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Predicting Rapid Intensification Events Following Tropical Cyclone Formation in the Western North Pacific Based on ECMWF Ensemble Warm Core Evolutions

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Abstract: When the environmental conditions over the western North Pacific are favorable for tropical cyclone formation, a rapid intensification event will frequently follow formation. In this extension of our combined three-stage 7-day Weighted Analog Intensity Pacific prediction technique, the European Centre for Medium-range Weather Prediction ensemble predictions of the warm core magnitudes of pre-tropical cyclone circulations are utilized to define the Time-to-Formation (35 knots) and to estimate the Likely Storm Category. If that category is a Typhoon, the bifurcation version of our technique is modified to better predict the peak intensity by selecting only Cluster 1 analog storms with the largest peak intensities that are most likely to have under-gone rapid intensification. A second modification to improve the peak intensity magnitude and timing was to fit a cubic spline curve through the weighted-mean peak intensities of the Cluster 1 analogs. The performance of this modified technique has been evaluated for a sequence of western North Pacific tropical cyclones during 2019 in terms of: (i) Detection time in advance of formation; (ii) Accuracy of Time-to-Formation; (iii) Intensification stage prediction; and (iv) Peak intensity magnitude/timing. This modified technique would provide earlier guidance as to the threat of a Typhoon along the 15-day ensemble storm track forecast, which would be a benefit for risk management officials.

Keywords: tropical cyclone intensity forecasts; rapid intensification; ensemble model predictions

1. Introduction

Elsberry et al. (2020) [1] have developed ensemble-based tropical cyclone (TC) formation guidance products based on the European Centre for Medium-range Weather Forecasts ensemble (ECEPS) and the National Centers for Environmental Prediction Global Ensemble Forecast System (GEFS). Elsberry et al. [1] used the Marchok (2002, 2020) [2,3] vortex tracker outputs from the ECEPS and GEFS to provide precise (nearest 6-h time) Time-to-Formation (T2F) timings and positions along Weighted-Mean Vector Motion (WMVM) track forecasts in which the largest (smallest) weight is given to the ensemble member motion vector that is closest to (farthest from) the most recent 12-h WMVM vector. The T2F (25 kt) timing is defined to be when the weighted-mean (same weighting factors as for the track) intensities of the various ensemble members exceed the 25 kt threshold (>22.5 kt for the ECEPS). For the T2F (35 kt) timing, two Marchok vortex tracker [2,3] "genesis parameters" along the ensemble member tracks are utilized to calculate the weighted-mean (again, same weighting factors as for the track forecast) Warm Core Magnitude (WCM) along the WMVM track forecast. To reflect the (1/p) factor in the hypsometric equation, the Upper (600–300 mb)-layer warm core is weighted two times the Lower (900–600 mb)-layer warm core.

Elsberry et al. [1] used examples of pre-TC circulations in the western North Pacific during the latter half of the 2019 season to calibrate the weighted-mean WCM thresholds that are associated with the T2F (35 kt) for both the ECEPS and the GEFS. Elsberry et al. [1] provided detailed validations for Typhoons Lingling and Bualoi (and one hurricane in the eastern North Pacific and one hurricane in the Atlantic). The T2F (35 kt) timing and position errors were often smaller and more consistent than the T2F (25 kt) timing and position errors. The likely explanation for the more erratic T2F (25 kt) timing errors is the initial intensities of the pre-TC circulations in the ECEPS and (especially) GEFS were often already 25 kt.

An example of the ECEPS weighted-mean WCM evolutions for a series of forecasts from 00 UTC 27 August (082700) through 12 UTC 1 September (090112) for Typhoon (TY) Lingling (2019) is provided in Figure 1b. The corresponding WMVM track forecasts in Figure 1a illustrate that Lingling originated east of the Philippines and had a poleward track that is typically more difficult to predict than a westward-mover at lower latitudes or a recurver storm. According to the Joint Typhoon Warning Center (JTWC) Working Best Track (WBT), Lingling became a Tropical Storm at 06 UTC 2 September 2019 near 16.8° N, 125.1° E. The 00 UTC 29 August forecast with 23 ensemble members (inset, Figure 1b) had the earliest detection (-4.5 days) of the pre-Lingling circulation before the T2F (35 kt), and yet the WCM threshold corresponding to that T2F (35 kt) was predicted very accurately (-0.25 days; Elsberry et al. [1], Figure 16, column 13). Indeed, all nine of these ECEPS predictions of when the WCM evolution surpassed the threshold for the T2F (35 kt) were accurate within 0.75 days.

The actual Lingling intensity is over-plotted in Figure 1b (kt, dash-dot line, right-axis). While the WCM = 25 threshold is for a tropical storm, the actual intensity of Lingling was only 25 kt at the time the ECEPS-predicted WCM threshold was exceeded. Whereas the ECEPS WCM= 45 threshold for a typhoon is surpassed by all nine of these forecasts, eight of the nine forecasts in Figure 1b achieve that typhoon threshold 24–36 h after the actual time that Lingling became a typhoon according to the JTWC WBT (00 UTC 3 September). Thus, the ECEPS does predict WCM evolutions that exceeded the WCM threshold value corresponding to a Likely Storm Category (LSC) of Typhoon, the timing of when that typhoon intensity (surface winds > 64 kt) is achieved as not well-predicted by the ECEPS in this Lingling case. Since this poor intensification guidance inferred just from the WCM evolution was found with all typhoons (and the two hurricanes examined), Elsberry et al. [1] provided intensity forecasts following the T2F from the Tsai and Elsberry (2019) [4] combined three-stage 7-day Weighted Analog Intensity Pacific (WAIP) prediction technique (see Section 2 for details of the WAIP). While these WAIP intensity predictions were successful in predicting the timing and magnitude of the intensification from the T2F to the Typhoon stage, the WAIP intensity would then level off and under-predict the peak intensity—especially when rapid intensification (RI; here $\geq$ 30 kt/24 h) occurred. Furthermore, it was difficult to estimate the timing of the peak intensity within that extended period of level intensities.

Predicting RI events is a difficult forecasting problem in all TC basins (see comprehensive reviews in Courtney et al., 2019a [5], Courtney et al., 2019b [6]), and many research studies have focused on RI (see summaries in Hendricks et al., 2019 [7]; Braun et al., 2018 [8]; and Vigh et al., 2018 [9]). When the environmental conditions over the western North Pacific (WPAC) are favorable for TC formation, a RI event will frequently follow formation. The intensity evolutions for the WPAC cases studied by Elsberry et al. [1], and including the TY Lekima case studied by Tsai et al. (2020) [10], are displayed in Figure 2. These cases form the database for this study that focuses on the importance of the T2F accuracy and of a modification of the combined WAIP to better predict the peak intensity when at least one RI event follows the T2F.
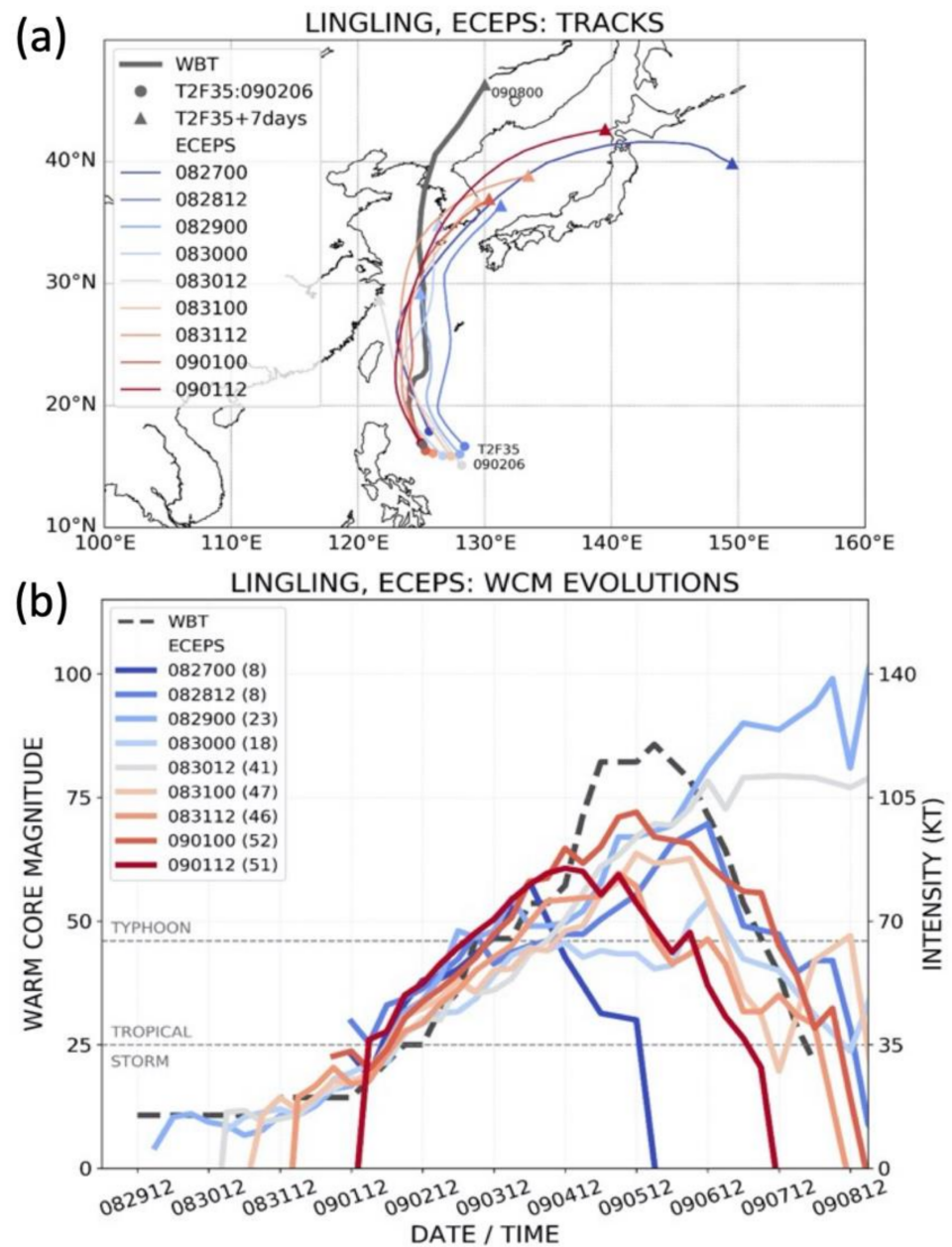
Figure 1. (**a**) A sequence of ECEPS WMVM track forecasts initiated from the month-day-hour (MMDDHH) in the inset, with origins (colored dots) at the T2F (35 kt) of 06 UTC 2 September 2019 for the pre-Typhoon Lingling circulation and ending points (colored triangles) seven days after the T2F (35 kt) compared with the JTWC Working Best-track (WBT, solid black line) with ending time of 00 UTC 8 September. (**b**) ECEPS-predicted Warm Core Magnitude evolutions (left ordinate) along the WMVM track forecasts for the dates and times in panel (**a**) and the JTWC WBT intensity (kt, black dashed line, right ordinate). The calibrated WCM threshold values of 25 for a Tropical Storm and 46 for a Typhoon are indicated along the left ordinate and by the horizontal thin dashed lines (see text).
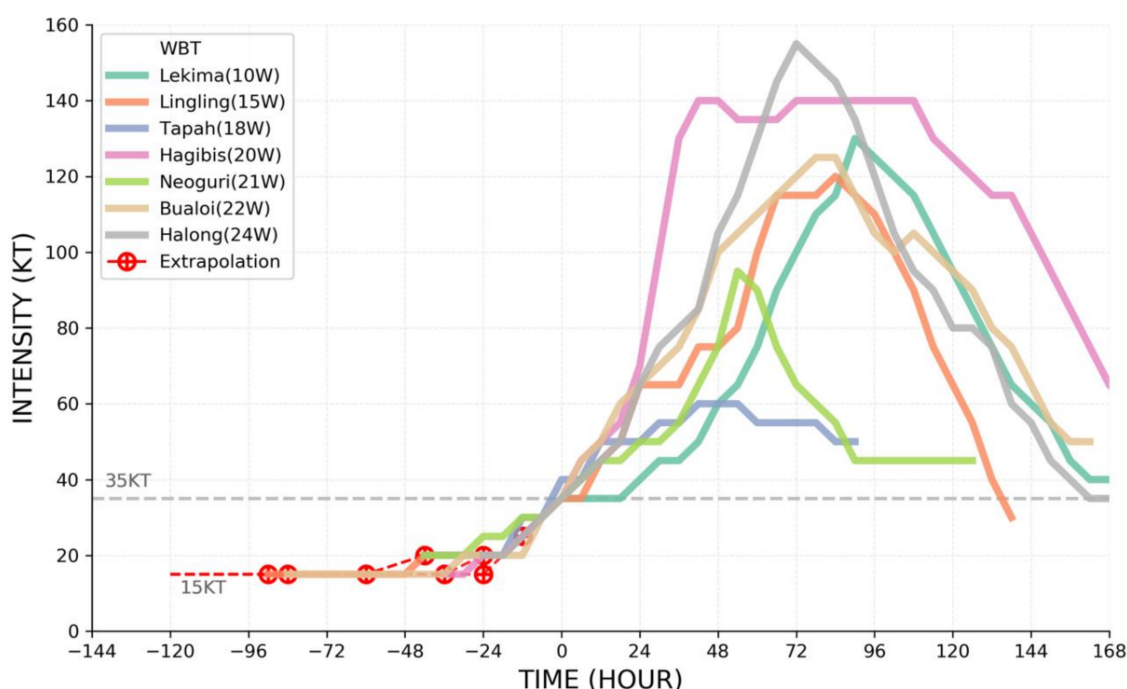
Figure 2. JTWC Working Best-Track (WBT) intensities (kt) plotted relative to the T2F (35 kt) labeled as Time = 0 for seven western North Pacific tropical storms (names and JTWC numbering in inset) during the 2019 typhoon season. For pre-T2F (35) times when the ECEPS had predicted a pre-TC circulation starting prior to the beginning of the JTWC WBT, a backward intensity extension (blue dashed line with circled blue crosses) of the WBT intensities was used to specify an intensity for validation of the ECEPS intensity predictions (see Appendix A).

Based on the JTWC WBT, the TY Hagibus (20 W) case is an example of the extreme RI events that can occur in WPAC, and that extreme RI began only 18 h after the T2F (35 kt), which was only 36 h after JTWC WBT began for 20 W (Figure 2). TY Halong (24 W) was the most intense among this sample of cases from the 2019 WPAC season, and the intensification from 50 kt just 18 h after T2F (35 kt) to 155 kt only 54 h later is obviously an extremely difficult intensity forecast challenge. The TY Bualoi (22 W) rapidly intensified almost linearly from 20 kt at 12 h before the T2F (35 kt) to 100 kt only 48 h after T2F (35 kt). However, other typhoons such as Lekima (10 W) [Neoguri (21 W)] did not immediately rapidly intensify after T2F (35 kt), but starting from 45 kt [50 kt] at T2F (35 kt) + 36 h [+30 h] then rapidly intensified to 130 kt [95 kt] in just 60 h [24 h]. Although Tapah (18 W) only reached 60 kt according to the JTWC WBT (Figure 2), it is included within this sample to emphasize that an intensity forecast technique must also address slower intensification cases, and of course non-developers.

The objectives of this study are to: (i) demonstrate the ECEPS performance in early detection of pre-TC circulations in WPAC; (ii) predict the T2F (25 kt) via weighted-mean model intensity changes and the T2F (35 kt) via the predicted WCM evolution; and (iii) utilize the Likely Storm Categories based on the predicted WCM to better select the analogs in the combined WAIP technique to predict the magnitude and timing of the peak intensity of the storm within 7 days after the T2F. Section 2 will describe the changes in methodology compared to the Elsberry et al. [1] and the Tsai et al. [10] studies of these same storms during the 2019 WPAC season. Examples of the ECEPS performance and some statistical results in terms of Mean Absolute Errors (MAEs) and Mean Biases (MBs) will be presented in Section 3. A summary and some concluding remarks will be given in Section 4. Although Elsberry et al. [1] also described the performance of the GEFS, a new FV3 version of the GEFS was implemented in late September 2020, so it is uncertain whether that performance evaluation of those original GEFS forecasts during the 2019 season is still relevant.

2. Methodology

The Tsai and Elsberry [4] combined three-stage 7-day WAIP technique was developed to provide the intensity evolution and the intensity uncertainty that is most likely to occur given the track forecast. The basic hypothesis is that the predominant factor in the intensity forecast beyond 72 h is the TC track, and thus in the selection of analogs more weight is given to the portion of the track beyond 72 h (Tsai and Elsberry 2014) [11]. In each step in the development of the combined WAIP technique, the JTWC best-track was utilized rather than the official track forecast, which allowed Tsai and Elsberry (2015) [12] to extend the WAIP technique to 7 days even though JTWC did not have official 7-day track forecasts. Thus, the evaluations of the combined WAIP technique in Tsai and Elsberry [4] are labeled as an "optimum performance demonstration."

The three stages in the combined WAIP intensity predictions are: (i) Pre-formation stage from the first detection of a pre-TC circulation in the ECEPS until the Time-to-Formation (T2F), where formation may be defined as either Tropical Depression (25 kt) or Tropical Storm (35 kt); (ii) Intensification stage immediately following T2F, in which 16 analog storm intensities are weighted according to the same weighting factors that were assigned to the analog tracks to generate the weighted-mean forecast intensities each 12 h (rather than a simple mean intensity that assumes each analog intensity is equally likely); (iii) Ending storm stage, which may be due to landfall, extratropical transition, or to non-development within the 7-day forecast interval. A highly accurate ECEPS track forecast is obviously very important for determining landfall timing, and also for anticipating intensity changes associated with extratropical transition. Each of these three stages is defined in terms of the weighted-mean warm core magnitude (WCM) evolution along the WMVM forecast track of the ensemble storm predicted by the ECEPS starting from the first detection of a pre-TC circulation.

The preparatory steps for the modified combined WAIP intensity predictions in this study are summarized at the top of Figure 3. As indicated in Section 1, the ECEPS 51-member ensemble WMVM track forecasts are the basic input to the combined WAIP intensity prediction technique, so that the potential real-time performance can be demonstrated. Three important benefits from these ECMWF ensemble forecasts are that they often detect a pre-TC circulation 2–3 days before the JTWC typically begins issuing storm warnings, the 7-day track forecasts after TC formation are usually highly accurate, and the up to 15 day total length of the tracks provides a longer-range outlook as to what regions/countries may be affected.

Elsberry et al. [1] describe the methodology for calculating the weighted-mean WCM from the two Marchok genesis parameters, which originally are from the Hart (2003) [13] Cyclone Phase Space variables along the WMVM track forecast, and then how the T2F (35 kt) timing was estimated when the WCM exceeded a threshold value as illustrated in Figure 1b for pre-TY Lingling. While Elsberry et al. [1] attempted to distinguish an early and a later T2F (35 kt) timing with two WCM threshold values, these two threshold values were typically surpassed at the same time or within six hours for the rapidly intensifying storms. Consequently, only the WCM threshold for the early T2F (35 kt) described in Elsberry et al. [1] will be utilized in this study.

Elsberry et al. [1] also describe how the maximum positive weighted-mean WCM for the ECEPS forecasts could be used to define the Likely Storm Category (LSC): Maximum WCM < 25.0 for Tropical Depression; $25.0 \leq$ WCM < 46.0 for Tropical Storm; and WCM $\geq$ 46.0 for TY. Note that this WCM value for a TY is also displayed on the left ordinate of Figure 1b, and eight of the ECEPS forecasts surpassed that maximum WCM threshold for a Likely TY. Whereas six of these ECEPS forecasts had maximum positive WCM values just beyond the 46.0 threshold for a TY to magnitudes ~70, the ECEPS forecast from 00 UTC 29 August (082900) with a maximum WCM ~140 and the forecast from 12 UTC 30 August with a maximum WCM ~110 far exceed the threshold value such that the JTWC forecaster could have confidence that the pre-Lingling circulations in those forecasts would become a typhoon.

Flowchart for Modified Combined Weighted Analog Intensity Pacific (WAIP)
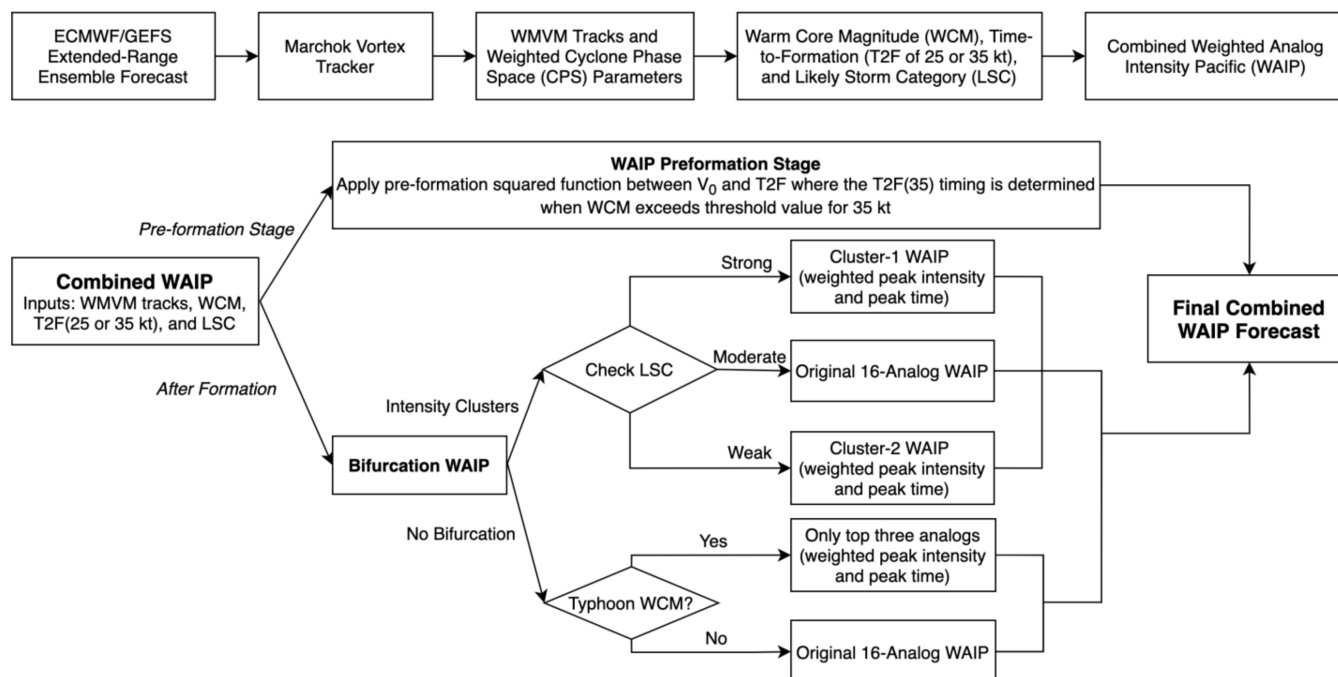

Figure 3. Flowchart summarizing in the first row the preparatory steps necessary to generate from the ECEPS forecast the inputs to the combined WAIP intensity forecasts. The larger lower flowchart summarizes the modified combined WAIP intensity forecasts in this study. No modifications are made for the WAIP pre-formation stage. The WAIP after-formation stage intensity forecasts are modified utilizing the bifurcation WAIP intensity Cluster-1 (Cluster-2) when there is a strong (weak) indication from the Likely Storm Category (LSC) that only those analogs with (without) a rapid intensification (RI) should be selected for the WAIP. Even if there is no bifurcation, an indication from the LSC of a likely typhoon will limit the analog selection to RI-type analogs and will stipulate that a weighted peak intensity and peak time will be applied (see text).

Whereas Elsberry et al. [1] had calibrated the WCM threshold for the T2F (35 kt) timing along the WMVM track, they found the likely timing of when TY intensity would be achieved could not be inferred from just the predicted WCM evolution. Consequently, Elsberry et al. [1] calculated the intensity forecasts after the T2F from the Tsai and Elsberry [4] combined three-stage 7-day WAIP. These variables are then the preparatory steps for the modified combined WAIP intensity forecast (Figure 3, top row).

The pre-formation stage for the modified WAIP utilized in this study is not changed (Figure 3, middle). The bifurcation version of the Tsai and Elsberry [4] combined WAIP is utilized for the intensification stage after formation (Figure 3, lower flowchart). If the weighted-mean intensity spread over the 7-day forecast period exceeds a specified threshold value, a hierarchical cluster analysis (Wilks 2011) [14] separates the 16 analog intensities into two clusters. If there are at least three analogs in each cluster, the WAIP technique is separately applied to these two clusters to produce weighted-mean intensities (and weighted-mean intensity spreads) each 12 h over the 7-day forecast period. The intensity Cluster-1 is always that cluster with the larger peak intensities, and Cluster-2 is the alternate solution with the lower peak intensity. These two cluster WAIP forecasts are considered to represent a substantial intensity bifurcation if a 15 kt intensity difference threshold is exceeded for at least 25% of the 12-h forecast intervals within the 7-day forecast period.

The new procedure in this modified WAIP is to now check the LSC based on the maximum positive WCM as described above. If there is a strong LSC indication of an early and long-lasting WCM increase indicative of a likely TY (e.g., almost all of the storms in Figure 1b), then the bifurcation WAIP Cluster 1 is selected. As indicated in Section 1, a simple mean of the analog peak intensities that occur at different times results in an extended time period of level intensities. Therefore, a special weighting of the analog

intensities with the largest weight given to the analog with the largest peak intensity is added in order to increase the Cluster-1 peak intensity and to define a specific timing of the peak intensity (see Appendix A). This special weighting of the peak intensities results in a larger peak WAIP intensity at a better-defined peak intensity time estimate compared to an average of all Cluster-1 analog intensities.

If the WCM evolution indicates a more moderate intensification rate, the original 16-analog WAIP intensification scale is considered to be a more appropriate choice when there is no clear indication of a rapid intensification based on the predicted WCM evolution (Figure 3, middle). If there is only a weak (or no) indication of a substantial intensification following the T2F (which may be for 25 kt), then the bifurcation WAIP Cluster-2 is selected, and the weighted peak intensity and peak intensity time procedure is applied. In the latter case, the objective is to identify in the ECEPS forecasts those situations in which the environmental constraints (e.g., vertical wind shear and sea-surface temperature) are likely to inhibit intensification beyond the T2F (35 kt).

In some ECEPS forecasts there may be no bifurcation indicated by the analog intensity spread according to the rules in the Appendix of Tsai and Elsberry [4], but the maximum positive WCM value clearly indicates a likely TY (Figure 3, bottom branch of the flow chart). This situation may occur over the most favorable TC formation areas of the WPAC (e.g., east of the Philippines) when nearly all of the selected analogs have similar large intensification rates such that the potential Cluster-1 and potential Cluster-2 do not meet the required 15 kt intensity difference threshold for at least 25% of the 12-h forecast intervals. Rather than averaging a large number of similar analogs with peak intensities at different times, which again would lead to an extended period with level intensities, a weighted-mean peak intensity and peak intensity time are defined from only the top three analog peak intensities. Finally, if no bifurcation exists and the maximum positive WCM value does not indicate a likely TY, the original WAIP that is the weighted-mean intensities of the 16 analogs becomes the final combined WAIP intensity forecast (Figure 3, bottom decision in the flow chart).

In summary of this extension of the Elsberry et al. [1] article, the ECEPS forecasts during the 2019 WPAC season from the first detections will be examined with the objective of obtaining the earliest possible predictions that the pre-TC circulation will have a precise formation time (T2F) and will likely have a RI such that it is highly likely a typhoon will subsequently occur. As indicated in Figure 1b, Elsberry et al. [1] had calibrated the T2F (35 kt) timing in terms of a WCM threshold representative of a Tropical Storm, and had defined a second WCM threshold that would indicate a Likely Storm Category of Typhoon would occur at some time during the life cycle. Whereas Elsberry et al. [1] had applied the Tsai and Elsberry [4] combined WAIP technique to predict the intensification after the T2F (35), they had included all 16 analog intensities rather than selecting only analog intensities that included an RI when a typhoon was being predicted. Consequently, the WAIP tended to have an extended period of level intensities rather than a well-defined peak intensity since the different timings of the peak intensities were not accounted for. The modified combined WAIP in Figure 3 that will be applied after the T2F (35 kt) in this study utilizes the bifurcation version and then also uses three categories of the maximum WCM-based Likely Storm Categories to be highly selective as to which analog intensities should be used. Selecting only bifurcation WAIP Cluster-1 intensities that have RI events leading to the largest peak intensities will be utilized when the WCM-based Likely Storm Category is TY. Another important modification will be to implement a weighted peak intensity technique that takes into account the different times (and magnitudes) of those more appropriately selected analog intensities for the bifurcation WAIP cluster intensity predictions, with the objective of predicting larger peak WAIP intensities associated with RI events at a better-defined time of peak intensity. A description of this weighted peak intensity procedure is given in first section of the Appendix A.

3. Examples of the Modified Combined WAIP Intensity Predictions

A detailed description of the modified combined WAIP intensity predictions based on both the ECEPS T2F (25 kt) and the T2F (35 kt) timing forecasts for pre-TY Lingling (Figure 4) will first be given, and then for the other examples only the WAIP predictions based on the ECEPS T2F (35 kt) forecasts will be described. These WAIP intensity predictions will be compared with the JTWC WBT intensities as the post-season best-track files were not available. However, when the ECEPS has predicted a pre-TC circulation existed before the JTWC had begun a WBT, it was necessary to extrapolate the WBT intensities back in time to the beginning of the pre-TC circulation in the ECEPS, which is assumed to have an intensity $V_{max} \geq 15$ kt. If the WBT initial intensity (V_0) is already 15 kt, the intensity records are simply backward-extended as 15 kt to the beginning of the pre-TC circulation (Figure 2, lower left). If V_0 is 20 kt, the timing of 15 kt is estimated by using the decreasing trend between the 20 kt timing and 25 kt timing of that WBT. If the initial V_0 in the WBT is 25 kt, the timing of the 15 kt is backward-extended based on the trend between the 25 kt timing and the 35 kt. As indicated by the blue-circled crosses in Figure 2, these backward-extended intensities/timings provide reasonable values for validation of the predicted WAIP intensities during the pre-formation stage.

This modified WAIP intensity prediction in Figure 4a based on the ECEPS T2F (25 kt) has been included for pre-TY Lingling from the ECEPS because seven of the nine predictions are outstanding in terms of the sustained rapid intensification and peak intensity predictions. As indicated in Figure 1a, these pre-Lingling circulation track forecasts began just east of the Philippines (note that the dots indicating the T2F are for 35 kt rather than 25 kt), and then had a long track poleward over warm ocean water, which would be favorable for a sustained RI event. Two-thirds of these ECEPS forecasts also predicted well the timing of the rapid decay following the peak intensity. Consequently, the intensity Mean Absolute Errors (MAEs; Figure 4c) are incredibly small for the 7-day WAIP intensity forecast period following the T2F (25 kt). While the inclusion of the first ECEPS forecast (inset, 082700) and last ECEPS forecast (090112) no doubt contributed to an intensity MAE = 20 kt at tau = 126 h, most of the other forecast intervals have MAEs < 15 kt. The intensity Mean Bias (MB; Figure 4e) is plotted relative to the actual T2F (25 kt, tau = 0 h) to illustrate that the pre-T2F period of the combined WAIP has very small errors, which may be attributed to most of the ECEPS forecasts not predicting the pre-Lingling circulation very early prior to the T2F (25 kt). As is also evident in Figure 4a, the last (090112) ECEPS forecast prior to the T2F (25 kt) had a large under-forecast bias, and the first (082700) forecast had an increasingly larger under-forecast bias from tau = +48 h to tau = +90 h. These two under-forecast bias cases distorted the MB at the end of the forecast period because the remaining ECEPS forecasts of the T2F (25 kt) had only small positive biases until tau = +72 h.

For the pre-Lingling case, the modified WAIP intensity predictions in Figure 4b based on the ECEPS T2F (35 kt) and WCM evolution are not as accurate as the T2F (25 kt)-based WAIP intensity predictions in Figure 4a. The pre-formation period WAIP intensity predictions in Figure 4b are slightly better because the T2F (35 kt) is better predicted, except for the first (082700) ECEPS forecast. Consequently, the MAEs (Figure 4d) during the first 72 h and the MB during the pre-formation period are slightly smaller. After the T2F (35 kt), almost all of the modified WAIP intensification stage predictions were about one day late to typhoon stage and missed the extremely rapid intensification on 4 September.
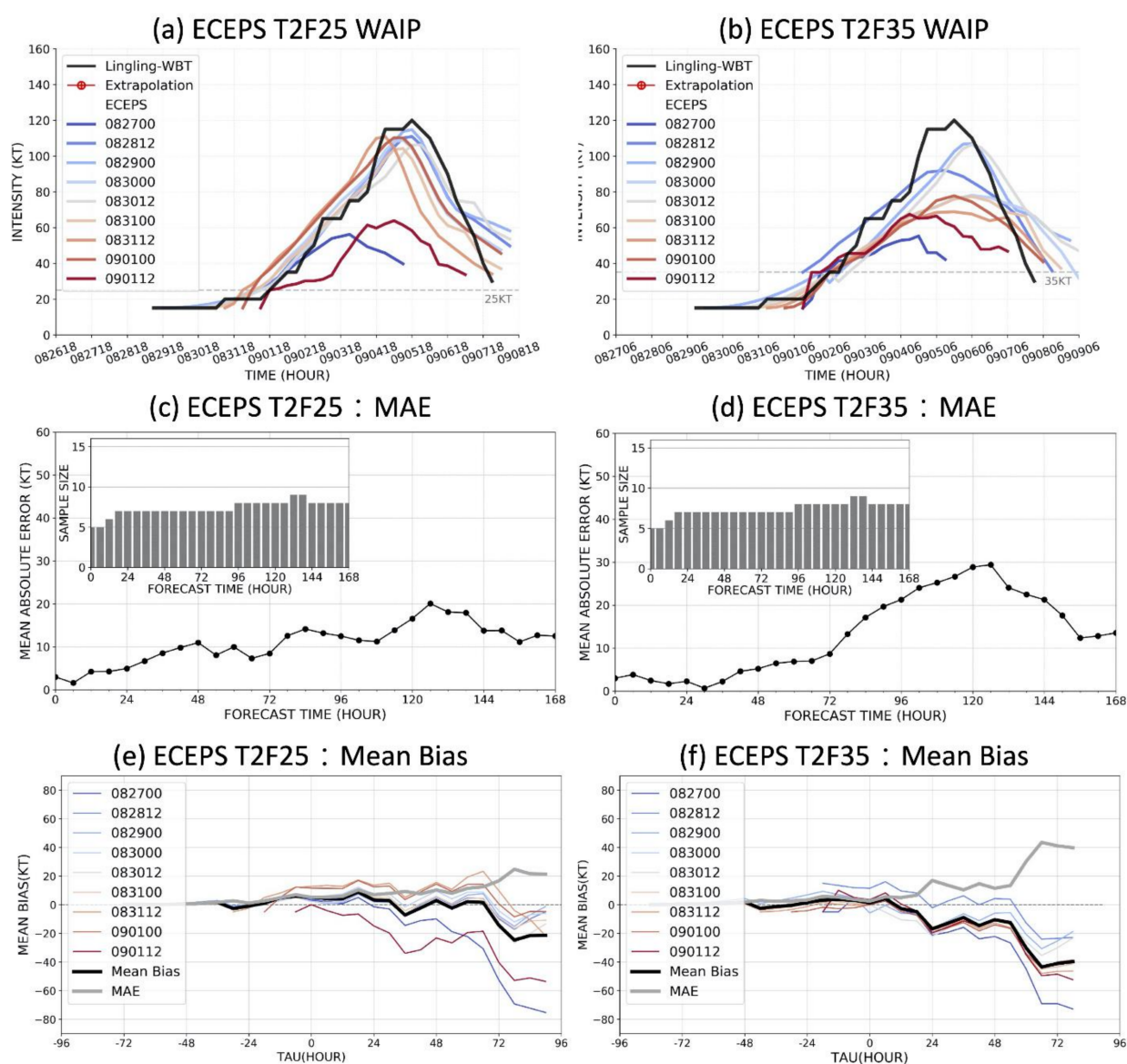
Figure 4. Pre-Lingling circulation modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (25 kt) in left column and the T2F (35 kt) in right column: (**a**,**b**) Nine intensity forecasts (see initiation MMDDHH times in inset) versus JTWC WBT intensities in black line; (**c**,**d**) Intensity Mean Absolute Errors (MAEs) for the sample sizes indicated in the insets; and Mean Bias errors of the individual forecasts (see MMDDHH times in inset) relative to the JTWC WBT for forecast times relative to the (**e**) T2F (25 kt) and (**f**) T2F (35 kt) labeled as tau = 0. When more than one intensity forecast is available at a forecast time, the mean bias (black line) and MAEs (grey line) are indicated.

The two exceptions were the 082812 ECEPS forecast, which detected the pre-Lingling circulation of the 082906 [note that this is four days before T2F (35 kt)] and the 083012 ECEPS forecast, which both predicted well the time-to-typhoon and then achieved a peak intensity of ~105 kt (albeit more than one day late). The first exception in predicting the RI of Lingling was from the first ECEPS forecast that had a very early detection of the pre-Lingling circulation and also had an accurate T2F prediction, but the ECEPS then under-predicted the vortex spin-up. It was not unusual for the first detection of a pre-TC circulation in the ECEPS to have an under-prediction of the intensification, and especially as in this case when that intensification is occurring ~5 days after the first detection. We can only speculate that the more-accurate next ECEPS forecast 12 h later had the benefit from initial conditions that had a better definition of the pre-Lingling circulation. [Note: ECMWF does not bogus the vortex based on warning center TC Vitals.] The second exception in

predicting the RI of Lingling was from the ECEPS forecast that was initiated just 6 h before Lingling became a Tropical Storm according to the JTWC. Without any history of the earlier stage of the pre-Lingling vortex, and again ECMWF does not bogus the vortex, the T2F WAIP diagram in Figure 4a indicates the Lingling vortex was only slowly spun-up, which means the WCM only slowly increased in the model. Consequently, the WCM threshold for a Typhoon was not met (i.e., only Cluster 1 analog intensities were not selected), and therefore all 16 analog intensities were selected for the T2F WAIP (Figure 4b). With those 16 analog intensities, and a decay stage following the first peak intensity that was not well-defined, our peak intensity modification was not applied.

Note the five WAIP intensity forecasts (Figure 4b) with peak intensities between 65 kt and 75 kt, and that the timings of those peak intensities are not well-defined as in Figure 4a. For these five WAIP forecasts the weighted peak intensity modification technique was not applied because the bifurcation WAIP Cluster 1 versus Cluster 2 intensity difference (15 kt over at least 25 percent of the 12-hourly intensities) was not satisfied. That is, too few Cluster 1 peak intensity analogs were identified, presumably because of the favorable formation conditions that exist north and east of the Philippines where the pre-Lingling circulation began (first set of dots in Figure 1a). Consequently, the MAEs (Figure 4d) increase to 30 kt at the time of peak intensity of Lingling, but then decrease to near 10 kt during the decay stage because all but two decayers of the ECEPS T2F (35 kt)-based WAIP intensity predictions are relatively accurate during the decay stage. The MAEs are inversely related to the MB errors, which are negative (under-forecast) and grow slowly during the first 48 h after the T2F (35 kt), but then become large negative during the extreme RI period of TY Lingling.

While the ECEPS T2F (35 kt)-based WAIP intensity predictions are not as accurate as the T2F (25 kt)-based predictions, they do include highly accurate formation (35 kt) timing forecasts and all but the first (082700) ECEPS-based WAIP prediction indicate that the pre-Lingling circulations will intensify to at least typhoon intensity within 2–3 days after that T2F (35 kt). In conjunction with the ECEPS WMVM track forecast (Figure 1a) that now also provides the positions at which formation (35 kt) and the TY intensity will likely occur, these WAIP intensity predictions would be helpful guidance for many TC disaster preparation activities even if the actual peak intensity of 120 kt is not predicted.

4. Additional Examples of ECEPS T2F (35 kt) Modified WAIP Intensity Predictions

4.1. Pre-Lekima Modified WAIP Intensity Predictions

Tsai et al. [10] have extensively described the opportunity for early warnings of the formation and subsequently seven-day WAIP intensity predictions for pre-Typhoon Lekima (2019). The formation of TY Lekima was in the far western North Pacific and it rapidly intensified to a Super-Typhoon as it approached Ishigaki-jima and Miyako-jima of the Ryuku Islands, and then made landfall on the densely populated East China coast with heavy rains and flooding. Fortunately, more than 800,000 people were successfully evacuated from Zhejiang, and 250,000 people from Shanghai. Nevertheless, 2.7 million homes lost power and there was great damage.

In the first ECEPS forecast from 072812 (12 UTC 28 July 2019), the WMVM track forecast (Tsai et al., 2020, their Figure 1a) for pre-TY Lekima circulation starts at 080306 (model forecast time at 138 h) and correctly predicts landfall near Zhejiang around August 10. The corresponding ECEPS-predicted WCM evolution along the WMVM track forecast is provided by Tsai et al. in their Figure 1c, and the WCM = 25 threshold value for predicting the T2F (35 kt) was achieved at 080412, which exactly agreed with the formation time according to JTWC. However, the ECEPS-predicted WCM evolution after the T2F (35 kt) only slowly increased in time and it was only at 080806 (i.e., 90 h after formation) that the ECEPS-WCM threshold for a typhoon was first, and just barely, exceeded. The implication from the modified combined WAIP intensity prediction flowchart in Figure 3 is that this only "moderate Likely Storm Category" indication of a typhoon was that all 16 analogs should be used in the bifurcation version of the combined WAIP, rather than the Cluster 1

analog intensities with peak intensities that are indicative of RI events typically following TC formation in the western North Pacific.

The six modified WAIP intensity predictions for pre-Typhoon Lekima based on the ECEPS-predicted WMVM tracks and WCM evolutions are shown in Figure 5a. Note that the JTWC WBT started at 25 kt and it was only 12 h before the T2F (35 kt), and thus backward-extended intensities (dashed line) were necessary for validation purposes. As described above, the first prediction of a pre-TC circulation that became Lekima was from the ECEPS at 072812 (Figure 5a, inset), which is seven days before the T2F (35 kt) and it had a perfect prediction of that T2F (35 kt). The 073100 ECEPS forecast, which was initiated 5.5 days before T2F (35 kt), also had a perfect prediction. Although the other four ECEPS forecasts were early, it was only by 12 h to 24 h (Tsai et al. [10], their Figure 7, column 13). The standard WAIP procedure is that the intensification stage begins with a value of 35 kt at the (near-perfect in this case) diagnosed T2F (35 kt) time. However, Lekima did not begin to intensify at that first time of 35 kt. According to JTWC, Lekima remained at 35 kt for another 18 h (Tsai et al. [10]), their Figure 7b). Since each of the WAIP intensification stage predictions began from the diagnosed first T2F (35 kt) rather than 18 h later when Lekima actually began to intensify, those WAIP predictions have an early time bias, which also means the predicted peak intensities have an early bias. As mentioned above, when the ECEPS-predicted WCM evolutions barely exceed the WCM threshold for a typhoon, all 16 analog intensities would be utilized in the WAIP intensity predictions (Figure 3, Moderate LSC). Because the peak intensities of those analogs occur at a variety of times after formation, the WAIP intensity predictions in Figure 5a tend to level out and do not have well-defined peak intensity times and magnitudes, as for example in Figure 4a. Even if these WAIP predictions were adjusted to correct for the early time bias, their peak intensities would still be well below the 130 kt peak intensity of Lekima.

The combined MAEs and MBs for these six pre-Lekima WAIP predictions are provided in Figure 5b. The intensity MAEs during the pre-formation period are small and positive (over-forecast), and the MBs are positive, which is obvious in Figure 5a as all but the 073100 WAIP predictions during the pre-formation period have higher intensities than the backward-extended validation intensities. As indicated in Figure 5a, all of the WAIP intensification stage intensities are higher than the JTWC WBT intensities until a cross-over time around 54 h after the T2F (35 kt). During this intensification stage, the intensity MAEs and the MBs are larger until that cross-over time (Figure 5b). The signature signal of the intensity under-forecasts during RI events preceding the peak intensity of Lekima is the very large MAEs in response in association with a very large negative MB. However, both the MAEs and MBs are then reduced to near-zero magnitudes as the ECEPS track forecasts of the Lekima landfall are excellent, and thus the decay stage intensity errors are smaller (Figure 5a).

In summary, the ECEPS has provided quite early predictions of the pre-Lekima circulation with one forecast 7 days prior to the T2F (35 kt) (Figure 5a, inset). Although the predicted T2F (35 kt) timing based on the predicted WCM evolution was in near-perfect agreement with the first time of 35 kt for Lekima, according to JTWC Lekima did not begin the intensification stage until 18 h later. This unusual delay of intensification contributed to an early time bias in the WAIP-predicted intensification and an early timing bias in the predicted peak intensity. Furthermore, the ECEPS-predicted WCM evolution failed to strongly indicate a Likely Storm Category of a Typhoon, which then led to the use in WAIP of all 16 analog intensities, which results in poor predictions of peak intensity timing and magnitude. Consequently, there is a large under-forecast of the continued RI event to Super-Typhoon intensity when the ECEPS-predicted WCM evolution was utilized in the modified WAIP intensity prediction. By contrast, the GEFS-predicted WCM values increased more rapidly after T2F (35 kt) and indicated more strongly that a Typhoon was likely (Tsai et al. [10], their Figures 3d and 4d). Use of this information in the flowchart in Figure 3 would have resulted in the use of bifurcation WAIP Cluster 1 intensities, and the application of the peak intensity magnitude and timing modification of those Cluster

1 analog intensities. As indicated in the Introduction, the GEFS version evaluated by Elsberry et al. [1] has been replaced by a new FV3 version with considerably modified physical process representations. Thus, it cannot be assumed that the new FV3 version of the GEFS will have similar characteristics of more rapid increases in WCM to larger peak WCM values during RI events that were found with the previous version of GEFS during the 2019 typhoon season.
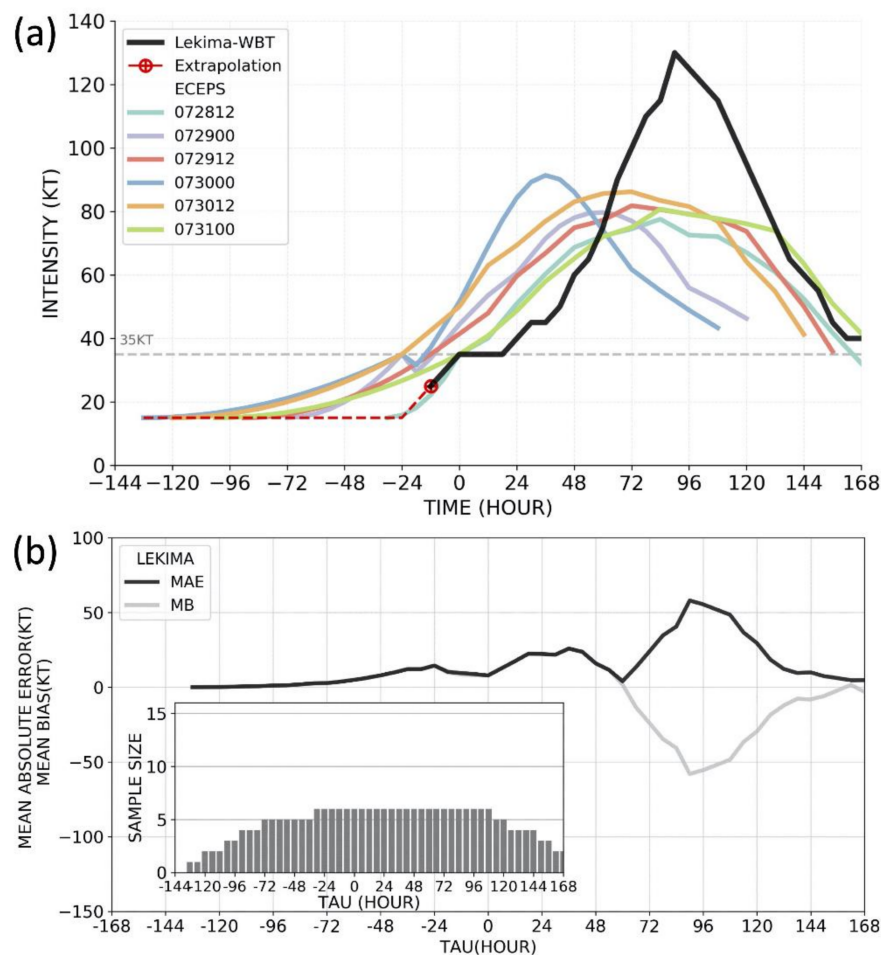

Figure 5. (**a**) Modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (35 kt) as in Figure 4b, except for the pre-TY Lekima (2019) circulations. (**b**) Intensity MAEs (solid line) and intensity MBs (gray line) as in Figure 4d,f except combined here for pre-TY Lekima.

4.2. Modified WAIP Intensity Predictions for Strong Tropical Storm Tapah (2019)

The ECEPS-based WAIP intensity predictions for strong Tropical Storm Tapah circulations are provided in Figure 6a as an example that the modified WAIP can also predict a strong Tropical Storm and thus not always predict a Typhoon. Note the early starts for most of the pre-Tapah circulations that were as early as 84 h prior to the T2F (35 kt). The exception is for the last forecast (091800), which was initiated just 36 h prior to formation (35 kt). Two of the early start forecasts (091600 and 091612) had T2F (35 kt) times that were early by 12 h, but they still predicted the WAIP intensification stage prediction very nicely and matched well the Tapah peak intensity magnitude (60 kt) and timing. Furthermore, they then matched well the decay stage and even the ending time. The last (091800) ECEPS forecast that had the 24 h early T2F (35 kt) timing also had a good forecast of the peak intensity of the decay stage. One of two early stage forecasts (091400) that had a 24 h late T2F (35 kt) time also had a delayed WAIP intensification stage and had a too-small peak intensity by 15 kt. The second early stage ECEPS forecast with a 24 h late T2F (35 kt) time (091412) was the only WAIP prediction that had analog selections that included RI events.

Consequently, WAIP-predicted peak intensity was 30 kt too high and the decay stage persisted too long, which would have been quite misleading for the forecaster. Another misleading forecast was the first one (091312) that had an early start but then intensified very slowly and thus was 5 days late in T2F (35 kt) timing. Fortunately, the ECEPS forecast just 12 h later provided much better guidance, including that pre-Tapah would not become a Typhoon.
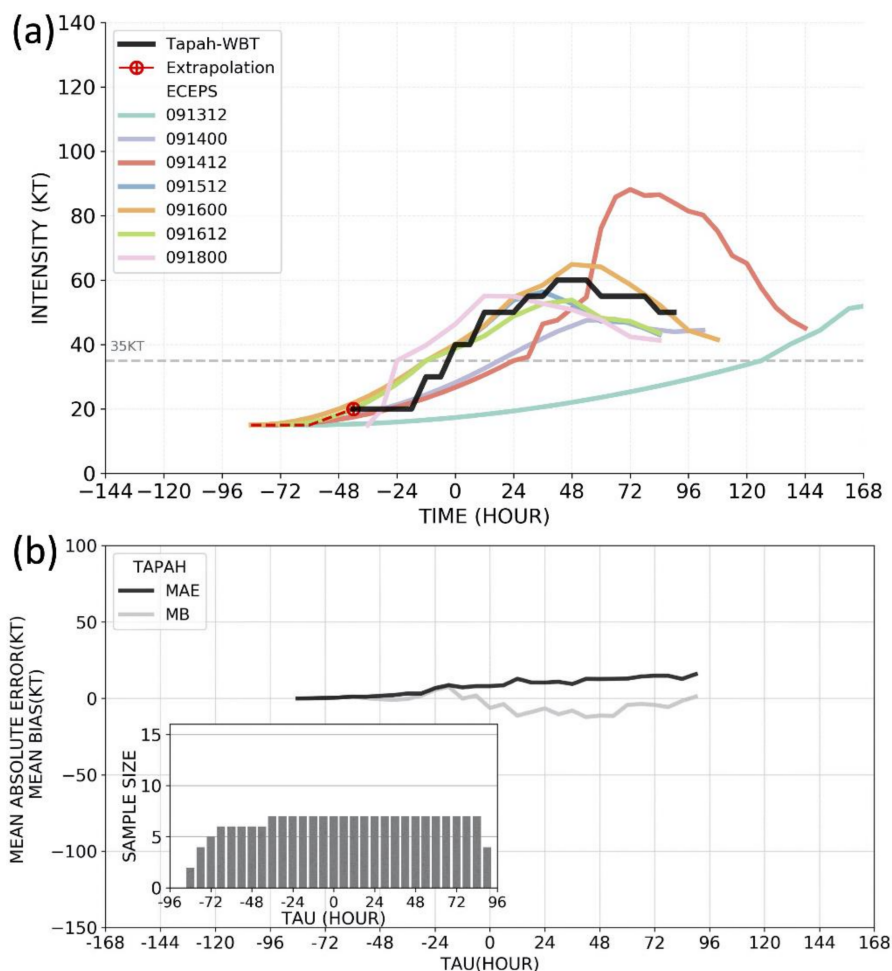

Figure 6. (**a**) Modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (35 kt) as in Figure 4b, except for the pre-TS Tapah (2019) circulations. (**b**) Intensity MAEs (solid line) and intensity MBs (gray line) as in Figure 4d,f except for pre-TS Tapah.

The intensity MAEs and MBs for these ECEPS-based WAIP predictions for the pre-Tapah circulations are provided in Figure 6b. As might be expected from the WAIP intensities during the pre-formation stage shown in Figure 6a, the MAEs are very small during that long pre-formation period. Even after the T2F (35 kt), the MAEs increase at a relatively small rate–first primarily due to the large under-forecast of the 091312 prediction. Then, after the RI during the 091412 prediction, both of these predictions contributed to the error growth. Since MAEs are not calculated after TS Tapah ended at T2F (35 kt) plus 92 h, the MAEs do not get very large even though six of these seven ECEPS forecasts first detected the pre-Tapah circulation 66–84 h before the T2F (35 kt). Similarly, the MBs were near zero during the pre-formation period until T2F (35 kt) minus 24 h, which is when the increasingly large negative intensity bias of the first (092312) "outlier prediction" became the dominant factor. Then, the large positive intensity bias after the RI in the 091214 WAIP prediction becomes an offsetting factor, and the MBs shrink to near-zero for the remainder of Tapah.

In summary, these T2F-WAIP predictions would be helpful guidance to the forecasters, because it is important to know that a pre-TC circulation over the western North Pacific in the middle of typhoon season is going to become a Tropical Storm for 3–5 days, but it is only going to achieve strong Tropical Storm intensity. It is noteworthy that a correct prediction of the timing of when that peak intensity would be achieved is also provided. Furthermore, the WAIP correctly predicted the ending storm time because of an accurate ECEPS WMVM track (not shown), which is critical for risk management.

4.3. Modified WAIP Intensity Predictions for Pre-Typhoon Bualoi (2019)

Elsberry et al. ([1], Section 3.1.3) describe the ECEPS (and GEFS) forecasts of pre-Typhoon Bualoi. These are challenging track, formation, and intensity forecasts as the pre-Bualoi circulation began at a low latitude (near 5° N) near the Dateline (178° E). The first ECEPS forecast from 12 UTC 12 October started pre-Bualoi at 6.4° N, 172.2° E, but some later ECEPS forecasts started pre-Bualoi farther to the west between 165° E and 168° E. These different initial positions led to bifurcation track forecasts with the early forecasts correctly predicting the recurvature-type track of Bualoi, but the later forecasts that started farther west continued to have tracks that were biased to the west. Another effect of the low-latitude starting position with only weak steering flow, and of the track bifurcation, is a slow along-track bias.

One positive aspect of the many ECEPS forecasts (Figure 7, inset) was the very early starts of the pre-Bualoi circulation with some starting as early as 84 h ahead of the T2F (35 kt; 06 UTC 19 October). While a few of the first ECEPS forecasts had T2F (35 kt) timing around 12 h late, a substantial fraction of the ECEPS-based T2Fs (35 kt) were 26 h to 60 h late (Figure 7a), which is likely due to the slow track bias. Note that while Bualoi began its RI from 20 kt and intensified to 125 kt in 84 h, the WAIP predictions had much smaller intensification rates, which is likely because so few of the analog storms that matched the low-latitude, far-to-the-east WMVM track would be expected to have had such strong RI events. In combination with the delayed T2F (35 kt) times from which the WAIP predictions began, more than half of these ECEPS forecasts had WAIP predictions that vastly under-forecast the Bualoi peak intensity. A few forecasts, and notably the 101500 (orange line) forecast, had a vigorous WAIP intensification stage (as associated with RI events in the western North Pacific) and then the modified peak intensity time and magnitude led to a peak intensity even larger than that of Typhoon Bualoi. Because the T2F (35 kt) for that ECEPS forecast was 48 h late, it is not surprising that the peak intensity for that WAIP prediction is also 48 h late. Indeed, this pre-Bualoi case is an excellent example of the importance of an accurate T2F forecast, and also the importance of the selection of analogs including RI events to get an accurate prediction of the intensification stage.

The intensity MAEs and MBs for these ECEPS-based WAIP predictions for the pre-Bualoi case are given in Figure 7b. The most positive result is that the ECEPS detected the pre-Bualoi circulation very early, and the WAIP pre-formation stage MAEs are very small until a sustained RI event began starting from an intensity of 20 kt. Then, rapidly increasing MAEs begin due to the delayed start of the WAIP intensification stage, and the too-small intensification rate for at least half of the WAIP predictions. Consequently, the intensity MBs become progressively larger negative with magnitudes exceeding 50 kt by 48 h after T2F (35 kt). Due to the slow translation speed forecast, the WAIP intensity predictions are just peaking when Bualoi has already recurved and is rapidly decaying.
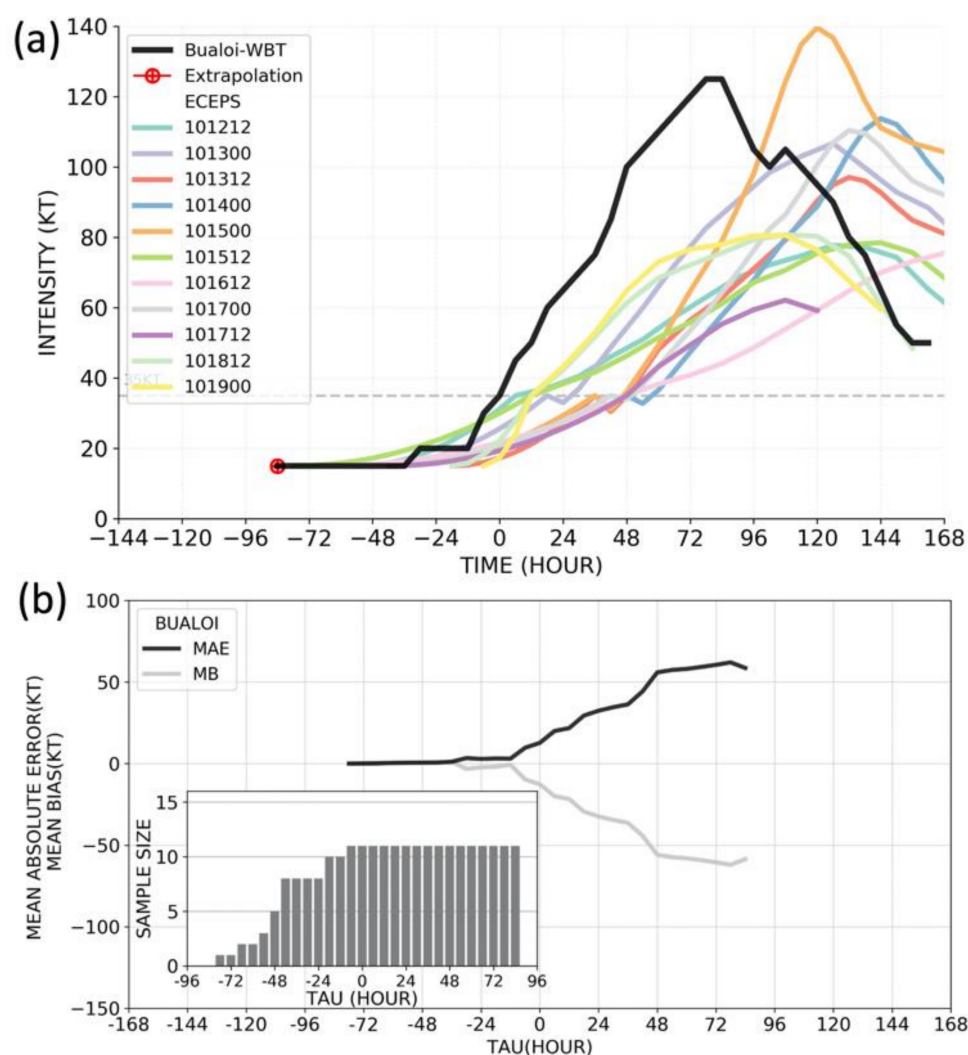
Figure 7. (**a**) Modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (35 kt) as in Figure 4b, except for the pre-TY Bualoi (2019) circulations. (**b**) Intensity MAEs (solid line) and intensity MBs (gray line) as in Figure 4d,f except for pre-TY Bualoi.

4.4. Failure of Modified WAIP Intensity Predictions for STY Hagibis (2019)

It is only fair that the modified WAIP predictions based on the ECEPS forecast of pre-Super Typhoon (STY) Hagibis also be shown (Figure 8), as this is an example of multiple failures of the T2F-WAIP technique. The first ECEPS forecast that had detected the pre-Hagibis circulation was from 12 UTC 1 October (Figure 8a, inset). Although the detection was at 12 h before the actual T2F (35 kt), the predicted formation time based on the WCM = 25 threshold was late by 42 h when STY Hagibis was already a STY with 140 kt wind speeds (Figure 8a). The modified WAIP prediction from that late T2F (35 kt) was for a relatively slow intensification with a peak intensity of ~85 knots about 120 h after Hagibis had first reached its 140 kt peak intensity. It was 3 days later (100412) that the next ECEPS forecast detected the pre-Hagibis circulation, which was also the time of the first entry in the JTWC WBT, but that was only 36 h before the T2F (35 kt). The third ECEPS forecast (100500) was only 18 h before T2F (35 kt). While both of these forecasts predicted within 6 h when the WCM would exceed the threshold for a Tropical Storm, these were very late detections of the pre-Hagibis circulations, especially since the ECEPS forecasts typically are not available at JTWC until 10–11 h after synoptic time. Furthermore, the two WAIP intensity forecasts started from those T2F (35 kt) times had very slow intensification rates and only reached peak intensities of 75–80 knots five days later (Figure 8a). While it is not expected that an analog intensity technique such as WAIP will have many RI events of

105 knots in 36 h after formation at any location in WPAC, the slow intensification rates of these three WAIP predictions indicate no RI events were included for the WMVM track forecasts and WCM evolution of these ECEPS forecasts.
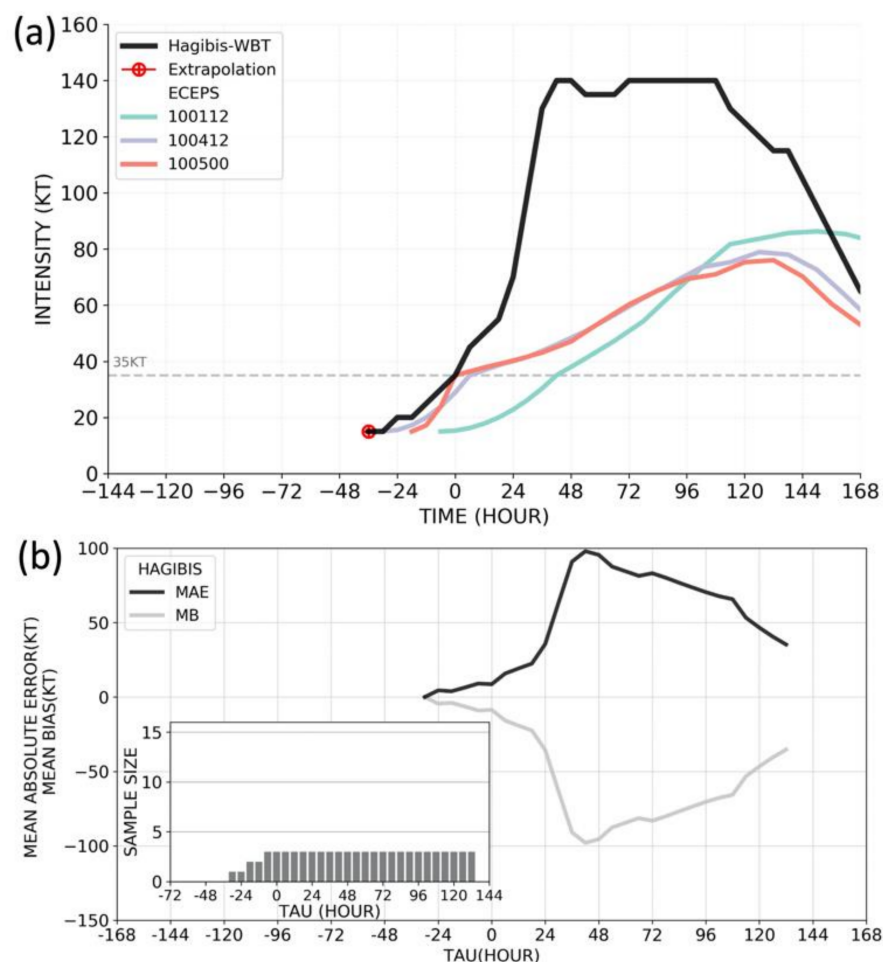

Figure 8. (**a**) Modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (35 kt) as in Figure 4b, except for the pre-STY Hagibis (2019) circulations. (**b**) Intensity MAEs (solid line) and intensity MBs (gray line) as in Figure 4d,f except for pre-STY Hagibis.

The intensity MAEs and MBs for the ECEPS-based WAIP predictions (Figure 8b) document the failure for pre-STY Hagibis. In contrast to the previous storms, there is only a very short pre-formation period when the MAEs are small. Especially with the first ECEPS forecast (100112) having only a 12-h detection of pre-Hagibis and with a delayed T2F (35 kt), the MAEs increase before formation, and then rapidly increase to 100 knots as the extreme RI is under-forecast. Those extreme under-forecasts are also responsible for the negative MBs that also reach 100 knots. It is purely a coincidence that the MAEs and MBs later decrease in magnitude when the slow-intensifying WAIP predictions after the T2F (35 kt) happen to coincide with the rapidly decreasing intensity of Hagibis.

5. Summary and Discussion

When the environmental conditions over the western North Pacific are favorable for tropical cyclone formation, a RI event will frequently follow formation. Thus, an accurate prediction of that RI event will require an accurate prediction of formation. Elsberry et al. [1] have used the Marchok [2,3] vortex tracker outputs from the ECEPS to provide precise (nearest 6-h synoptic time) T2F timings and positions along WMVM track forecasts. The T2F (25 kt) timing, which is simply the weighted-mean of the times that the various ECEPS ensemble storm members exceed 22.5 kt, is occasionally quite accurate, and when

that accurate T2F (25 kt) leads to analog selections in the WAIP that had RI events following their formation, then an accurate WAIP intensification stage was predicted. Even though the ECMWF often predicts the existence and track of a pre-TC circulation 3–4 days before the T2F (25 kt), the predicted intensities of those circulations tend to be irregular with a T2F (25 kt) that is biased early, which leads to too-early predictions of RI.

For the T2F (35 kt) timing, Elsberry et al. [1] utilized two Marchok vortex tracker "genesis parameters" to calculate the WCM along the WMVM track forecast, and defined weighted-mean WCM thresholds that defined the T2F (35 kt) for pre-TC circulations in the western North Pacific during the latter half of the 2019 typhoon season. Similarly, Elsberry et al. [1] defined a weighted-mean WCM threshold that for the ECEPS was indicative of a Typhoon intensity. Whereas the ECEPS does frequently predict WCM evolutions that exceeded the WCM threshold value corresponding to a Likely Storm Catetgory (LSC) of Typhoon, the timing of when that typhoon intensity is achieved tends to be biased late. Therefore, Elsberry et al. [1] also provided 7-day WAIP intensity predictions following T2F (35 kt) that generally improved the timing of when the typhoon stage would be achieved. However, the WAIP intensity evolutions tended to level-off after reaching typhoon intensity such that the peak intensity timing was not well-defined and the magnitude was under-predicted (e.g., Figure A1a).

A summary of the ECEPS-predicted T2F and modified WAIP intensity predictions for the western North Pacific TCs during the late 2019 typhoon season as displayed in Figure 2 is given in Table 1. As the first objective of the T2F-WAIP technique is to provide earlier guidance as to the intensity during the pre-formation stage of WAIP, the first column in Table 1 is the time before formation that the pre-TC circulation is detected in the ECEPS forecasts. In all but one TC, the circulation was detected at least 66 h prior to T2F (35 kt), and in the pre-TY Lekima case the first detection was 132 h in advance (Figure 5). The exception is for pre-TY Hagibis, which was detected in only three ECEPS forecasts that originated from only—6 h to—36 h in advance of T2F (35 kt). Such a short detection time is a likely indicator that the ECEPS did not have a good handle on this pre-TC circulation, and that is reflected in the "very poor" in Table 1, columns 3 and 4, respectively, for pre-TY Hagibis.

Table 1. Summary of the performance for four objectives of the modified WAIP for the tropical cyclones in this study.

Storm Figure	Detection Time (Hours)	Accuracy of T2F	WAIP Intensification Stage Prediction	Peak Intensity Timing/Magnitude
Lingling Figure 4a	−66	Good (slightly early)	Excellent	Excellent
Lingling Figure 4b	−66	Excellent	Good	Good (mixed)
Lekima Figure 5a	−132	Good (slightly early)	Good (mostly slow)	Poor (not applied)
Tapah Figure 6a	−84	Generally good	Excellent	Excellent
Bualoi Figure 7a	−84	Very delayed	Very delayed	Good (but delayed)
Hagibis Figure 8a	−6 to −36	Excellent (2) Very poor (1)	Very poor	Very poor (not applied)
Neoguri Figure A2a	−48 to −66	Early by 24 h	Good (but early)	Fair (not applied)
Halong Figure A3a	−30 to −72	Good (slightly early)	Very poor	Very poor (not applied)

Tsai and Elsberry [4] had demonstrated the potential benefit for highly accurate WAIP pre-formation stage intensity predictions, IF an accurate T2F timing is provided. In the Tsai and Elsberry [4] "optimum performance" test, that timing was from the best-track file. In Table 1, column 2, the T2F timing accuracy of these ECEPS forecasts during the late 2019 typhoon season is evaluated. The most common entry is "Good-slightly early," which

means within 12 h of the actual T2F. Two entries are "Excellent," which means perfect timing or within 6 h, but in the Hagibis case those two excellent predictions were for very short detection times (Table 1, column 1). The "Very delayed" T2F entry for pre-Bualoi is noteworthy because the WAIP intensification stage (Table 1, column 3) and the peak intensity (Table 1, column 4) were also very delayed, and consequently the intensity MAEs and MBs were quite large (Figure 7b).

The first objective of the modified WAIP prediction in the flowchart in Figure 3 was to improve the bifurcation WAIP intensification rate following the T2F (35 kt) by being more selective when the WCM evolution indicated a Likely Storm Category of Typhoon. Specifically, by selecting only the Cluster 1 analogs with the larger peak intensities in these situations, the WAIP intensification rate will be based on RI events following T2F (35 kt). However, the first "Excellent" entry for pre-TY Lingling in Table 1, column 3, is actually for T2F (25 kt), because it was used in Figure A1 to illustrate the modified peak intensity timing and magnitude. A majority of the storms in Table 1, column 3, have at least a "Good" WAIP intensification rate, but some also have qualifying notations such as "mostly slow" or "but early". As mentioned above for pre-Bualoi, the "very delayed" T2F (35 kt) leads to a very delayed intensification stage. The noteworthy Hagibis and Halong cases with "Very poor" performance ratings are examples in which extreme RI occurred, but the modified WAIP analog selection condition limiting those analogs to RI event cases was not appliable. Consequently, large intensity MAEs and large negative MBs are found for these cases in Figures 8b and A3b, respectively.

The second objective of the modified WAIP predictions in the flowchart in Figure 3 has been to improve the peak intensity magnitude and timing by fitting a cubic spline curve starting from a point on the intensification side through the weighted-mean of the peak intensities and then to a point on the decay side (Figure A1b). In addition to that "Excellent" example of a modified peak intensity magnitude and timing for the first pre-Lingling case (Table 1, column 4), the other "Excellent" result was for the pre-Tapah case in Figure 6a that had an "Excellent" WAIP intensification stage prediction all the way to peak intensity. For the pre-Bualoi case (Figure 7a), the modified peak intensity magnitudes were good, but they were delayed by two days due to the delayed T2F (35 kt). In four other cases in which the peak intensity was poor, the modified peak intensity conditions were not applied because the intensification stage or the decay stage did not meet the present criteria for a cubic spline fit. Consequently, further testing is required to improve the criteria for modification, although it is not expected that a statistical analog technique such as the modified WAIP will be able to match the extreme RIs that occurred in Hagibis (Figure 8a) or Halong (Figure A3a). Nevertheless, the ECEPS WCM evolutions and the modified WAIP predictions are successfully indicating that these pre-TC circulations detected as much as 3–4 days before T2F (35 kt) are going to be at least Typhoon intensity. Even if the very high peak intensities of Super Typhoons like Halong are not being matched, guidance that a typhoon threat exists along a 15-day ECEPS WMVM track could be used for improved risk management decisions.

One of the requirements for this T2F-WAIP guidance product is that it be objective as the forecasters do not have time to examine individual ensemble member forecasts among the 51 ECEPS members. Thus, the T2F (25 kt) and T2F (35 kt) timing (nearest 6-h synoptic time) and locations along the ECEPS and GEFS during the 2019 season WMVM track forecast are provided, and those variables are the inputs to the combined three-stage, 7-day WAIP intensity predictions following the T2F. Because of the larger track uncertainty in the TC pre-formation stage than in the mature stage, there is considerable uncertainty in the predicted variables that go into the T2F and thus into the WAIP predictions. Thus, these T2F-WAIP predictions must be considered by the forecasters in conjunction with other formation guidance (e.g., climatology, Madden-Julian Oscillation, deterministic global and regional models, etc.). Because T2Fs and 7-day WAIP intensity predictions are provided along the 15-day ECEPS WMVM track forecasts, the forecaster is able to consider the regions that might (or might not) be at risk of a typhoon. A good example is the pre-TY

Lekima formation predictions by the ECEPS described by Tsai et al. [10], in which there was an opportunity to provide early (10 days in advance) and consistent warnings of the threat to the Zhejiang, China area.

As an example of the critical need for forecaster interpretation of this T2F-WAIP guidance, the ECEPS forecasts of TS Peipah (2019) are presented in Figure 9. As described by Elsberry et al. ([1], Section 3.1.2), the first ECEPS track forecast from 00 UTC 13 September for pre-Peipah had a maximum of 22 of a possible 51 ensemble members, and although there was considerable scatter the WMVM track was northwestward toward Japan (Figure 9a). This early detection of pre-Peipah was 4.75 days before the T2F (25 kt) of 18 UTC 14 September, and the ECEPS perfectly predicted this T2F (25 kt) (Figure 9c). The WAIP intensity prediction based on that T2F (25 kt) timing and WMVM track was a relatively slow increase to a peak intensity of 80 kt after 120 h (Figure 9c). Note in Figure 9b that the WCM was near zero until 12 UTC 14 September and only slowly increased to the WCM = 25 threshold for a Tropical Storm at 00 UTC 17 September.
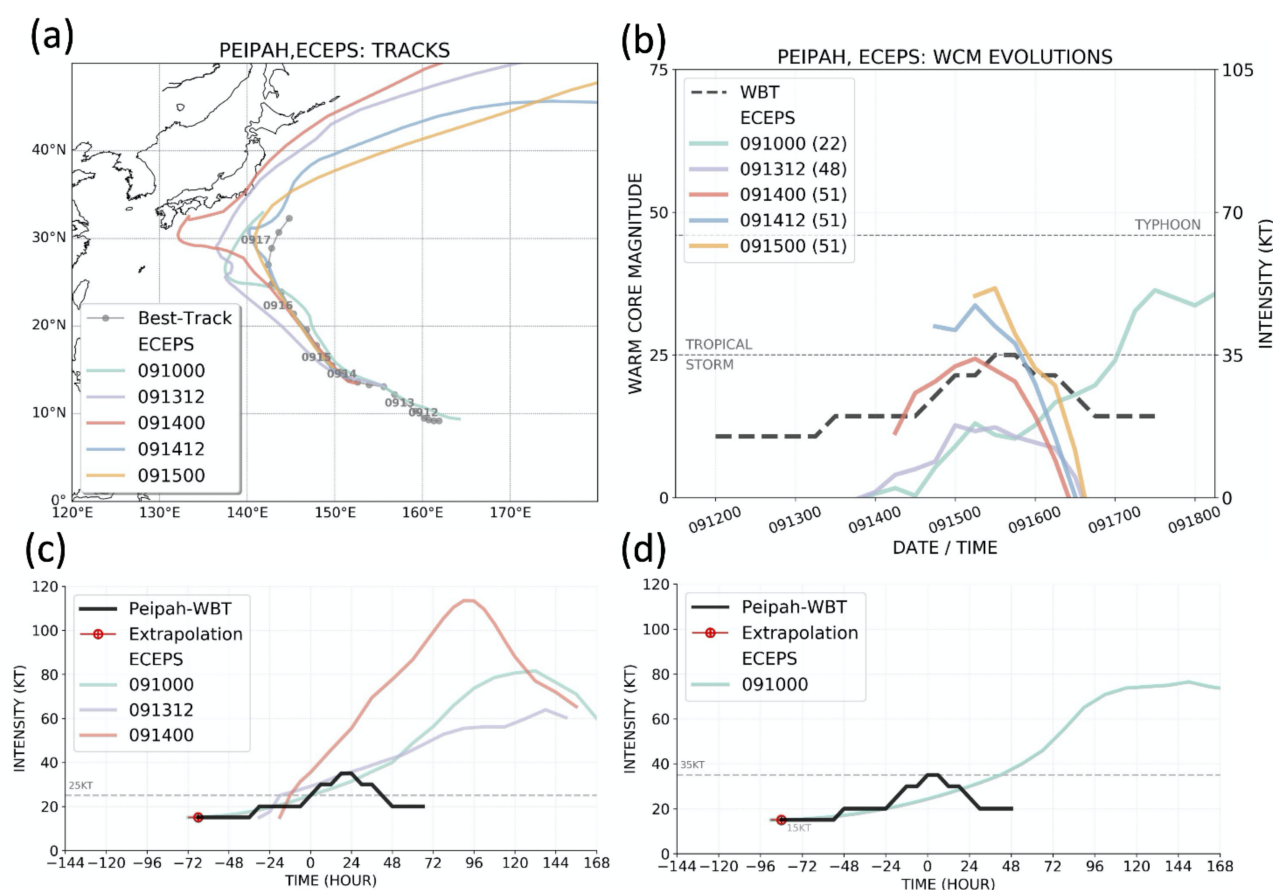

Figure 9. (**a**) Sequence of ECEPS WMVM track forecasts as in Figure 1a, except for pre-TS Peipah with a T2F (25 kt) of 18 UTC 14 September and a T2F (35 kt) of 12 UTC 15 September and an ending time of 12 UTC 17 September near 32° N, 145° E. Note that there is a 3.5 day gap between the first track forecast from 00 UTC 10 September which ended near 34° N, 142° E, and the second track forecast from 12 UTC 13 September, which recurved near 30° N, 137° E and then passed near the coast of Japan. (**b**) ECEPS-predicted Warm Core Magnitude evolutions as in Figure 1b except for pre-TS Peipah that had JTWC WBT intensities (kt, black dashed line, right ordinate). Pre-TS Peipah circulation modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (25 kt) in panel (**c**) and T2F (35 kt) in panel (**d**), and the JTWC WBT intensities are in the black lines. Note that only the first ECEPS forecast from 00 UTC 10 September had a WCM exceeding the Tropical Storm threshold in panel (**b**) that triggered a T2F (35 kt) WAIP intensity prediction in panel (**d**).

It is noteworthy that with the T2F (35 kt) estimate and the WMVM track forecast in Figure 9a, the WAIP intensity prediction was that the Peipah circulation would intensify to 75 kt at 96 h and maintain that intensity through 168 h after the T2F (35 kt) (Figure 9d). Given that this ECEPS forecast with a maximum of 22 ensemble members is predicting a track toward Japan as well as crossing a major maritime shipping lane, and with the WAIP intensity predictions of a typhoon based on both the T2F (25 kt) and the T2F (35 kt), presumably the forecaster should issue at least an alert of a Typhoon threat.

What complicates the situation is there was then a 3.5 day gap between the first ECEPS forecast and the next ECEPS forecast from 12 UTC 13 September, which had 45 of a possible 51 members and had pre-Peipah beginning at 13.2° N, 155.7° E, and later had a track brushing the south coast of Japan (Figure 9a). The next ECEPS forecast 12 h later starting from 00 UTC 14 September had an even longer track passing along the southern coast of Japan so the circulation would be moving over the Kuroshio ocean current. Both of these ECEPS forecasts had T2F (25 kt) times that were slightly early, and then the modified WAIP intensity predictions were ~65 kt and ~110 kt, respectively (Figure 9c). By contrast, neither of these forecasts had WCMs that surpassed the WCM = 25 threshold indicating a T2F (35 kt) time (Figure 9b). Consequently, no WAIP intensity predictions were triggered for these two ECEPS forecasts, which would be a conundrum for the forecaster when the T2F (25 kt) had led to such strong WAIP intensity forecasts.

Elsberry et al. [1], their Figure 7c also provide the GEFS forecasts from 12 UTC 13 September, and not only was the WCM threshold for a TS not met, the T2F (25 kt) was not met until 00 UTC 20 September, which was too late to initiate a 7-day WAIP intensity forecast. Because Elsberry et al. (2020) had repeatedly documented that the model physical processes in the GEFS were more active than in the ECEPS, the fact that the GEFS forecasts did not indicate a Tropical Storm would have given the forecaster a basis to not re-initiate an alert after the 3.5 day gap, even though the first ECEPS had seemed to strongly indicate the threat of a typhoon.

Finally, the last two ECEPS from 12 UTC 14 September and 00 UTC 15 September had accurate track forecasts (Figure 9a) of a recurvature rather than a landfall, neither had weighted-mean intensity exceeding 22.5 kt so there were no WAIP intensity forecasts in Figure 9c for those forecast times. While both of these forecasts had initial WCM values above the threshold for a Tropical Storm (Figure 9b), those WCM values then quickly decreased to zero, which indicated extratropical transition so no WAIP forecasts were generated (Figure 9d).

The purpose of this discussion of pre-Peipah forecasts has been to emphasize the need for forecaster involvement for interpreting these T2F-WAIP predictions in conjunction with other guidance. Secondly, this case indicates that FV3 GEFS-based forecasts should also be tested for their performance so that an alternative to the ECEPS is available for confirmation. We are confident that the forecasters will quickly learn the characteristics of each version and how to access the level of threat of a typhoon, and now be able to issue alerts or warnings earlier with WAIP analogs that include (or do not include) the second modification to optimize the RI events when the Likely Storm Category is for (is not for) a Typhoon, and with the WAIP peak intensity timing and magnitude, the forecasters will have an opportunity to provide better typhoon risk management guidance.

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Appendix A

Appendix A.1. Methodology for Improved WAIP Peak Intensity Magnitude and Timing

In the Tsai and Elsberry [11] bifurcation version of the WAIP intensity prediction technique, all members of Cluster 1 with the largest peak intensities were combined by simply weighting each of the Cluster 1 analog intensity evolutions by the same weighting factors for combining the tracks to provide the WMVM track forecast. As indicated in Section 1, such a simple mean of the analog peak intensities that occur at different times after the T2F results in an extended time period of level intensities rather than a well-defined time and magnitude of the peak intensity. An example of the original WAIP peak intensities is provided in Figure A1a for the same nine ECEPS forecasts for the pre-TY Lingling T2F (22.5 kt) WAIP intensity predictions in Figure 4a. For the seven ECEPS WAIP peak intensities between 85 kt and 100 kt, there is a tendency to have a 12–24 h period of level (near-constant) peak intensities. Note also that the last (090112) forecast has a slow rate of decay over 2–3 days.

An important modification of the bifurcation version of the Tsai and Elsberry [4] combined three-stage 7-day WAIP technique has been to implement a weighted Cluster 1 peak intensity magnitude (V_p) and peak intensity time (T_p), which are computed again using the same weighting factors as for the track forecasts. In a second step following the determination of the V_p at the time T_p, a cubic spline interpolation is applied to the original WAIP intensities at T_p-30 h and T_p-24 h in advance of T_p and after T_p applied to the WAIP intensities at T_p+24 h and T_p+30 h to obtain a smoothly varying intensity evolution from T_p-24 h through the V_p at T_p and descending through the WAIP intensity at T_p+24 h. The third step is to replace the original WAIP intensities at T_p-24 h and T_p+24 h with the cubic spline interpolated values to ensure that all of the WAIP intensities between T_p-30 h and T_p+30 h are smoothly varying.

The modified WAIP peak intensities for the same nine ECEPS forecasts for pre-TY Lingling in Figure A1a were shown in Figure 4a and are repeated here in Figure A1b. Note that the modified peak intensities of the seven larger peak intensities in Figure A1a are now 10–15 kt larger with well-defined peak intensities that are in much better agreement with the JTWC WBT peak intensity. Furthermore, these modified peak intensities magnitudes and timings also lead to much better agreement with the JTWC WBT during the decay stage. Modification of the WAIP peak intensity of the last (090112) ECEPS forecast in Figure A1b is more realistic in timing, which improves the transition to the decay stage.
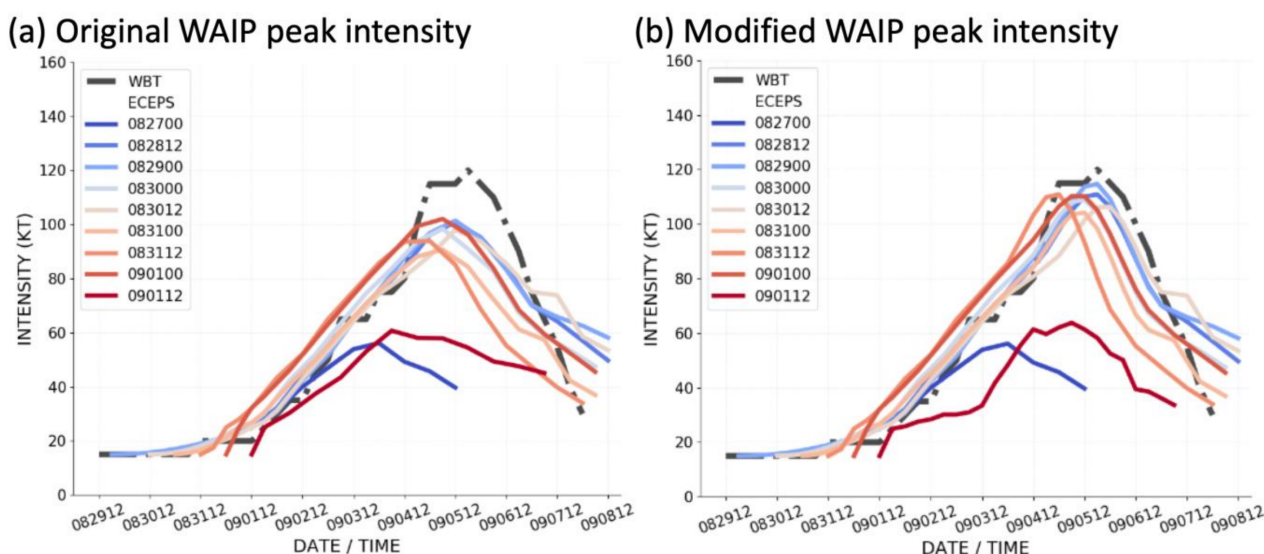
Figure A1. Pre-Lingling circulation WAIP intensity (kt) forecast verifications for the ECEPS T2F (25 kt) as in (**a**) Original combined WAIP of Tsai and Elsberry [4] and (**b**) as modified in this study to improve peak intensity magnitude and timing. Note that panel (**b**) is a repeat of Figure 4a.

Appendix A.2. Modified WAIP Intensity Predictions for Typhoon Neoguri (2019)

The ECEPS-based WAIP intensity error patterns for pre-Typhoon Neoguri (Figure A2) were quite similar to those for pre-TY Lingling (Figure 5). Although there were only three ECEPS forecasts (Figure A2, inset) that matched well the pre-formation WMVM track, the starting times of these pre-Neoguri circulations in the ECEPS forecasts were 48–66 h prior to the T2F (35 kt). As was the case for pre-TY Lingling, the T2F (35 kt) predictions of Neoguri were consistently early by about one day, and thus the modified WAIP intensification stage predictions up to ~60 kt were relatively good but were one day early. Similar to pre-TY Lingling, the predicted WAIP peak intensities were well below the Neoguri peak intensity of 95 kt, which had followed an RI event of 45 kt in 24 h.

The intensity MAEs and MBs for these ECEPS-based WAIP predictions for Neoguri (Figure A2b) are also similar to those for pre-TY Lingling (Figure 5b). During the pre-T2F (35 kt) period, the intensity MAEs begin at zero at tau—66 h and slowly increase to ~10 kt, and then continue at this magnitude until the cross-over time between the WAIP predictions and the rapidly increasing WBT intensities. Then the MAEs reach maximum values at time of peak intensity of Neoguri when the MBs reach maximum negative values due to the WAIP under-predictions of the peak intensity magnitude at the correct time. Finally, the MAEs and MBs reduce to zero at the second cross-over of the WAIP predictions with the intensity decay stage of Neoguri.

Since these three ECEPS forecasts have detected the pre-Neoguri circulation from—48 h to 66 h in advance of the formation (35 kt), the associated WAIP intensity forecast errors for the Neoguri peak intensity roughly 3 days later with a maximum MAE of ~25 kt may be acceptable. The primary error source of that peak intensity is clearly due to the one-day error in specifying the T2F (35 kt) as a one-day decay in the beginning of WAIP prediction to the correct time would have minimized the intensity errors during the intensification stage and minimized the WAIP prediction errors in the peak intensity timing.
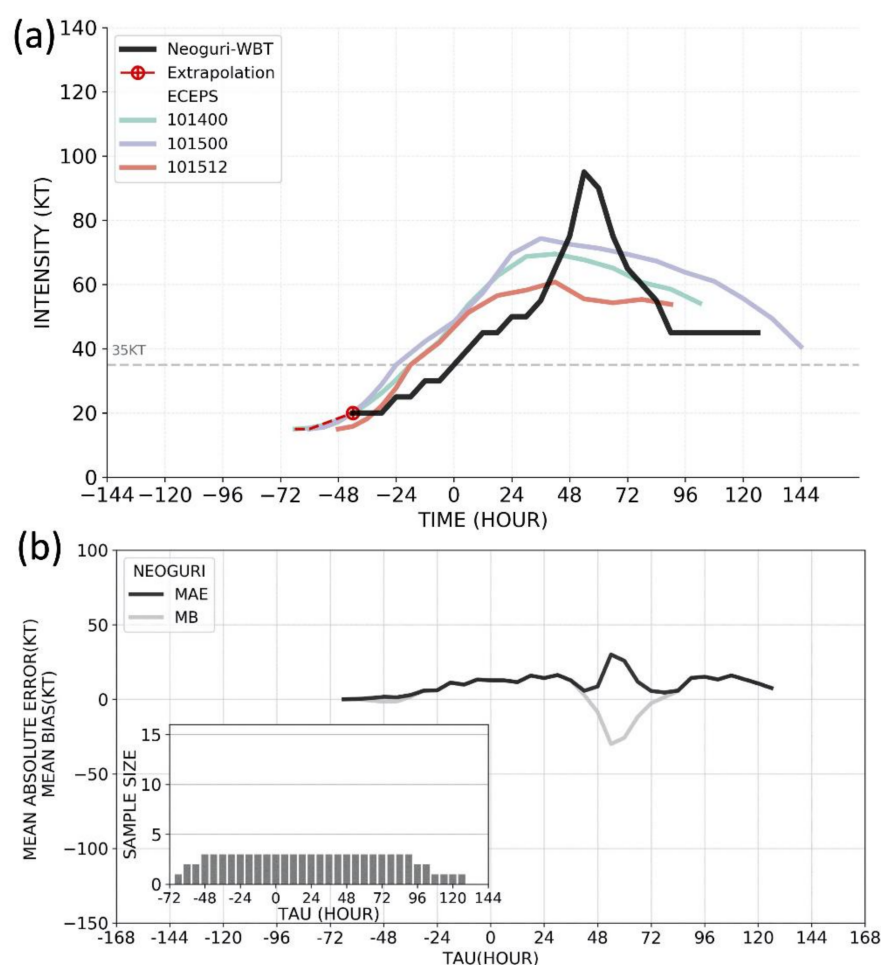
Figure A2. (**a**) Modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (35 kt) as in Figure 5a, except for the pre-TY Neoguri (2019) circulations. (**b**) Intensity MAEs (solid line) and intensity MBs (gray line) as in Figure 5b, except for pre-TY Neoguri.

Appendix A.3. Modified WAIP Intensity Predictions for Supertyphoon Halong (2019)

Pre-STY Halong was somewhat similar to pre-STY Hagibis described in Section 4d in that it formed far to the southeast near 11° N, 160° E and even later in the season in early November. The ECEPS forecast from 12 UTC 26 October had an early detection (174 h prior to T2F (35 kt)), but there was then a 4-day gap before the next detection in the 12 UTC 30 October ECEPS forecast. Not only was the T2F (35 kt) accurately predicted (−6 h), the WMVM track forecast position at formation time was accurate (not shown; 0.11° latitude to the south and 2.03° longitude to the east). Furthermore, the maximum WCM indicated that the pre-Halong circulation would likely become at least a strong Tropical Storm. All but one of the subsequent ECEPS forecasts prior to T2F (35 kt) also had accurate formation times (Figure A3a) with accurate positions (not shown).

The question is then why did the modified WAIP predictions based on the ECEPS forecasts so under-predict the intensity of STY Halong? During the first 24 h after the T2F (35 kt), the WAIP intensification rates were accurate, but Halong then intensified 90 kt in 48 h. It is clear from the small WAIP intensification rates that the historical analog intensities selected for the WAIP predictions did not include RI events, let alone the extreme RI magnitude of Halong. As was the case for pre-STY Hagibis, the explanation is that the historical analogs in the far southeastern region, and within ±30 days of 1 November, do not have the kind of RI event observed in Halong. Consequently, all but one of the WAIP intensity predictions in Figure A3a reach Typhoon intensity at roughly the correct peak intensity time, but the weighted-means of the analog intensities have leveled-off at

magnitudes between 70 knots and 80 knots. The modification of these peak intensities with a cubic spline is not triggered in this pre-Halong case due to the absence of RI events among the analogs in that formation region late in the typhoon season.

As indicated in Figure A3b, the early detections and the accurate T2Fs (35 kt) lead to very small MAEs with only small MBs through 18 h after those T2Fs, which is when the extreme RI event of Halong began (Figure A3a). Extremely large MAEs are found at the peak intensity time of Halong. However, the MAEs decrease rapidly during the Halong decay stage as the WAIP predictions also have decaying intensities, because the ECEPS WMVM track forecasts correctly predicted the recurvature time of Halong (not shown), and those recurvature track forecasts are a critical component of the WAIP analog selection. Thus, the signature large MAE due to a large negative (under-forecast) intensity bias error occurs for the pre-Halong case (Figure A3b) as it did in the pre-TY Lekima case (Figure 5b), pre-TY Bualoi case (Figure 7b), pre-STY Hagibis (Figure 8b), and to a lesser extent in the pre-TY Neoguri (Figure A2). In general, the larger the peak intensity of the Typhoon, the larger the under-forecast of the peak intensity by the WAIP, and thus the larger MAEs at the time of the Typhoon peak intensity. For this pre-STY Halong case and several others in which the modification of the peak intensity and timing was not applied (Table 1, column 4), further improvement in the criteria and methodology for the modified peak intensity are required to decrease the MAEs and MB at peak intensity.
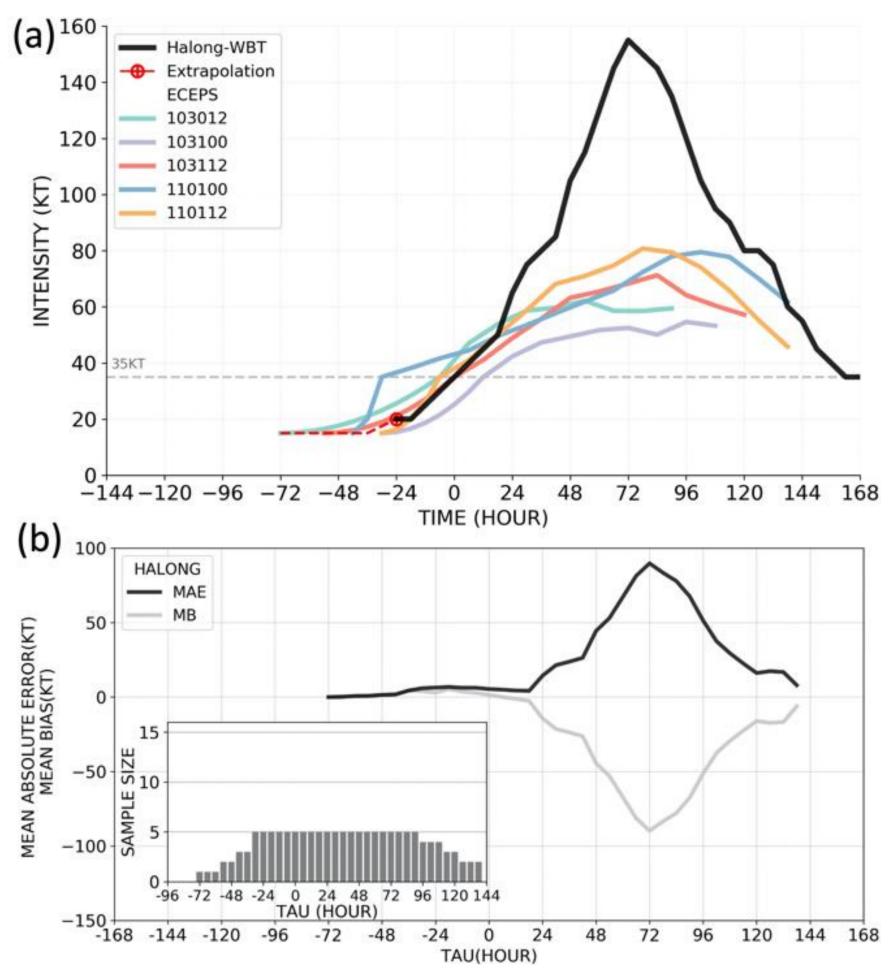

Figure A3. (**a**) Modified WAIP intensity (knots) forecast verifications for the ECEPS-predicted T2F (35 kt) as in Figure 5a, except for the pre-STY Halong (2019) circulations. (**b**) Intensity MAEs (solid line) and intensity MBs (gray line) as in Figure 5b, except for pre-STY Halong.

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