCM(25)	WCM(30)
072812	3	11	080306	14.9°	129.6°	081212	31.8°	120.9°	4.0	69.3	TY	080318	080412	080412	081018	081112	081112

Figure 1. Summary of the European Center for Medium-range Weather Forecasts ensemble (ECEPS) forecast from 12 UTC 28 July 2019 for the pre-Typhoon (TY) Lekima circulation: (**a**) weighted-mean vector motion (WMVM) track (red line) and ensemble member tracks (grey lines); (**b**) Table of Latitude and Longitude WMVM positions and number of ensemble; (**c**) Warm Core Magnitude (WCM) (m s^{-1} mb^{-1}) along the WMVM track each 6 h; and (**d**) Table of the WCM values and the intensity each 6 h. A summary table is provided at the bottom of the key features of the forecast (see text), the Time-to-Formation (T2F (25)) time in green; two (T2F (35)) times in blue, and the three Weighted Analog Intensity Pacific (WAIP) Ending Times corresponding to the three T2Fs.

The verifying positions at the T2F (25) and at the T2F (35) are indicated by the green and the blue colors in Figure 1b for the convenience of the reader. The pre-Lekima circulation in this ECEPS forecast began just 18 h (30 h) prior to the time Lekima became a tropical depression (Tropical Storm). While the Joint Typhoon Warning Center has typically provided the formation time 24–36 h in advance (Tsai and Elsberry [8]), this ECEPS forecast is predicting the pre-Lekima circulation track to start 138 h in advance. If the time-to-formation along that WMVM track forecast is correct, this forecast will provide accurate formation guidance as early as 156 h to 168 h for T2F (25) or T2F (35), respectively.

In "TC activity" studies such as Yamaguchi et al. [9] and the genesis probability studies such as Halperin et al. [10], the event timing is only provided as occurring at any time during 0–48 h or 0–120 h. In this study, two T2Fs will be provided along the WMVM track forecast for both the GEFS and for the ECEPS. The first T2F (25) estimate is defined as the 6-h time the weighted-mean (again, using the same weighting factors as for the WMVM calculation) of the intensities of the ensemble members included in the pre-Lekima circulation first exceed 25 kt, which is diagnosed directly from the Marchok ([11,12]) vortex tracker. In both the 2017 season developmental sample and the 2019 season test, it was found that both ensemble model's weighted-mean intensity predictions were useful only up to the 25 kt threshold, as the model's (presumably due to coarse horizontal resolution) weighted-mean intensities only slowly increased beyond 25 kt, and thus could not accurately predict 35 kt times. The ECEPS forecasts tend to have weaker intensities than for the GEFS, so the threshold for the ECEPS intensity (column 3 in Figure 1d) is defined as 22.51 kt. If digitized to the nearest 5 kt value, this would be considered to be an intensity of 25 kt. The T2F (25) is therefore 080318 for this ECEPS intensity forecast (column 3, Figure 1d). Note that this T2F (25) forecast is just 6 h early compared to the verifying T2F (25) time of 080400 in green box in column 1 of Figure 1d.

As identical as the criteria used in Elsberry et al. [1], the second T2F (35 kt) time is diagnosed from the Marchok vortex tracker "genesis parameters", which are derived from the Hart [13] cyclone phase space (CPS) parameters along the ensemble member tracks. Two genesis parameters utilized in this procedure to calculate the weighted-mean (same weighting factors as for the track forecast) warm core magnitude (WCM) along the WMVM track forecast: (i) CPS Lower-layer warm core; and (ii) CPS Upper-layer warm core, which are positive (negative) for a warm-core TC (cold-core extratropical cyclone or tropical upper-tropospheric trough). Because the Lower- (Upper-) layer is 900–600 mb (600–300 mb), the Upper-layer warm core is weighted two times the Lower-layer warm core in the WCM to reflect the (1/p) factor in the hypsometric equation. As further explained in Elsberry et al. [1], the threshold values for WCM corresponding to the T2F (35) were first established based on an extensive study of the GEFS forecasts for the 2017 western North Pacific season. Following the near-real time test during August–November 2019, a recalculation of the WCM threshold values for both the GEFS and the ECMWF forecasts was made. These recalculated WCM threshold values are being utilized during the 2020 season test, and will be re-examined following the season.

The ECEPS-predicted WCM evolution along the WMVM track forecast is plotted in Figure 1c. Note that the initial WCM is 4.0, which means the air column above the surface pressure center has only a very small warm core, but then the WCMs increase steadily as the ECEPS intensity (Figure 1d, column 3) increases. After examining many ECEPS forecasts (Elsberry et al. [1]), the WCM threshold for an early (late) T2F (35) time was set at 25 (30). In this ECEPS forecast of pre-TY Lekima, the WCM > 25 and WCM > 30 thresholds were both achieved at 080412, and these key results from the ECEPS are highlighted in the blue T2F (35) boxes in the summary table at the bottom of Figure 1. Compared to the verifying T2F (35) time of 080412 (blue box in column 1 of Figure 1d), these T2F (35) predictions with either the WCM > 25 or the WCM > 30 threshold are perfect. Note that these are times along the WMVM track forecast, and thus the positions at these two ECEPS-predicted T2F (35) times can be found in Figure 1b. It is emphasized that the weighted-mean WCM values have the same weighting factors for each ensemble member as for the WMVM track forecast so that a WCM for an ensemble member track that greatly deviates from the WMVM track would be given a very small weight. Given these

T2F times along the WMVM track forecast, the T2F locations can then be provided for situation-specific guidance to the forecaster.

The combined three-stage 7-day weighted analog intensity Pacific (WAIP) prediction technique of Tsai and Elsberry [1,8] has been applied to provide the intensity changes of the pre-Lekima circulation in the ECEPS and GEFS forecasts. During the pre-formation period, a square function is used to estimate the intensity evolution between that initial intensity and either 25 kt or 35 kt, as applicable. The second stage of the combined WAIP starts from the T2F, and the intensity evolution is the weighted-mean (weighting factors are determined by the track differences between the WMVM track and historical analogs) of intensity evolutions from 16 historical analog. These analogs are not only required to have tracks similar to the WMVM track forecast after the T2F, but also have initial intensities that closely match either 25 kt or 35 kt. The WAIP forecasts will provide some guidance as to the sensitivity of the peak intensity based on the three T2Fs. The ending-storm stage due to extratropical transition, landfall, or to non-development within the 7-day forecast intervals is represented in the third stage of the combined WAIP [1,8].

The two combined WAIP intensity forecasts based on two of the three ECEPS-predicted T2Fs, the WMVM track forecast in Figure 1a, and the two WAIP Ending Times at the bottom of Figure 1, are displayed in Figure 2 (see Figure 8 for validation relative to Joint Typhoon Warning Center (JTWC)). Each intensity forecast begins at 15 kt since a WBT intensity is not yet available, and is a square function to the corresponding T2F at which the intensity is either 25 kt or 35 kt. After the T2F, the combined WAIP intensity forecasts are based on the intensity evolutions of 16 analogs that have tracks that closely match the WMVM track and have initial intensities close to either 25 kt or 35 kt as appropriate. With these constraints on analog selection, most of the same analogs will be selected, and in this case the WAIP intensity forecasts after the T2F have a similar variation with slightly different (<5 kt) peak intensities. Note that the decay stages of these intensity forecasts are constrained by the different WAIP Ending Times. As expected for an analog statistical TC intensity prediction technique, these peak intensities will be much smaller than the verifying 130 kt peak intensity of TY Lekima. However, it is noteworthy that these two peak intensities are of Typhoon strength, which confirms/supports the likely storm category of typhoon based on the maximum WCM value (see summary table at bottom of Figure 1) as described in Elsberry et al. [1].

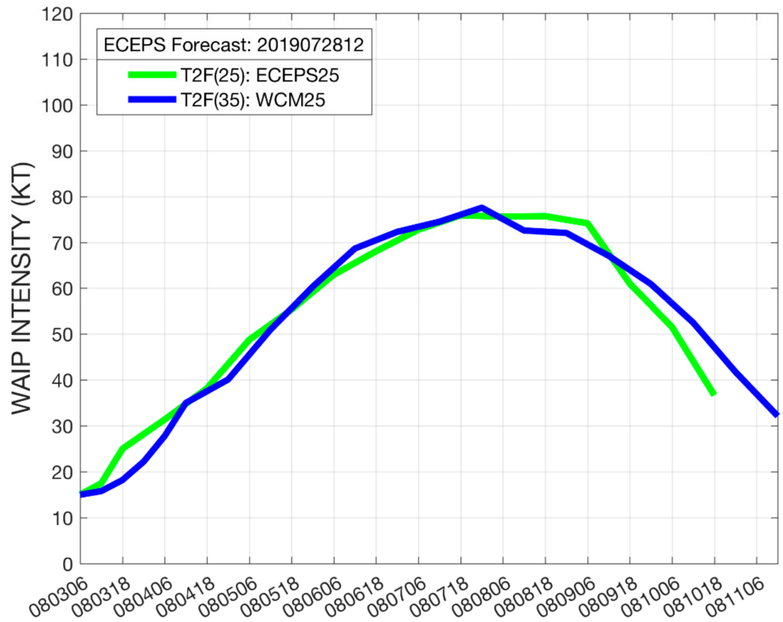


Figure 2. WAIP intensity forecasts (kt) based on the T2F(25, green) and the early T2F(35, blue) for the ECEPS forecast in Figure 1.

In summary, the ECEPS forecast from 12 UTC 28 July predicted that the pre-Lekima circulation would begin at the model forecast time Tau = 138 h near the correct position and would make landfall near Zhejiang after 9–10 days. The weighted-mean of the intensities of the ensemble members first exceeded 25 kt just six hours early compared to the verifying T2F (25). Furthermore, the weighted-mean WCM along the WMVM track forecast perfectly predicted the verifying T2F (35). Finally, the combined WAIP intensity prediction and the maximum WCM value both indicated that the pre-Lekima circulation would later become at least a Typhoon. Although this is just one forecast, it is an excellent example of the opportunity to in the future issue earlier warnings of a landfalling typhoon based on the ECEPS forecasts.

3. Comparison of ECEPS and GEFS Forecasts of T2F and Intensity for Lekima

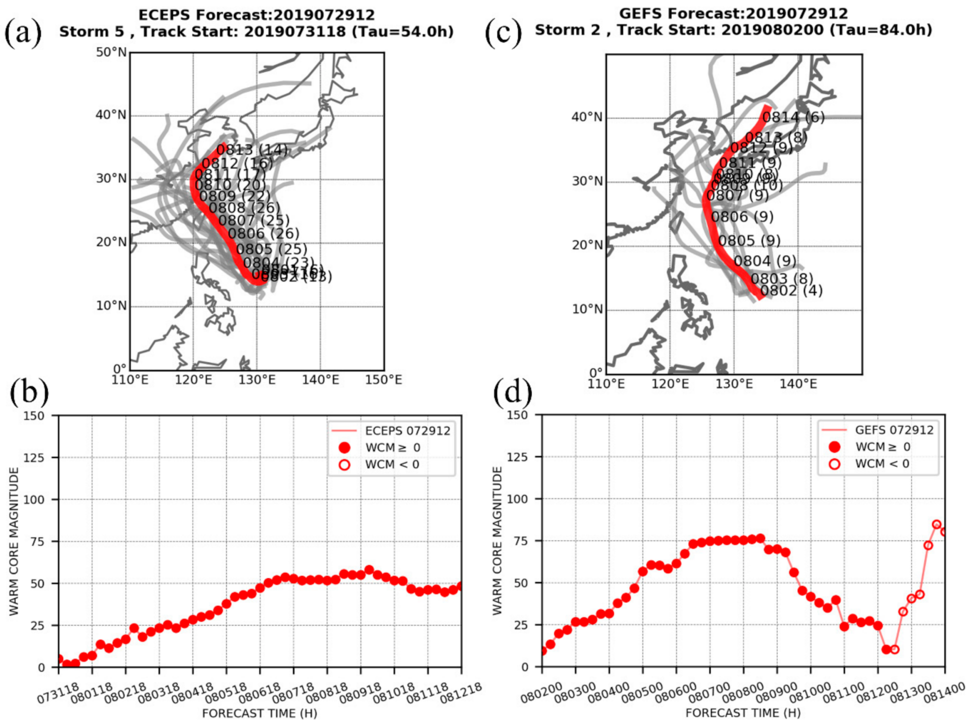
The ECEPS forecast and the GEFS forecasts for pre-Lekima will now be compared on 12 UTC 29 July, which was the first time that a GEFS had also detected the pre-Lekima circulation. Although the procedure at the Joint Typhoon Warning Center is to prepare 12-hourly analyses of the formation guidance, for space reasons in this article, the second comparison will be 24 h later with the 12 UTC 30 July forecasts. Unfortunately, there is then a four-day gap with missing ECEPS and GEFS forecasts due to the NCEP replacement of the computers on which the Marchok [11,12] vortex tracker is executed. After the four days when the computer system had been fully restored, the deterministic global models may be the alternate choice for forecast guidance rather than the ensemble model guidance. In the validation summaries in Section 4, all of the available forecasts will be included.

3.1. ECEPS and GEFS Forecasts from 12 UTC 29 July

In the ECEPS forecast, the WMVM track forecast (Figure 3a, red line) now has a maximum of 26 of a possible 51 ensemble members. The pre-Lekima circulation initial position at 073118 (18 UTC 31 July, or Day 2.25 in the forecast) is at 14.9° N,130.5° E, which is the same latitude but is about one degree longitude to the east of the ECEPS position 24 h previously. Although the ensemble member track spread is very large about the WMVM track forecast (gray lines in Figure 3a), a landfall near Zhejiang is again predicted on 9 August. This is then the third consecutive ECEPS forecast to predict a landfall near Zhejiang since the 00 UTC 29 July forecast had also predicted such a landfall (not shown).

Because the initial ECEPS intensity was already 21 kt, the T2F (25) was achieved at 080200 (green box in ECEPS summary table at bottom), which is then early by 48 h compared to the verifying T2F (25) time of 00 UTC 4 August. However, initial value of the weighted-mean WCM was only 5.0 (column 5 in ECEPS summary table at bottom), which indicated the pre-Lekima warm core was only beginning. Furthermore, the slow steady rate in increase in WCM (Figure 3b) indicates a slower intensification. Specifically, the WCM = 25 (WCM = 30) threshold value for the early (late) T2F (35) is achieved at 080400 (080500), as is recorded in the blue box(es) in the ECEPS summary table at the bottom. Since the verifying T2F (35) time is 080412, this early (late) ECEPS-predicted T2F (35) is 12 h early (12 h late). Finally, the ECEPS-predicted maximum WCM = 58.0 corresponds to a likely storm category of TY (see columns 6 and 7 in ECEPS summary table at bottom).

The combined WAIP intensity forecasts are based on the T2F (25) time (Figure 4, green solid line) and the T2F (35) time (Figure 4, blue solid) and are derived from the weighted-mean intensities of the 16 analogs that have tracks matching the WMVM track forecast in Figure 3a. Since there is no indication from the ECEPS-predicted WCM evolution in Figure 3b that an extratropical transition will occur (namely, a negative WCM value) within seven days after these T2Fs, the no-constraint WAIP Ending Times are just seven days after those T2F times. Recall that the T2F (25) based on the weighted-mean ECEPS intensities was achieved at 080200, so that WAIP intensity prediction starts at 25 kt. Because the 16 analogs are selected to closely match that initial intensity, the WAIP intensification rate is faster and pre-Lekima is predicted to reach 75 kt rather quickly (Figure 4, green solid line). By contrast, the combined WAIP based on the T2F (35) time of 080400 starts at the initial time of pre-Lekima with an initial intensity of 15 kt, and the 16 analogs selected to closely match that smaller initial intensity have slower intensification rates. Consequently, the combined WAIP intensity prediction based on that T2F (35) increases more slowly but does have a peak intensity of 81 kt (Figure 4, blue solid line).



ECEPS	Storm Start			Warm Core Mag.		Likely Storm Cat.	T2F(25)	T2F(35)	
	Time	Lat(N)	Long(E)	Start Mag.	WCM Max.		ECEPS (22.51)	WCM(25)	WCM(30)
072912	073118	14.9°	130.5°	5.0	58.0	TY	080200	080400	080500

GEFS	Storm Start			Warm Core Mag.		Likely Storm Cat.	T2F(25)	T2F(35)	
	Time	Lat(N)	Long(E)	Start Mag.	WCM Max.		GEFS (25)	WCM(50)	WCM(55)
072912	080200	12.4°	134.1°	9.3	76.3	TS	080200	080500	080500

Figure 3. Summaries as in Figure 1a,c, except for forecasts from 12 UTC 29 July 2019 by the ECEPS in panels (**a**,**b**) and by the Global Ensemble Forecast System (GEFS) in panels (**c**,**d**), and separate summary tables are provided at the bottom.

The WCM-T2F prediction from the GEFS forecast from 12 UTC 29 July is provided in Figure 3c,d. The pre-Lekima circulation initial position at 080200 (00 UTC 02 August, or Day 3.5 in the forecast) is at 12.4° N,134.1° E, so the GEFS is picking up the circulation later and 2.5 degrees to the south and 3.6 degrees to the east of the ECEPS initial position in Figure 3a. The GEFS ensemble member track spread (gray lines in Figure 3c) is also large about the WMVM track forecast, which has a recurvature about six degrees to the east of Zhejiang rather than a landfall.

As indicated in Elsberry et al. [1], the initial GEFS intensity is too high, and the intensity changes are larger than for the ECEPS. In this pre-Lekima example, the initial GEFS intensity is already 25 kt at 080200 when the initial WCM is only 4.7 (Figure 3d) and thus is indicating only the beginning of a warm core. Consequently, the GEFS weighted-mean intensity indicates the T2F (25) is at the initial time, which is 2.0 days prior to the verifying time of 080400.

It is found that the GEFS WCM evolution (Figure 3d) is more rapid WCM increases [1]. A larger WCM threshold must be used to estimate the T2F (35) than in the ECEPS forecasts (Figure 3b). Thus, the two T2F (35) times based on the WCM thresholds are adjusted to be 50 and 55. For this GEFS forecast of pre-Lekima, the two T2F (35) times are then both 080500 (blue boxes in the GEFS summary table at bottom) because of the rapidly increasing WCM values (see Figure 3d). Thus, the T2F (35) timing errors relative to the verifying time of 080412 are both 12 h late. The larger WCM thresholds for a T2F(35) in the GEFS also then required a larger WCM threshold (92.8) for the likely storm category of typhoon, which is not surpassed in this GEFS forecast with a maximum WCM of 76.3 (column 6 in the GEFS summary table at bottom of Figure 3).

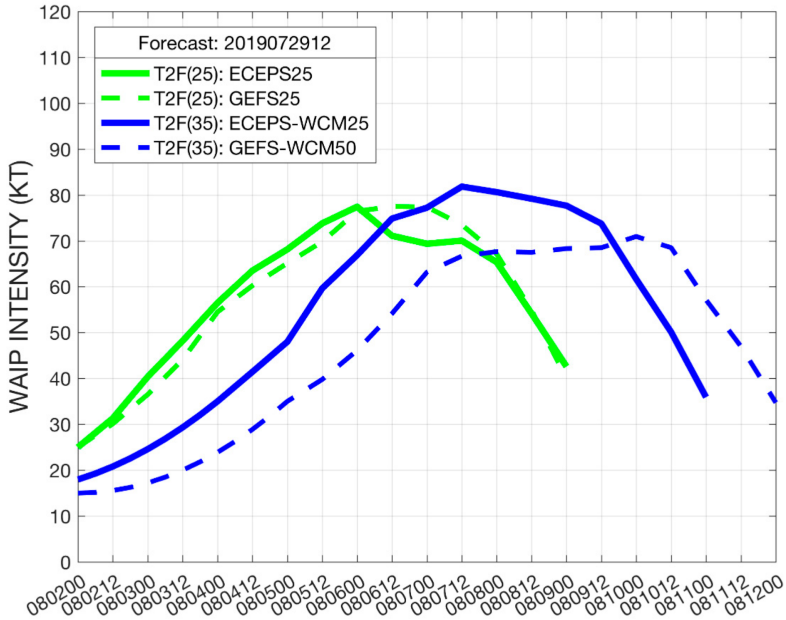


Figure 4. WAIP intensity forecasts as in Figure 2, except with the addition of dashed green and dashed blue lines for the GEFS forecast in Figure 3c.

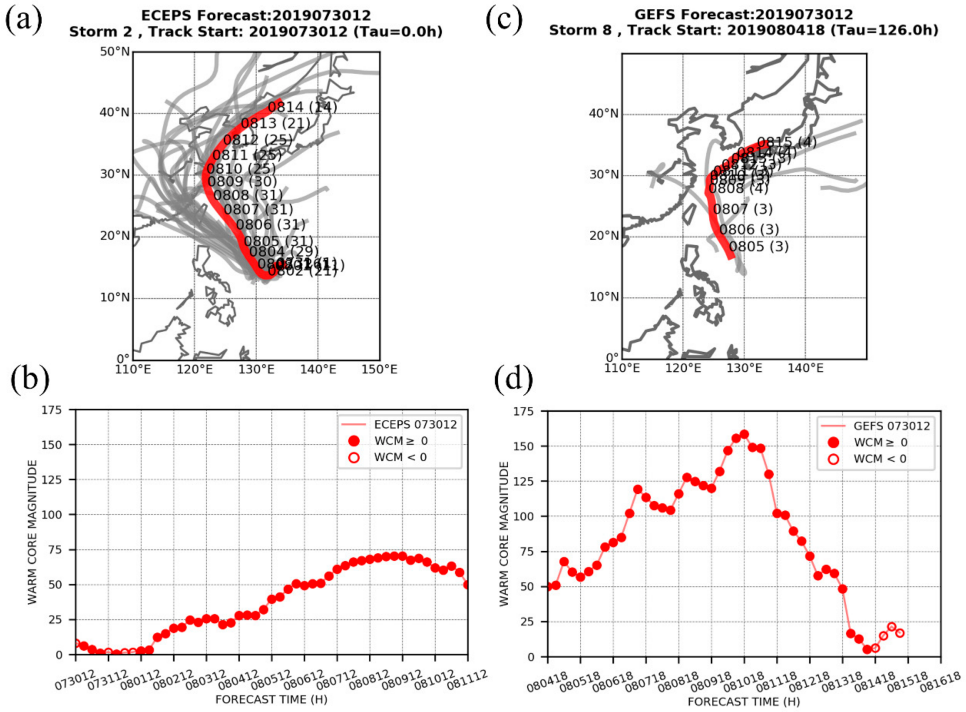
The two combined WAIP intensity forecasts based on the two GEFS-predicted T2Fs and the WMVM track forecast in Figure 3c are shown with dashed lines in Figure 4. Because the combined WAIP for the T2F (25) starts from 25 kt and will be based on analogs selected to have initial intensities closely matched to 25 kt, the weighted-mean GEFS25 intensification rate is large (Figure 4, green dashed line). By contrast, the combined WAIP based on the T2F (35) time of 080500 starts with an initial intensity of 15 kt, and the 16 analogs selected to closely match that initial intensity have slower intensification rates. Consequently, the combined WAIP intensity prediction based on that T2F (35) increases more slowly and only has a peak intensity of 70 kt (Figure 4, blue dashed line) much later than the ECEPS-based T2F (35) WAIP intensity prediction (Figure 4, blue solid line). This GEFS-based WAIP peak intensity of a very weak typhoon is consistent with the likely storm category of a relatively strong TS (see GEFS summary table at bottom of Figure 3).

In summary, the ECEPS forecast from 12 UTC 29 July predicted that the pre-Lekima circulation would begin at Day 2.25 near the correct position according to the Joint Typhoon Warning Center. More importantly, this was the third consecutive ECEPS forecast to correctly predict (more than 10 days in advance) the Lekima landfall near Zhejiang. By contrast, the GEFS forecast started the pre-Lekima circulation at Day 3.5 at a position far to the south and east of the ECEPS initial position. Rather than predicting a landfall near Zhejiang, the GEFS track forecast was that Lekima would recurve about 6 degrees longitude to the east.

Both the ECEPS forecast and the GEFS forecast from 12 UTC 29 July started the pre-Lekima circulation at too large initial intensities and their T2F (25) timing errors were early by two days. However, the ECEPS and the GEFS both had more accurate T2F (35) predictions based on the early WCM thresholds being surpassed: ECEPS was 12 h early, and the GEFS was 12 h late. Since the combined WAIP intensity predictions based on the T2F (25) for both the ECEPS and the GEFS started two days early and with an initial intensity of 25 kt, the pre-Lekima circulation was predicted to intensify to 75 kt relatively rapidly based on both models. The combined WAIP predictions based on the T2F (35) started with the same 15 kt initial intensity. However, the WAIP intensification rate for the GEFS was slower, and the fact that the analog selection was constrained by the extratropical transition along the more eastern track forecast of the GEFS, the peak intensity was smaller.

3.2. ECEPS and GEFS Forecasts at 12 UTC 30 July

In the ECEPS forecast, the WMVM track forecast (Figure 5a, red line) now has a maximum of 31 of a possible 51 ensemble members. The pre-Lekima circulation at 073012 (12 UTC 30 July) at 15.4° N, 134.3° E was for the first time in the initial conditions rather than being developed later in the forecast. Although the ensemble member track spread (gray lines in Figure 5c) is extremely large about the WMVM track forecast, a landfall near Zhejiang is again predicted on 9 August. This is now the fifth consecutive ECEPS forecast to predict a landfall near Zhejiang since the 00 UTC 30 July forecast had also predicted such a landfall (not shown).



ECEPS	Storm Start			Warm Core Mag.		Likely Storm Cat.	T2F(25)	T2F(35)	
	Time	Lat(N)	Long(E)	Start Mag.	WCM Max.		ECEPS (22.51)	WCM(25)	WCM(30)
073012	073012	15.4°	134.3°	-8.2	70.3	TY	080200	080312	080506

GEFS	Storm Start			Warm Core Mag.		Likely Storm Cat.	T2F(25)	T2F(35)	
	Time	Lat(N)	Long(E)	Start Mag.	WCM Max.		GEFS (25)	WCM(50)	WCM(55)
073012	080418	17.0°	127.8°	50.0	158.3	TY	N/A	080418	080506

Figure 5. Summaries as in Figure 3a,c, except for forecasts from 12 UTC 30 July 2019 for the pre-Lekima circulation by the ECEPS in panels (**a**,**b**) and by the Global Ensemble Forecast System (GEFS) in panels (**c**,**d**), and separate summary tables are provided at the bottom.

Even though the initial ECEPS weighted-mean intensity was smaller in this forecast at 16 kt, and the weighted-mean intensification rate was smaller, the T2F (25) was again achieved at 080200 (green box in ECEPS summary table at bottom of Figure 5), which is then early by 48 h compared to the verifying T2F (25) time of 00 UTC 4 August. As indicated by some open circles in Figure 5b, and the −8.2 initial value of the weighted-mean WCM (column 5 in ECEPS summary table at bottom), the pre-Lekima circulation was actually cold core at the beginning. Furthermore, the delay before an increase in WCM occurred (Figure 5b) indicates a slower intensification. Specifically, the WCM = 25 (WCM = 30) threshold value for the early (late) T2F (35) is achieved at 080312 (080506), as is recorded in the blue box(es) in the ECEPS summary table at the bottom. Since the verifying T2F (35) time is 080412, this early (late) ECEPS-predicted T2F (35) is 12 h early (18 h late). Finally, the ECEPS-predicted maximum WCM = 70.3 corresponds to a Likely Storm Category of TY (see columns 6 and 7 in ECEPS summary table at bottom of Figure 5).

The combined WAIP intensity forecasts are based on the ECEPS weighted-mean T2F (25) time (Figure 6, green solid line) and the T2F (35) time (Figure 6, blue solid line) are derived from the weighted-mean intensities of the 16 analogs that have tracks matching the WMVM track forecast in Figure 5a. Since there is again no indication from the ECEPS-predicted WCM evolution in Figure 5b that extratropical transition will occur, the no-constraint WAIP Ending Times are just seven days after those T2F times. Recall that the T2F (25) based on the weighted-mean ECEPS intensities is achieved at 080200, but the WAIP intensity prediction starts at 15 kt. Consequently, the WAIP intensification rate is slower than in Figure 4 and pre-Lekima is predicted to reach 80 kt much later (Figure 6, green solid line). The combined WAIP intensity prediction based on the T2F (35) time of 080312 also starts with an initial intensity of 15 kt, and again the 16 analogs selected to closely match that initial intensity have slower intensification rates. Therefore, the combined WAIP intensity prediction based on that T2F (35) increases more slowly but does have a peak intensity of 86 kt (Figure 6, blue solid line).

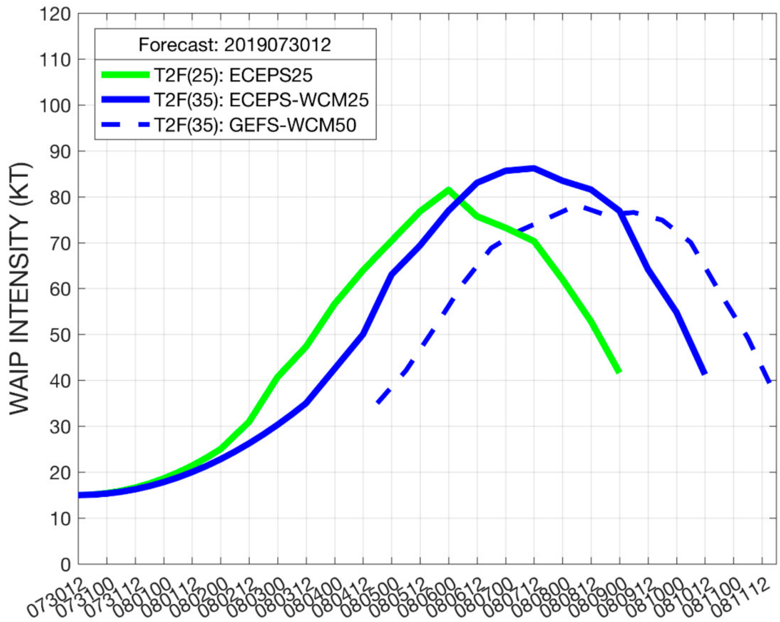


Figure 6. WAIP intensity forecasts as in Figure 4, except for the GEFS forecast in Figure 5c.

The corresponding WCM-T2F prediction from the GEFS forecast from 12 UTC 30 July is provided in Figure 5c,d. Whereas the ECEPS has been gaining in the number of ensemble members with each succeeding forecast, the maximum number of members in this GEFS forecast is only 4 of a possible 21 members (Figure 5c). While one of the four member tracks does make landfall near Zhejiang, the other three members have recurvature tracks, and thus the WMVM track recurves about five degrees longitude to the east of Zhejiang. The pre-Lekima circulation is not detected until 080418 (18 UTC 4 August), so the GEFS is picking up the circulation much later. Furthermore, the initial position is 17.0° N, 127.8° E, which is 0.9 degrees to the north and 3.8 degrees to the east of the verifying T2F (25) position. Indeed, the initial GEFS weighted-mean intensity is already 37 kt, so no T2F (25) can be deduced from this initial intensity. This situation is recorded as Not Available (N/A) in the green box in the GEFS summary table at the bottom of Figure 5.

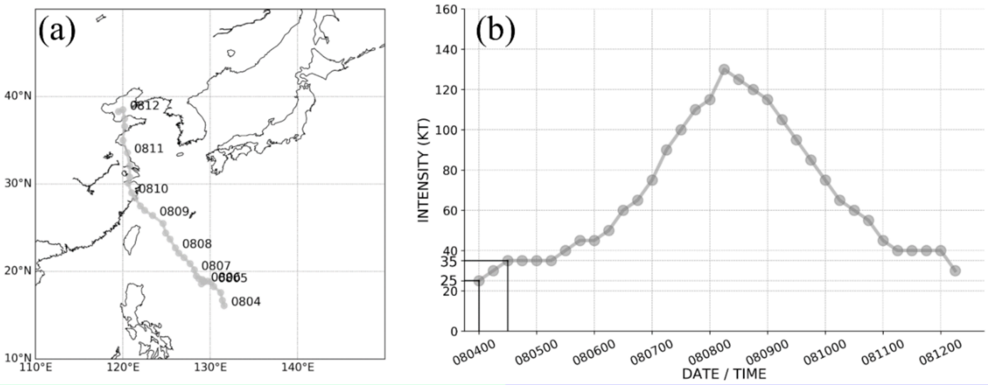
In this GEFS forecast of pre-Lekima, the initial weighted-mean WCM at 080418 is already 50 (Figure 5d), which satisfies the WCM threshold used to estimate the early T2F (35). The WCM = 55 threshold is satisfied just 12 later at 080506 (blue boxes in the GEFS summary table at the bottom). Thus, the T2F (35) errors relative to the verifying time of 080412 are 6 h late and 18 h late. It is not surprising that when the GEFS has an initial well-established warm core vortex (WCM = 50), and a poleward track over a warm ocean region beginning just east of the Philippines, the WCM will be predicted to rapidly increase (Figure 5d) and achieve a large WCM (158.3) that corresponds to a likely typhoon (columns 5 and 6 in GEFS summary table). As indicated above, a combined WAIP intensity prediction based on a T2F (25) cannot be provided for this GEFS forecast that begins with an initial GEFS intensity of 37 kt. For the combined WAIP intensity prediction based on the early T2F (35), the initial (080418) intensity is taken to already be 35 kt and the WAIP intensity relatively rapidly increases to a maximum of 76 kt (Figure 6, dashed blue line). A further increase is not predicted because the analog selection is constrained due to an extratropical transition that is predicted to occur shortly after (081412) the ending time of 081206 for this WAIP intensity prediction.

In summary of the 12 UTC 30 July ECEPS and GEFS forecasts of pre-Lekima, the most remarkable difference was that the ECEPS forecast had a maximum of 31 of a possible 51 ensemble members (and thus tending to a more confident forecast), and the GEFS forecast included only four of a possible 21 ensemble members, which is indicative of a low-confidence forecast. Whereas this was the fifth consecutive ECEPS track forecast to predict a landfall near Zhejiang, the GEFS for the third consecutive time predicted a recurvature well to the east rather than a landfall. The initial weighted-mean ECEPS intensity was too high and led to a T2F (25) that was 48 h early, and the corresponding GEFS initial intensity was so high that a T2F (25) could not be diagnosed. Both ensemble models provided more accurate T2F (35) timing with the early (late) ECEPS predictions of 12 h early (18 h late) and the early (late) GEFS-predictions of 6 h early (18 h late). As indicated in Figure 6, the combined WAIP intensity predictions have slower intensification rates than 24 h earlier in Figure 4, but the peak intensities are in the range of 76 kt–86 kt for both ensembles, which supports/confirms the likely typhoon intensity diagnosed from the peak WCM predictions.

4. Validation Summaries for the T2F Forecasts and WAIP Intensities

The validation summary tables for the ECEPS and GEFS forecasts for pre-TY Lekima will be presented in this section, which will include a preliminary verification of the WAIP intensity predictions as well as the T2Fs. The ECEPS forecast validation for pre-TY Lekima is presented in Figure 7. The Joint Typhoon Warning Center WBT in Figure 7a was utilized to search for ECEPS-WMVM track forecasts that had track differences < 300 km during the seven days prior to the T2F (35). However, the track difference search had to be expanded for the first two forecasts in Figure 7. One example is the ECEPS forecast from 12 UTC 28 July in Figure 1 that was described in detail in Section 2. Note that the WMVM track in Figure 1a during the first days prior to the beginning of the WBT is displaced to the east of the WBT in Figure 7a by about four degrees, which required an expansion of the allowable track difference beyond 300 km. Elsberry et al. [1] documented larger uncertainty in the initial positions when the number of ensemble members to begin the ensemble storm was small (column 4 in Figure 1b). Elsberry et al. [1] also note that there is often considerable uncertainty in the WBT positions during the pre-formation stage. Specifically, for this ECEPS forecast, the maximum WCM was 69.3 and that corresponds to a likely storm category of (weak) Typhoon.

As identical as in Elsberry et al. [1], three key validations of the ECEPS forecast in Figure 1 are then summarized in Figure 7. In addition to being 0.25 days early, the ECEPS forecast T2F (25) position was 0.72 degrees to the south and 2.71 degrees to the east of the verifying T2F (25) position. The early T2F (35) timing error for the ECEPS forecast in Figure 1 was 0.00 Days and was 0.83 degrees to the north and 4.17 degrees to the east of the verifying T2F (35). The two maximum WAIP intensities of 75.9 and 77.6 kt support that this pre-Lekima circulation will at least become a typhoon rather than only a tropical storm or a tropical depression. It is noted that an analog-statistical intensity prediction technique such as WAIP is not expected to be able to predict the 130 kt maximum intensity in Figure 7b.



BT_25kt: 2019080400(Lat:16.1°N, Long:131.6°E); BT_35kt: 2019080412(Lat:17.6°N, Long:131.2°E);

BT peak intensity: 130kt (first time:2019080806)

ECEPS	Storm No.	Members		Storm Start			Warm Core Mag Max	Likely Storm Cat.	T2F(25)			T2F(35)			WAIP max intensity	
		Start	Max	ECEPS Days	Lat(°N)	Long(°E)			ECEPS(22.51) Days	Lat error deg. N	Long error deg. E	WCM(25) Days	Lat error deg. N	Long error deg. E	ECEPS (22.51)	WCM (25)
072812	16*	3	11	5.75	14.93	129.63	69.3	TY	-0.25	-0.72	-2.71	0.0	-0.83	-4.17	75.9	77.57
072900	11*^	3	21	3.5	16.08	128.47	59.0	TY	-2.25	-0.25	-3.37	-1.0	-0.65	-5.34	73.26	70.96
072912	5*^	4	26	2.25	14.95	130.52	58.0	TY	-2.0	-2.1	-1.08	-0.5	-1.45	-3.42	77.43	81.82
073000	2^	3	28	0.0	15.53	136.9	62.3	TY	-1.25	0.02	-2.81	-1.0	-0.25	-3.75	68.82	77.83
073012	2	1	32	0.0	15.43	134.3	70.3	TY	-2.0	-2.34	0.23	-1.0	-1.68	-1.72	81.46	86.19
073100	4	3	30	0.25	14.53	132.7	70.3	TY	-2.75	-2.05	0.66	0.0	-0.72	-3.01	77.25	80.75

GEFS	Storm No.	Members		Storm Start			Warm Core Mag Max	Likely Storm Cat.	T2F(25)			T2F(35)			WAIP max intensity	
		Start	Max	GEFS Days	Lat(°N)	Long(°E)			GEFS(25) Days	Lat error deg. N	Long error deg. E	WCM(50) Days	Lat error deg. N	Long error deg. E	GEFS (25)	WCM (50)
072912	2	4	10	3.5	12.37	134.08	76.3	TS	-2.0	-3.73	2.48	0.5	2.49	-3.72	77.5	70.94
073006	4*	5	22	0.25	15.44	134.07	166.0	TY	-2.25	-2.37	0.61	-0.5	-0.51	-0.88	73.41	75.16
073012	8	3	5	5.25	16.98	127.78	158.3	TY	N/A	N/A	N/A	0.25	-0.62	-3.42	N/A	78.18
073018	3	3	21	0.0	15.0	132.9	192.7	TY	-3.25	-2.63	-0.77	-1.25	-3.1	0.11	70.07	81.61

* : Track difference average >300 km ; ^ : Time difference > 48 h

Figure 7. Validation summary tables for the (top) ECEPS and (bottom) GEFS forecasts for pre-TY Lekima with (**a**) JTWC working best track (WBT) positions shown at 00 UTC on the Month Day; (**b**) JTWC WBT intensities (kt) with the times of T2F (25) and T2F (35) as indicated in green and blue boxes below the panels (**a**,**b**), along with the peak intensity in the red box. The first nine columns are storm characteristics that are repeated from the bottom of each forecast summary (e.g., Line 1 of the table is from the bottom of Figure 1). Columns 10–12 in green are the T2F (25) timing (days) and position errors in latitude and longitude, Columns 13–15 in blue are the T2F (35) timing and position errors for the early T2F (35), and Columns 16–18 are the peak combined WAIP intensity (kt) forecasts for the two T2Fs.

The validation of the ECEPS forecast from 12 UTC 29 July in Figure 3a,b is on line 3 of the ECEPS table in middle of Figure 7. As noted previously in the discussion of Figure 3, there was a maximum of 26 members of a possible 51 members. Due again to the uncertainty and westward displacement of the initial few ensemble storm positions, the allowable track difference for this pre-Lekima circulation had to be expanded beyond 300 km. Recall from the discussion of Figure 3 that the T2F (25) was 2.0 days early, and this T2F (25) timing error is entered in Line 3, column 10 in the ECEPS table in Figure 7. The associated T2F (25) position error was 2 degrees to the south and 1.08 degrees to the west, which may be attributed to the early timing error and the ensemble storm initial position was to the south and to the west. As noted in the description of the WCM evolution in Figure 3b, the early T2F

(35) was 12 h early (Line 3, column 13). The associated T2F (35) position error was 1.45 degrees to the south and 3.42 degrees to the west, which again may be attributed to the initial position error of the WMVM track forecast in Figure 3a.

As discussed in relation to Figure 4 (solid lines), the WAIP-predicted maximum intensities related to the two T2Fs and the WMVM track forecast are 77.4 kt and 81.4 kt (Line 3, columns 10 and 17 in the ECEPS table in Figure 7). These WAIP peak intensities are consistent with the likely storm category of a (weak) typhoon based on a maximum WCM of 58.0 (Line 3, columns 8 and 9 in the ECEPS table).

The validation of the ECEPS forecast from 12 UTC 30 July in Figure 5a,b is in Line 5 of the ECEPS table in Figure 7. As noted in the discussion of this forecast, the pre-Lekima circulation was now in the initial conditions, but the initial weighted-mean intensity was too high and the T2F (25) was again 2.0 days early (Line 5, column 10 in green). Due to this early timing error, the associated T2F (25) latitudinal error was 2.34 degrees to the south (column 11). However, the longitudinal error was only 0.23 degrees to the east (column 12), which may be attributed to the early WMVM track in Figure 5a has become oriented along the correct longitude. As noted in the discussion of Figure 5b, the early T2F (35) was 1.0 days early (Line 5, column 13 in the ECEPS table). Note in columns 14 and 15 that the corresponding T2F (35) position errors were only 1.68 degrees to the south and 1.72 degrees to the west. This tendency for the ECEPS to have smaller T2F (35) positions may be attributed to the pre-Lekima circulation was in the initial conditions at a time that the Joint Typhoon Warning Center had begun to follow the pre-Lekima system. Thus, the ECEPS was also detecting the circulation with a more consistent initial position even though the ECMWF does not insert a bogus vortex. Indeed, the initial weighted-mean ECEPS intensity was too high, which likely contributed to the too early WCM threshold of 25 being attained too early by 1.0 day (see Figure 5b).

As illustrated in Figures 2, 4 and 6, and summarized for the maximum WAIP intensities in last two columns in the ECEPS table in Figure 7, the ECEPS inputs of WMVM track forecasts plus the initial intensity resulted in consistent WAIP predictions of 75–85 kt peak intensities. These WAIP peak intensities support the likely storm category of typhoon consistently derived based on the maximum WCM (columns 8 and 9 in the ECEPS table in Figure 7). However, these analog-statistical WAIP predictions cannot predict the peak intensity of 130 kt (Figure 7b).

All of the ECEPS WMVM track forecasts that are available due to modifications being installed on the NCEP research computers are plotted in Figure 8a. Note the sensitivity of these track forecasts to the initial positions, and then the early westward motion, before the northwestward path to a landfall near (or south of) Zhejiang. It was that initial position uncertainty that required an expansion of the 300 km track difference with the WBT criterion during the seven days prior to the T2F (35). Because these different starting positions contribute to the track spread in longitude as well as in latitude, a future task is to reduce the initial position uncertainty.

The most important result in the ECEPS validation summary table in Figure 7 is the very small early T2F (35) timing errors in column 13. A time series plot of both the T2F (35, red) and T2F (25, blue) timing errors is provided in Figure 8c. The accuracy of the ECEPS forecasts of T2F (35) are quite impressive with two of the six forecasts having zero timing errors, and the other four forecasts having less than or equal to 1.0 day errors. Whereas the T2F (25) timing errors are not as impressive because they are generally two days early, these are for ECEPS forecasts initiated 4–6 days in advance of the verifying T2F (25) in the blue vertical dashed line.

The latitude and longitude errors of the T2F (25) and the T2F (35) are plotted in Figure 8b. As described above, some of the T2F position errors may be attributed to the WMVM initial position errors due to only a small number of ensemble members. So even though an accurate T2F (35) time can be inferred from the WCM evolution along a WMVM track forecast that does not begin at the correct initial position, the T2F (35) position error will be affected by that incorrect initial WMVM position.

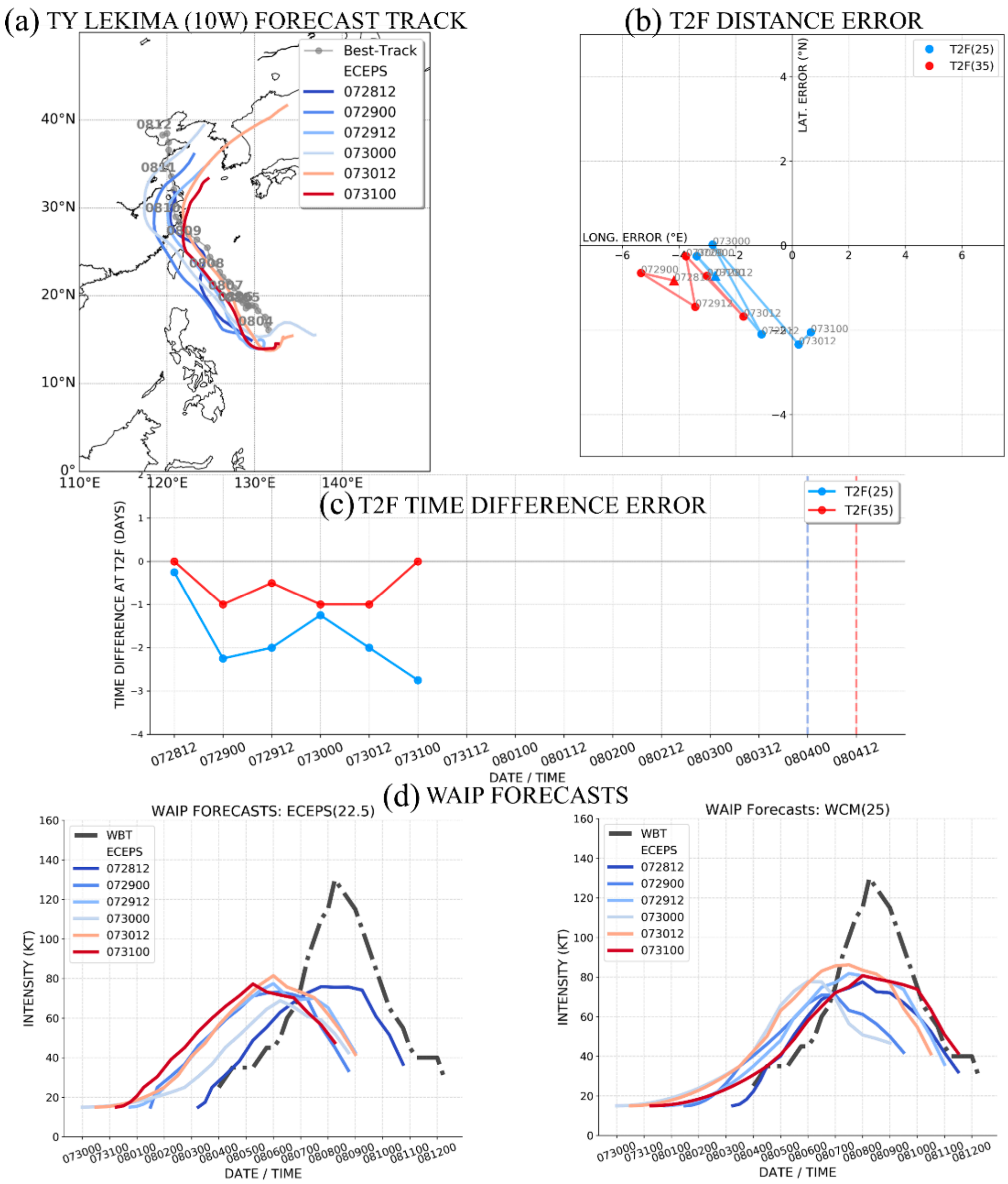


Figure 8. (**a**) WMVM track forecasts by the ECEPS, (**b**) T2F(25, blue) and T2F(35, red) position errors relative to verifying T2F positions, (**c**) T2F(25, blue) and T2F(35, red) timing errors (Days) relative to verifying T2F times, and (**d**) Combined WAIP intensity forecasts of pre-TY Lekima based on the T2F(25, left panel) and T2F(35, right panel) for the ECEPS forecasts versus the JTWC WBT intensity (dash–dot line).

The combined WAIP intensity predictions for the ECEPS are compared with the verifying Joint Typhoon Warning Center WBT intensities in Figure 8d. Because the T2F (25) timing errors (Figure 8c) are almost all two days early, the pre-formation stages of the combined WAIP intensity predictions are too short and the intensification stages begin too soon (Figure 8d, left panel). For the 072812 ECEPS forecast with a highly accurate T2F (25) time (Figure 8c), the WAIP prediction (blue line) is also very accurate up to an intensity of 75 kt. The key result is that for the more accurate T2F (35) times (Figure 8c) the corresponding WAIP predictions (Figure 8d, right panel) are quite accurate compared to the verifying intensities, at least up to 75 kt. However, the Lekima rapid intensification from 75 kt to 130 kt was not predicted by the combined WAIP. Nevertheless, the combined WAIP can provide seven-day intensity forecast guidance based on the ECEPS beginning from the pre-formation stage of TY Lekima even before the Joint Typhoon Warning Center begins a WBT file.

The corresponding validation summary table for the GEFS forecasts for the pre-TY Lekima circulation T2F (25) and T2F (35) timing and position errors and the WAIP intensity forecasts is provided at the bottom of Figure 7. The key characteristics of the pre-Lekima circulations in the 12 UTC 29 July and the 12 UTC 30 July GEFS forecasts from Figure 3andFigure 5, respectively, are in Lines 1 and 3 in the GEFS table in Figure 7. Note that these characteristics include that these GEFS ensemble storms had only a small number of the possible 21 ensemble members. In both of the GEFS track forecasts in Figure 3a andFigure 5a, the pre-Lekima circulation was not predicted to start as early as in the corresponding ECEPS forecasts, and both GEFS forecasts had initial position uncertainties similar to the ECEPS. Most importantly, the WMVM track forecasts both had a recurvature well to the east of Zhejiang rather than a landfall. As shown in Figure 9a, the two other GEFS track forecasts at 06 UTC and 12 UTC 30 July also had recurvatures to the east of Zhejiang.

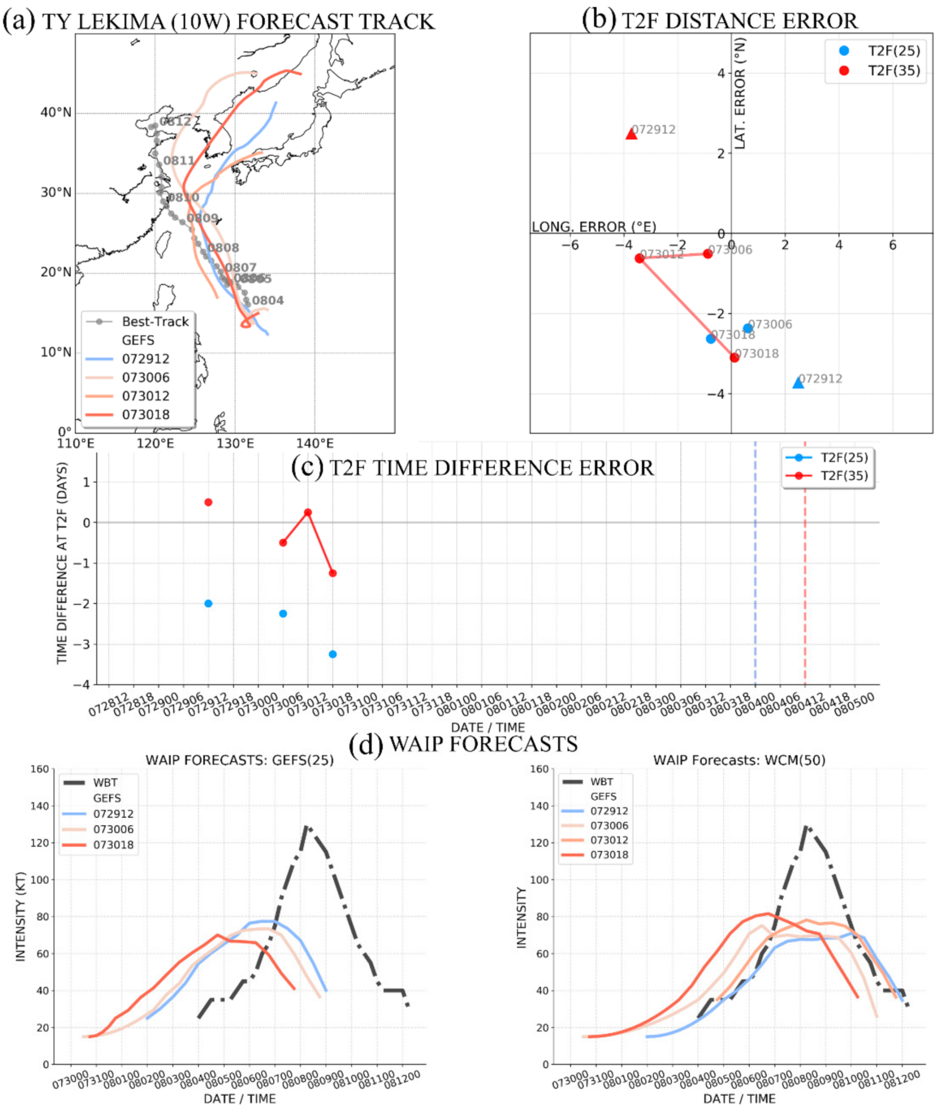


Figure 9. (**a**) WMVM track forecasts by the GEFS, (**b**) T2F(25, blue) and T2F(35, red) position errors relative to verifying T2F positions, (**c**) T2F(25, blue) and T2F(35, red) timing errors (Days) relative to verifying T2F times, and (**d**) Combined WAIP intensity forecasts of pre-TY Lekima based on the T2F(25, left panel) and T2F(35, right panel) for the ECEPS forecasts versus the JTWC WBT intensity (dash–dot line).

Both of the GEFS forecasts in Figure 3candFigure 5c had a weighted mean initial intensity that was too high and indeed the 073012 forecast initial intensity exceeded 25 kt so that a T2F (25) forecast could not be made. A result of the high initial intensity at 12 UTC 25 July (and also the 06 UTC and 12 UTC 30 July) forecast, the T2F (25) timing errors (column 10 in the GEFS table in Figure 7) were early by at least two days. Consequently, the T2F (25) latitudinal errors (column 11 in the GEFS table) were well to the south of the verifying latitude of 16.1° N. While the T2F (25) longitudinal error for 12 UTC 29 July forecast in Figure 3c is relatively large (2.48 degrees to the east, column 12 in the GEFS table), the errors for the 06 UTC and 18 UTC 30 July GEFS forecasts are less than one degree.

The most important validation result is the small T2F (35) timing errors for three of the four GEFS forecasts (column 13 in the GEFS table in Figure 7). This favorable result indicates that the GEFS predictions of the WCM evolution can be related to the formation time of the pre-Lekima circulation. As indicated above for the ECEPS, an accurate T2F (35) timing does not necessarily indicate an accurate T2F (35) position along the WMVM track forecast because of the difficulty to forecast the starting positions, and due to the existence of track biases. For example, the T2F (35) position errors in the 12 UTC 25 July forecast are 2.49 degrees to the south (column 14 in the GEFS table) and 3.72 degrees to the west. While these T2F (35) position errors may seem to be acceptable as they are from a GEFS forecast initiated six days in advance of the verifying T2F (35), a future objective will be to reduce these position errors by 50%.

These more accurate T2F (35) timing forecasts relative to the T2F (25) forecasts are displayed in the time series plot in Figure 9c. While from a warning perspective it is better to be early than be late, issuing a warning 2–3 days early of an event that will not occur for 5 days is unacceptable. Another impact from such early T2F (25) timing errors is that the T2F (25) positions are well to the south of the verifying position (Figure 9b). As described above, small T2F (35) timing errors do not necessarily lead to small T2F (35) position errors, and another display of this fact is in Figure 9b (red dots). Although the 06 UTC 30 July has small longitude/latitude errors of 0.51 degrees to the south and 0.88 to the east (Line 2 in the GEFS table in Figure 7) the other three GEFS forecasts have large errors in latitude or longitude or both.

In summary, the primary objective of this validation section has been to document the T2F timing and position errors for the ECEPS and the GEFS forecasts that were available in advance of the verifying T2F to illustrate the consistency in time of the T2F forecasts. A second objective has been to demonstrate the sensitivity of the combined WAIP intensity predictions to the T2F timing errors. The special focus of the example ECEPS and GEFS forecasts of the pre-Lekima circulations in Sections 2 and 3 has been given to the earliest forecast that had a WMVM track matching the early Lekima track, because such examples demonstrate the opportunity for earlier guidance to begin disaster preparedness activities. For this Lekima case, the first ECEPS forecast of T2F (35) was initiated seven days in advance of the verifying T2F (35) time, and the timing error was 0.0 days (Figure 8c). Each of the subsequent five ECEPS forecasts of the T2F (35) were less than or equal to 1.0 days early. With these accurate T2F (35) times as inputs to the pre-formation stage of the combined WAIP, and with a highly accurate track forecast as input to the intensification stage, those intensity predictions (Figure 8d, right panel) would have also provided useful guidance as to the time that Lekima would achieve typhoon intensity. By contrast, only the first ECEPS forecast of the T2F (25), which was 6.5 days in advance of the verifying T2F (25) time, had an accurate T2F (25), and consequently had an accurate WAIP intensity prediction to the typhoon stage. The subsequent ECEPS forecasts of T2F (25) were 1.25 days to 2.75 days early (Figure 8c), and thus had too early intensification stage predictions (Figure 8d, left panel).

As was the case for the ECEPS in Figure 8b (left panel), the very early T2F (25) timing errors for the GEFS (Figure 9c, blue dots) leads to large WAIP over-forecasts of the intensity during the pre-formation stage and early intensification stage. Although coincidentally the WAIP intensities are equal to the verifying intensities when Lekima was becoming a typhoon, the early T2F (25) start of the combined WAIP intensity forecast also leads to a too early decay stage of Lekima. Because the 12 UTC 29 July and 06 UTC 30 July GEFS forecasts had near-perfect T2F (35) times (Figure 9c), both the pre-formation stage and early intensification stage WAIP intensity forecasts are excellent—albeit only to when Lekima became a typhoon (Figure 9d, right panel). The other two GEFS forecasts with early T2F (35) times have the same over-forecast of the intensity during the pre-formation stage and early intensification stage as is the case for the combined WAIP intensity forecasts for the T2F (25) in Figure 9d (left panel).

The first GEFS forecast of T2F (35) was initiated 6.0 days in advance of the verifying T2F (35) time, and yet was only 12 h late (Figure 9c). This accurate T2F (35) time, plus a very long pre-formation stage, led to a highly accurate prediction of the intensity during the pre-formation stage and the early intensification stage (Figure 9d, right panel). However, the poor GEFS WMVM track forecast contributed to an early termination of the intensification stage at about 60 kt (Figure 9d, right panel). For the subsequent GEFS forecasts with too early T2F (35) times, the WAIP intensity predictions were over-forecasts by 20 kt to 30 kt. Similarly, the very early (2–3 days) T2F (25) forecasts by the GEFS (Figure 9c) led to too short pre-formation stages and too early intensification stages in the combined WAIP intensity predictions (Figure 9d, left panel).

As Elsberry et al. [1] have documented for two other typhoons and two hurricanes, the T2F (35) timing errors are typically smaller than the T2F (25) timing errors. Furthermore, those smaller T2F (35) errors will then contribute to a more accurate WAIP intensity prediction.

5. Opportunities and Challenges for Hydrological Predictions

In the Elsberry et al. [1] article, none of the three western North Pacific storms nor the single storms in the eastern/central North Pacific and in the eastern North Atlantic had made landfall. Thus, the atmospheric forecast focus would have been on the track and associated intensity/wind structure, and the oceanic forecast focus would have been on the sea-surface temperature and ocean thermal structure changes and perhaps the ocean surface waves. A special feature of TY Lekima was that it made landfall, which is an opportunity to also consider hydrological forecasts in support of water resource management.

Hydrological predictions for tropical cyclone-related hazards such as flooding, debris flow, and landslides as occurred in TY Lekima first of all require an accurate track forecast both for the location of the rainfall and for the duration, which crucially depends on the translation speed (Tsai and Elsberry 2013) [14]. As mentioned in the Introduction, the slow translation speed of Lekima gave more time for disaster preparedness activities. However, a slower translation speed can lead to larger rainfall accumulations, and thus a greater threat of flooding. It is also significant that after making landfall near Zhejiang, Lekima then turned poleward and had a long path parallel to the coast with the center over land. Whereas this path over land will diminish the high wind speeds around the center, heavy rainfall can continue in advance of the center of Lekima due to large onshore advection of warm, moist air from the adjacent ocean, and this could be very dangerous in an area with coastal topography. Lekima landfall timing of early August could have been a contributor to the debris flow and landslide mentioned in the Introduction if the heavy rainfall associated with the onset of the summer southwest monsoon in the Zhejiang area had saturated the soil and enhanced the river flow.

Tsai and Elsberry ([14], their Figure 9) had proposed a three-tier approach for a seamless approach for hydrological hazards related to tropical cyclones: (i) Tier 1 in the 15–30 day time scale would focus on extended-range outlooks of a tropical cyclone formation and subsequent track over the river basin of interest. It is also important to know that there would be no tropical cyclone in the 15–30 day outlook period since that can be an important factor in water resource management. If the summer monsoon onset, or a previous typhoon, had led to high water levels in the Zhejiang area, then an early outlook that a typhoon such as Lekima would alert the water resource management agency to the potential threat of dangerous water levels and severe flooding. If the summer monsoon onset, and the absence of prior typhoons, had resulted in low water levels, the primary question raised by an early outlook of a typhoon such as Lekima would be whether to delay imposing restrictions of agricultural water supplies.

At the time of the Tsai and Elsberry [14] article, the ECEPS was the only global ensemble extending to 30 days, and they documented the capability of the ECEPS to predict the formation and subsequent tracks of TY Morakot (2009) and Super-Typhoon Megi (2010) up to four weeks in advance. Since that time, much progress has been made in seasonal and subseasonal predictions of tropical cyclones (Titley et al. 2019) [15], and thus guidance products now exist for the Tier 1 outlooks on 30→15 day timescales. However, Tsai and Elsberry [14] had also documented that the ECEPS had a large number of false alarms in those Week 1 through Week 4 forecasts during the 2010 season, and the issues with distinguishing those false alarms from real storms have not been extensively studied.

The Tier 2 in the Tsai and Elsberry [14] proposed three-tier approach for a warning system for hydrological hazards was then in the 15→5 day timescale, although with many numerical weather prediction centers providing accurate seven-day deterministic guidance products the Tier 2 timescale might now be 15→7 days. With more specific and more frequent forecasts on the 15-day timescales, the support for hydrological operations can become progressively more specific. Because tropical cyclone formation and track type are governed by large-scale environmental conditions, forecast-to-forecast consistency in the 5–15 day forecasts is important in assessing confidence to be placed in each model forecast.

Tsai and Elsberry [14] had presented 15-day ECEPS forecasts of Super-Typhoon Megi (2010) that had a good formation location with a subsequent landfall on Luzon as early as 12–13 days prior to the formation day of Megi. Yamaguchi et al. [9] evaluated the skill of four operational global ensemble models in forecasting tropical cyclone activity in seven basins over the short-to-medium-range (timescales of 0–14 days). In general, the ECMWF ensemble was the most skillful model with forecasts that extended into Week 2. However, two multi-center grand ensembles tended to have better forecast skill than the best single-model ensemble. It is noted that using 35 kt (15 kt–25 kt) as the threshold value defining the tropical cyclone in the models tends to under-estimate (over-estimate) the numbers and lifetimes in the verification. The use of 15 kt by Yamaguchi et al. [9] would correspond to the pre-formation definition in this study, and their finding that utilizing 15 kt leads to an over-estimate indicates many of the circulations were actually false alarms. Finally, it is noted that neither the early Tsai and Elsberry [14] study nor the more recent Yamaguchi et al. [9] study addressed the opportunity for improved Tier 2 hydrological predictions, as their focus was tropical cyclone formation and subsequent tracks over the ocean rather than on landfall tracks in the 7–15 day timescale.

The assertion here is that an opportunity for Tier 2 with 15→7 day timescale support of hydrological hazard warnings has been demonstrated in this study of TY Lekima. The ECEPS consistently predicted the pre-Lekima circulation T2F timing (albeit with some initial position uncertainty) from as early as seven days in advance of the verifying T2F (35), and the WMVM track forecasts that consistently made landfall near Zhejiang and then continued along the East China coast (Figure 8a). In this pre-Lekima study, the ECEPS had consistent (and accurate) track forecasts with increasing numbers of members in each successive forecast. By contrast, the GEFS had only a small number of ensemble members, and although it consistently predicted a recurvature-type track, this was incorrect. While the ECEPS had a large spread in the ensemble that indicated a large uncertainty, the WMVM track was "down the middle" of that spread and can be interpreted as the most likely track.

The challenge was that (according to the Joint Typhoon Warning Center) the pre-Lekima circulation started on 4 August and became a Tropical Storm at 12 UTC 4 August, and Lekima made landfall five days later. Thus it is critical that the ECEPS forecast from 12 UTC 28 July was capable of predicting the pre-Lekima circulation would start at 06 UTC 3 August (Day 6 in the forecast), and become a hydrological hazard of major concern near Zhejiang on Day 13 of that forecast. In addition, the combined WAIP intensity predictions forced by those ECEPS forecasts consistently confirmed that pre-Lekima circulation would become a typhoon. It is noted that Elsberry et al. [1] have documented that the non-development of weak Tropical Storm Peipah (2019) beyond 35 kt could be diagnosed from a WCM that remained below the threshold for T2F (35), so the WCM-T2F technique has not been "tuned" to always predict a typhoon. Indeed, a future objective is to evaluate whether the predicted WCM evolution may also be utilized to distinguish false alarms.

Based on this limited study, the usefulness of the GEFS for hydrological predictions of landfalling tropical cyclones is less evident than for the ECEPS. Most importantly, the GEFS did not have a large number of ensemble members to calculate the WMVM track forecast, which predicted that the pre-Lekima circulation would subsequently recurve well to the east of Zhejiang rather than make landfall near Zhejiang. Future studies are necessary before any definite conclusions can be made about the usefulness of the GEFS for this purpose.

The Tier 3 is then defined as the 5→0 (or 7→0 day) timescale. As indicated above, deterministic models have been extended to seven days, and high-resolution regional deterministic and ensemble models are likely to provide more specific rainfall guidance. However, the ECMWF deterministic model provides 10-day track forecasts only for systems that have already been designated as a tropical cyclone by an official WMO warning center. At that stage, the circulations and their positions are better determined than during the early pre-formation systems addressed in this study. If the ECMWF deterministic model was to be applied to that early pre-formation stage, not only would there be larger position uncertainty, it would be just one solution and not the weighted-mean of all ensemble members as in the ECEPS ensemble storms studied here.

A special hydrological consideration in the Tier 3 timescale is the predecessor rain events (PREs), which are heavy mesoscale rainstorms that may occur ~1000 km in advance of the TC (Cote [16]). A middle- or upper-level jet entrance region is a favored synoptic location for PRE development, and the PRE heavy rainfall (>100 mm in 24 h) is concentrated in the region of a mesoscale surface boundary. Cote [16] found that approximately one third of Atlantic landfalling hurricanes had one of more PREs. Significant flooding may be triggered first by the PRE followed by the TC-related rainfall. Especially with the advancement in seven-day deterministic models, the occurrence of a PRE within the Tier 3 timescale is likely to be well-predicted. Further studies with global ensemble models are required to determine whether a PRE can be predicted within the Tier 2 timescale (7–15 days) as would have been the opportunity in the TY Lekima case.

6. Summary and Concluding Thoughts

Typhoon Lekima (2019) is an excellent example of the need for earliest possible warnings of the formation, intensification, and subsequent track before the typhoon makes landfall on a densely populated coast. The Marchok (2002) vortex tracker outputs from the ECEPS and GEFS ensembles are used to provide precise time-to-formation (T2F) timings and positions of the pre-Lekima circulation along weighted-mean vector motion (WMVM) track forecasts. One of the most important results in this study is that the ECEPS consistently predicted the pre-Lekima circulation from as early as seven days in advance of the verifying T2F (35) as a Tropical Storm, and the ECEPS WMVM track forecasts consistently made landfall near Zhejiang and then continued poleward along the East China coast.

The timing and position of that T2F (35) are diagnosed from two Marchok vortex tracker genesis parameters, which are combined to calculate a weighted-mean warm core magnitude (WCM) in the column over the center of the pre-Lekima circulation. The ECEPS-predicted WCM evolution was consistently successful in estimating the T2F (35) time defined as when the threshold WCM value of 25 was exceeded. Similarly, the GEFS-predicted T2F (35) times were also within one day of the verifying time even though this sample of forecasts was also initiated 5–7 days prior to verifying time. A second approach for estimating the T2F (25) was a direct calculation of the weighted-mean intensities of the ECEPS or GEFS ensemble members making up the pre-Lekima circulation. This approach was less successful than the WCM-based T2F (35) approach as the T2F (25) timing errors were typically 2 days early relative to the verifying T2F (25). The explanation for these early formation predictions as a 25 kt tropical depression is that the initial near-surface wind speeds as diagnosed in the Marchok vortex tracker for pre-Lekima were too strong, at least relative to the initial WCM.

The combined three-stage seven-day weighted analog intensity Pacific (WAIP) prediction technique of Tsai and Elsberry [14] was provided starting from the first detection of the pre-Lekima circulation in the ECEPS and GEFS forecasts. If the T2F (35) was accurate, this combined WAIP technique provided accurate predictions of the intensification to early typhoon stage. However, an analog/statistical technique such as the WAIP cannot predict the continued rapid intensification of Lekima to 130 kt.

Tsai and Elsberry [14] had proposed a three-tier approach to prepare for tropical cyclone-related hydrological hazards. Many advances have been made in providing their Tier 1 (15→30 day) guidance and similarly improved guidance products are available in their Tier 3 (0–5 day timescale). Yamaguchi et al. [9] have demonstrated that some global ensemble models are providing forecasts of tropical cyclone activity extending into Week 2. It is asserted that the ECEPS forecasts of pre-Lekima evaluated in this study demonstrate an opportunity now exists to provide Tier 2 (15→7 day timescale) warnings for hydrological hazards as occurred in Lekima during and after landfall.

The benefits of the on-scene forecaster-satellite analyst collaboration cannot be reproduced in this study. At the Joint Typhoon Warning Center, a forecaster/analyst is assigned to analyzing each 12 h the tropical cyclone formations in their area of responsibility. In this Lekima example, the forecaster analyzing the early ECEPS (GEFS) forecasts could have alerted the satellite analyst to pay particular attention to the area where Lekima was predicted to start. In turn, the satellite analyst could provide feedback as to whether the more accurate pre-Lekima circulation position was in the ECEPS or in the GEFS. With the availability of the ECEPS forecasts examined in this study, there would have been an opportunity to issue alerts/watches/warnings of Lekima even seven days in advance of when Lekima became a Tropical Storm, and provide guidance that a landfall on the East China coast near Zhejiang should be anticipated about five days later.

Author Contributions: Conceptualization, H.-C.T. and R.L.E. have together published journal articles since 2014 on the ensemble storm Weighted-Mean Vector Motion (WMVM) track forecasts and H.-C.T. and R.L.E. have jointly over five years developed the combined Weighted Analog Intensity Prediction (Pacific), and T.P.M. conceived and developed the tropical cyclone vortex tracker. Methodology, H.-C.T. and R.L.E. have jointly conceived the methodology of the Warm Core Magnitude (WCM) with the assistance of T.P.M.; Software coding for the Warm Core Magnitude has been done by H.-C.T., W.-C.C. and T.P.M. has continued to upgrade the vortex tracker code; Validation, H.-C.T. and R.L.E. have jointly conceived the validation technique; Writing, R.L.E. has been responsible for the text, and H.-C.T. and W.-C.C. have been responsible for creating the figures. All authors have read and agreed to the published version of the manuscript.

Funding: R.L.E. and H.-C.T. had a two-year Joint Hurricane Testbed grant from the NOAA OAR Office of Weather and Air Quality (OWAQ); R.L.E. is also funded by the Office of Naval Research Grant N00014-19-1-2465. H.-C.T. and W.-C.C. are supported by the Taiwan Ministry of Science and Technology (MOST 108-2111-M-032-002-MY3) and Central Weather Bureau (1092110B). T.P.M.'s participation was internally funded at the Geophysical Fluid Dynamics Laboratory.

Acknowledgments: Penny Jones is thanked for her excellent contributions to the preparation of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, the analyses or interpretation of the data, in the writing of the manuscript, or in the decision to publish the results.

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