Submitted to: OAR Office of Weather and Air Quality (OWAQ)

Federal Grant Number: NA17OAR4590139

Project Title: Ensemble-based pre-genesis watches and warnings for Atlantic and North Pacific tropical cyclones

Principal Investigator: Russell L. Elsberry, Senior Research Associate, University Colorado-Colorado Springs; relsberr@uccs.edu (c) 831-747-0757

Submission Date: January 31, 2019

Recipient Organization: Trauma, Health, Hazards Center, 1420 Austin Bluffs Parkway, Colorado Springs, CO 80918

Project/Grant Period: 07/01/17 to 06/30/19

Reporting Period Start/End: 06/30/18 – 12/31/18

Reporting Timeline: Year-2 first semi-annual report of a 2-year project

1. ACCOMPLISHMENTS

The objective of this proposal is to provide guidance products for the National Hurricane Center (NHC), Central Pacific Hurricane Center, and the Joint Typhoon Warning Center (JTWC) for the production of pre-genesis watches and warnings of Atlantic and eastern North Pacific, Central North Pacific, and western North Pacific, respectively. These guidance products will be based on the NOAA Global Ensemble Forecast System (GEFS) and the European Center for Medium-range Weather Forecasts (ECMWF) ensemble forecasts and will provide the genesis time and location along the Weighted-Mean Vector Motion (WMVM) ensemble storm tracks, and also the Weighted Analog Intensity Atlantic (WAIA) or corresponding Pacific (WAIP) intensity and intensity spread forecasts to seven days.

The proposed ensemble-based guidance, which includes the deterministic model forecasts plus either 20 (for GEFS) or 50 (for ECMWF) perturbed ensemble members, has the advantage of providing uncertainty information so that a probability metric or uncertainty in genesis timing, track, and intensity are also specified. Such uncertainty information is critically important for genesis (and intensity) forecasting because the tropical cyclone genesis depends not only on the environmental forcing that is relatively well forecast – rather, the precise timing and location of tropical cyclone genesis depends on mesoscale convective systems and convective-scale systems that are not well observed or well forecast. Ensemble prediction systems that include perturbed initial conditions and physical processes such as convection are intended to represent both the environmental and convective scale uncertainty that are not represented in the corresponding deterministic model forecast that represents a single model solution. The GEFS and ECMWF ensemble have the potential to predict formation of tropical cyclones from African Easterly Waves (AEWs) or other equatorial waves as well as the monsoon depressions, hybrids, etc. that are listed in program priority JHT-4 in the Announcement.

As will be described in detail below, the major advancement during the last half of 2018 has been to develop a procedure for specifying the T2F from the GEFS forecasts of 33 TCs during the 2017 season (not the 2018 season because best-track validation datasets are required for this development). This procedure uses a modified Hart (2003) Cyclone Phase Space (CPS) diagram to derive the time evolution of a weighted-mean, deep tropospheric Warm Core Magnitude (WCM) that may be used to diagnose the T2F. That WCM diagram also provides a preliminary indication of whether the pre-formation circulation is likely to become a Typhoon (TY), only a Tropical Storm (TS), or only a Tropical Depression (TD), and in conjunction with the GEFS WMVM track forecast also provides a preliminary "ending storm" timing for input to the third stage in the combined three stage WAIP. A similar WCM diagram for the twice-daily 15-day ECMWF ensemble is also in development that can be utilized to confirm the T2F from the four-times-per-day GEFS—based WCM diagram, which has been demonstrated to be more effective in providing the diurnal trend in both the T2F estimates and the likely peak intensities if formation is predicted to occur.

Tsai and Elsberry (2018b) have developed a combined three-stage 7-day WAIP that improves the original Tsai and Elsberry (2015) 7-day version by adding the Tsai and Elsberry (2017b) ending storm stage and the Tsai and Elsberry (2018a) bifurcation version. Tsai and Elsberry (2018b) tested the new combined version with JTWC best-track files (rather than real-time values) for the tracks and for the initial intensity. In addition, Tsai and Elsberry used the best-track file to specify the T2F (i.e., first time ≧ 25 kt) and the ending storm timing due to landfall, extratropical transition (T2ET), or simply non-development within 7 days. In these examples, the GEFS ensemble storm WMVM track forecasts will be the primary input to WAIP for the pre-formation stage. Specifically, the key T2F input to the combined 7-day WAIP will be estimated from the Marchok vortex tracker variables along the GEFS ensemble storm track forecasts. This vortex tracker first checks each 12 h along these ensemble storm track forecasts for a cyclonic circulation and a closed Minimum Sea-Level Pressure (MSLP) contour using an interval of 1 mb, and also checks that the circulation exists at least 24 h. Tim Marchok's "genesis parameters" determined from the Hart (2003) CPS parameters now used are: (i) CPS Low-level warm core (acronym ***V***tL), which is an indication of a warm-core TC if ***V***tL is positive but is negative for a cold-core extratropical cyclone; and (ii) CPS Upper-level warm core (acronym ***V***t***U***) that again will be positive (negative) for a warm-core TC (cold-core extratropical cyclone). In these two acronyms, the ***V***t refers to an integrated thermal wind in the 900-600 mb (**L**ower) layer or the 300-600 mb (***U***pper) layer that Hart (2003) related to either a warm (cold) core for a positive (negative) value.

In this JHT project, we used the Marchok vortex tracker files along the 20 GEFS WMVM track forecasts to calculate weighted-mean Lower-layer warm core VtL and weighted-mean Upper-layer warm core VtU using the same weighting factors as in the WMVM calculation. That is, the CPS parameters associated with that ensemble member that has a 12-h motion vector most similar (least similar) to the past 12-h WMVM vector is given the largest (smallest) weighting factor, so that the spatial and temporal variability in these parameters will be taken into account by the weighting factors. Specifically, a radius-squared dependence is assumed to ensure that the greatest weight is given to the CPS parameters of the ensemble member whose motion vector most closely is aligned with the WMVM.

Our validations of the ECMWF ensemble forecasts in the Atlantic during 2012 (Elsberry et al. 2014) and in the western North Pacific during 2009 (Tsai and Elsberry 2011) revealed that WMVM track forecasts of the ensemble storm cyclonic circulations typically began 2-3 days prior to the National Hurricane Center and the JTWC, respectively, designated that corresponding circulation in nature to be a TC. Our interpretation was that a weak warm core was being predicted by the ECMWF ensemble model (relatively coarse horizontal resolution at that time), but the vortex circulation was not well organized as a compact cyclonic circulation as a TC during that early pre-TC circulation stage. It was only later that the circulation became better organized and intensification began. We also discovered that many of the first entries in the JTWC best-track file had intensities of 25 kt and a better definition of formation may be 35 kt. We also anticipate that for Tropical Storms that further intensify to Typhoons, the 35 kt definition of T2F may also be the beginning time of sustained warm core increases predicted by the GEFS. This definition is consistent with the WAIP pre-formation concept of a slow intensification stage prior to the typical or rapid intensification stage, which in the basic WAIP is predicted by selecting historical analogs with a similar track and initial intensity. Thus, an initial intensity of 35 kt will be specified at this T2F time as diagnosed from the GEFS forecasts in WPAC.

An example of the three-panel diagram used to diagnose the T2F from the GEFS model predictions provided by Tim Marchok is given in Fig. 1. The JTWC best-track for TY Talim (Fig. 1a, black line) starts at 00 UTC 9 September 2017 and an intensity of 25 kt (35 kt) occurs just 6 h (18 h) later, and the best-track ends at 18 UTC 17 September [Fig. 1a, inset] for a total length of 8.75 days. The GEFS ensemble storm WMVM track prediction (Fig. 1a, red line) from 00 UTC 6 September (i.e., 72 h prior to beginning of the JTWC best-track) is matched within the threshold criteria of 5 days and 300 km of the Talim track. Although this ensemble storm has a maximum of seven (of a possible 21) members that are widely spaced (Fig. 1a, grey lines), the WMVM track is an excellent match with the Talim track that starts early on 8 September well to the south of the actual track.

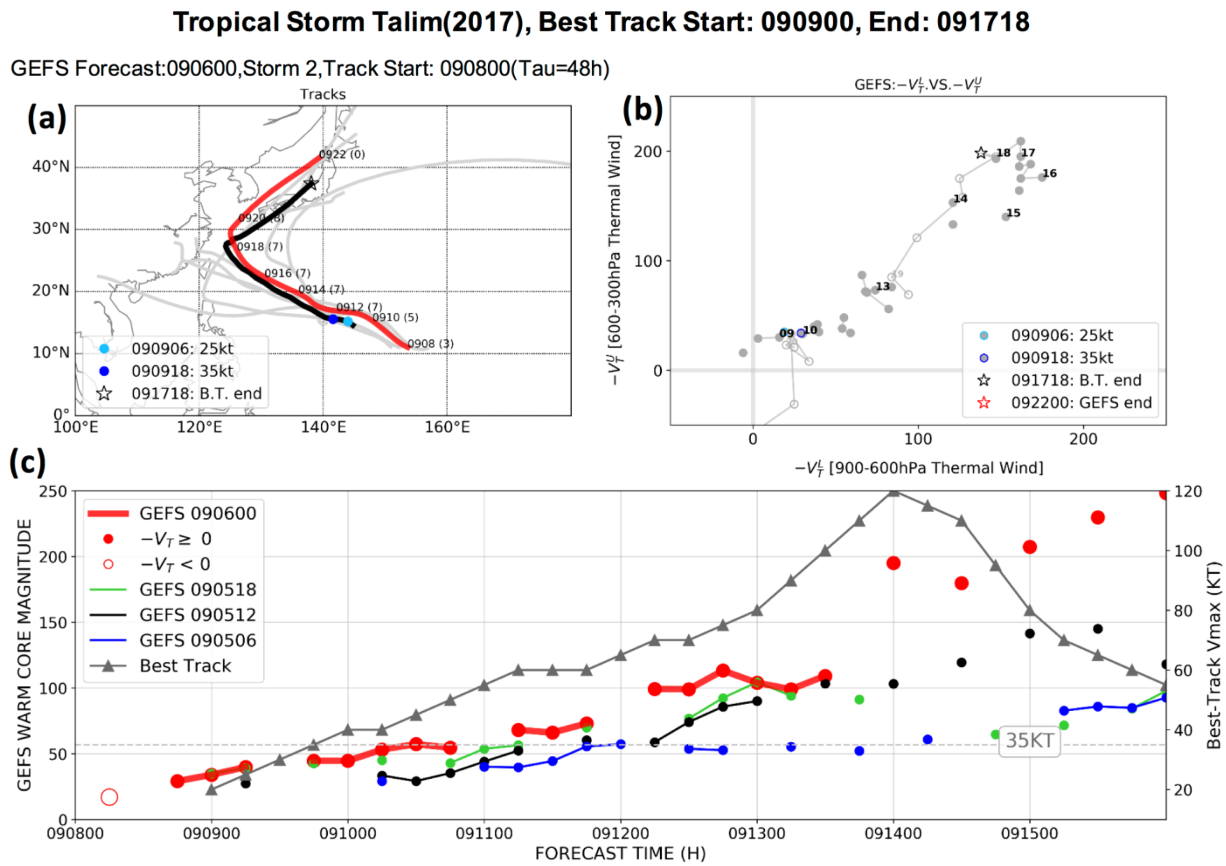

Fig. 1. Example of diagram used to diagnose T2F for Typhoon Talim (2017) matching the 00 UTC 6 September forecast GEFS (a) track and (c) Warm Core Magnitudes (WCMs, left ordinate) with the JTWC best-track and V_{max} (kt, right ordinate). Three previous GEFS forecasts of WCMs are also shown in panel (c; see MMDDHH times in inset). (b) Time evolution (dates at 00 UTC in black) of lower-tropospheric (abscissa) and upper-tropospheric (ordinate) thermal winds that correspond to WCMs in panel (c). See text for further discussion.

Good track agreement is important as the weighted-mean Lower-layer and Upper-layer thermal winds are calculated at 6-h intervals along the WMVM track. The time evolution of these thermal winds for the GEFS forecast is shown in Fig. 1b. Since the primary interest here is the establishment and intensification of warm cores in the two layers, only the upper-right panel of the traditional Hart (2003) CPS diagram is displayed. In this case, the early-stage warm cores tend to be in a small cluster with some scatter, so it is difficult to determine when the warm cores begin to increase in magnitude. Note that the warm core values at the times of 25 kt and 35 kt intensities and last time in the JTWC best-track are indicated by symbols in the inset of Fig. 1b. Even when both layer warm cores do increase in magnitude there is considerable scatter. The time of maximum departure from the origin in this diagram would be expected to be associated with the maximum intensity according to the GEFS forecast. As this model ensemble storm recurves (Fig. 1a), the circulation would be expected to under-go extratropical transition, and this is indicated in Fig. 1b with the open circles that represent cold cores rather than warm cores. In conjunction with the recurvature time along the WMVM track forecast, this transition time from warm core to cold core can be designated as an ending storm time due to extratropical transition in the WAIP forecast procedure.

The warm core magnitude (WCM) is then defined as

$$WCM = [(-V_T^L)^2 + (-V_T^U)^2]^{1/2}\,. \qquad (1)$$

The time evolution of the GEFS WCMs for this forecast (Fig. 1c, red line) and the previous three GEFS forecasts (see line definitions in inset) are plotted relative to the JTWC best-track intensities, and the key 35 kt intensity is indicated by the horizontal dashed line. The rationale to only begin to diagnose the T2F (35 kt) from these ensemble weighted-mean WCMs when a sequence of four consecutive six-hour GEFS forecasts was available was that more confidence could be placed in the T2F timing diagnosis when the GEFS model has "locked into" an increasing warm core solution. The gaps in the early WCM time evolutions in Figs. 1b and 1c occur when a new ensemble member joins the ensemble storm WMVM track forecast because the Marchok vortex tracker does not provide CPS values until two new positions are available to estimate the motion vector.

For this 00 UTC 6 September GEFS forecast (Fig. 1c, red line), the WCMs begin at 06 UTC 8 September with a WGM ~ 15 and by 18 UTC 9 September when the intensity is 35 kt the WCM ~ 50. The WCMs continue to increase (albeit with gaps in time) to values exceeding 100 at the last three times. The GEFS forecasts from 6 h (18 UTC 5 September, green dots) and 12 h (12 UTC 5 September, black dots) earlier have slower WCM increases, but both would indicate an intensification. However, the intensification of Talim was actually much larger (black triangles in Fig. 1c). In this 00 UTC 6 September GEFS forecast, the pre-formation stage of Talim is diagnosed to begin an initial intensity of (say) 20 kt at 06 UTC 8 September and end with the T2F of 18 UTC 9 September. Given these inputs to the pre-formation stage of the combined three-stage WAIP, the intensification stage of WAIP would then start with an initial intensity of 35 kt and the GEFS WMVM track Fig. 1a) from 18 UTC 9 September to 18 UTC 16 September (i.e., 7 days) would be used to predict the intensity of Talim (not shown). Note that no extratropical transition (i.e., cold cores in Fig. 1c) or landfall are indicated in Fig. 1, so the ending storm stage of the combined WAIP will not be a factor in this intensity forecast.

Another benefit from the weighted-mean WCM diagram of the time evolution of the vortex structure changes predicted by the GEFS model as in Fig. 1 will be to detect non-development to a Typhoon or perhaps even to a Tropical Storm (TS; $V_{max} \geq 35$ kt), within the 7-day period of the WAIP forecast. As will be demonstrated below, the weighted-mean warm-core parameters for a Tropical Storm should not have a substantial and/or sustained increase as in Fig. 1c over the next 7 days. Since ending storm conditions of landfall decay time (decreasing Lower-layer warm core) and extratropical transition (cold core versus warm core TC) may also be diagnosed with this weighted-mean WCM diagram, a series of diagnostic case studies will be presented from the 2017 WPAC season.

3a. *Case study of WCM evolution for TY Khanun (2017)*

In this TY Khanun case, a GEFS forecast initiated at 12 UTC 7 October gave an early (-114 h prior to the first entry at 06 UTC 12 October in the JTWC file) indication of a possible typhoon striking Luzon Island and continuing to Vietnam. That is, this was the first time four consecutive GEFS forecasts had WCMs > 50 that would indicate a circulation would at least exceed TS intensity (Fig. 2). This ensemble storm WMVM track forecast began at 00 UTC 10 October (i.e., Day 2.5 in the forecast) near 12°N, 136°E with only four members, but later had a maximum of nine members and the track spread among these members was relatively compact (Fig. 2a). Even though this ensemble storm had less than half of the possible 21 members, it was the fourth consecutive GEFS forecast that predicted a circulation would potentially impact Luzon and Vietnam in addition to maritime activities in the South China Sea.

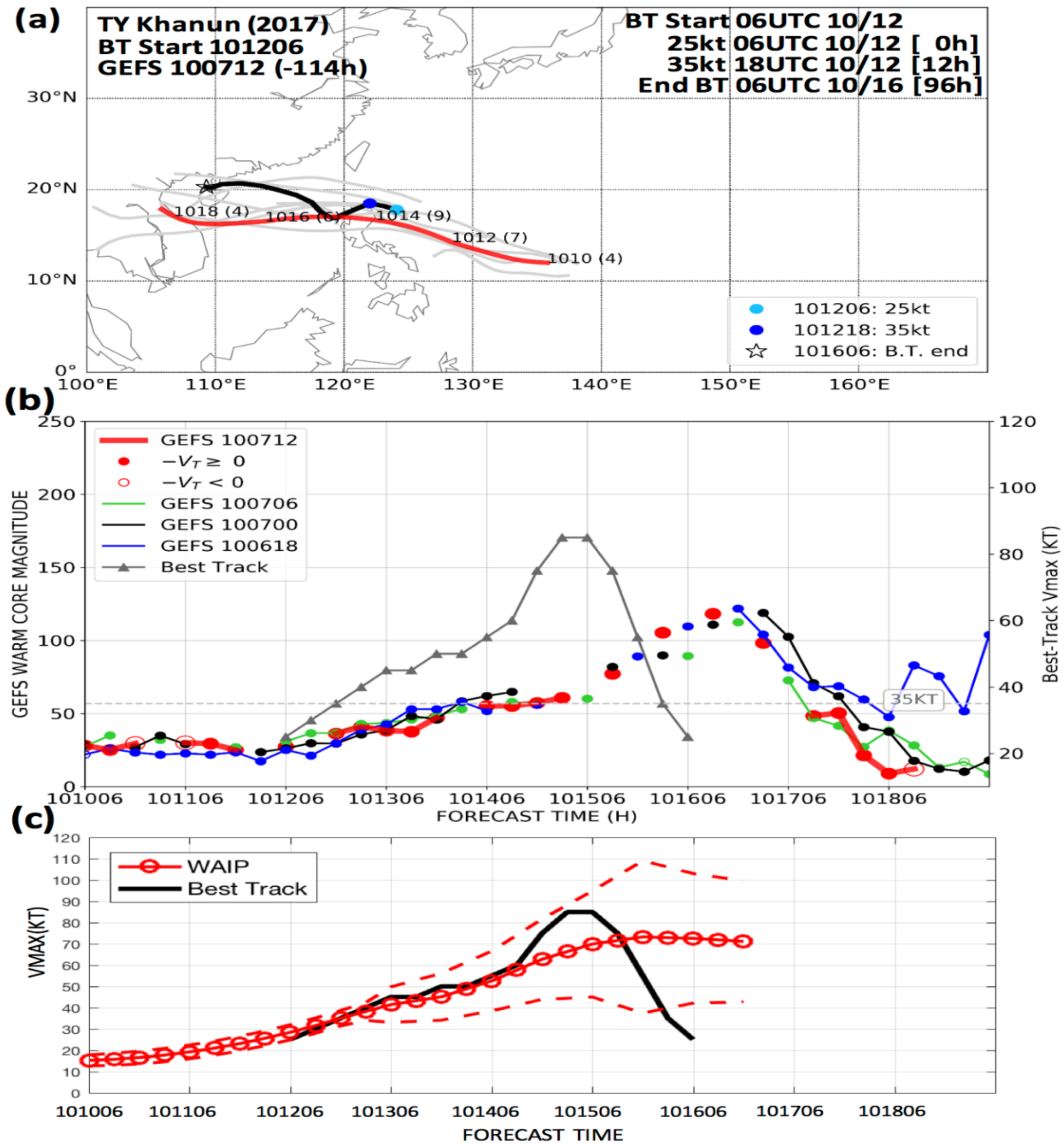

Fig. 2. Warm Core Magnitude (WCM) diagram as in Fig. 1a and Fig. 1c except for TY Khanun (2017) matching the 12 UTC 7 October forecast GEFS (a) track, (b) WCMs with the JTWC best-track and V_{max} (kt, right ordinate) and (c) WAIP intensity (kt, red circles) and intensity spread (red dashed lines) from 06 UTC 10 October with an initial intensity of 15 kt and T2F (35 kt) of 18 UTC 12 October, and with an ending storm condition applied at time of 18 UTC 16 October, compared with the JTWC intensity (black line).

The first indication of a warm core (WCM ~ 25) in this forecast (and two of the other three earlier forecasts) was at 06 UTC 10 October (Fig. 2b). While a circulation with the WMVM track as in Fig. 2a during early October in a normal season would have been expected to have intensified over warm water, all four of these forecasts predicted no intensification for 48 h until 06 UTC 12 October, which was the time of the first entry in the JTWC best-track file at an intensity of 25 kt. A rather subtle WCM increase in all four of these forecasts began at this time and continued until 06 UTC 15 October, when the rate of increase in WCM became larger and eventually the WCMs exceeded ~110 around 12 UTC 16 October. Khanun actually did intensify over a warm ocean current east of Luzon in only 12 h and attained an intensity of 85 kt at 00 UTC 15 October (Fig. 2b, black triangles). The fact that Khanun passed around the northern end of Luzon, but the WMVM track is directly over Luzon may explain why the WCM diagram indicates a delayed intensification until the circulation was well over the South China Sea.

Thus, the GEFS WCMs indicated a possible typhoon stage circulation, but greatly under-estimated the actual intensification rate. According to the WCMs from this GEFS forecast, the circulation had existed for 48 h prior to its first indication in the JTWC file, and the initial intensity at the start of the pre-formation stage (06 UTC 10 October) may be specified at 15 kt. Based on the WCM evolution, we infer the intensification starts at 06 UTC 12 October and (based on many 2017 cases) that 12 h later will be the T2F (35 kt). Furthermore, the combined WAIP ending storm constraint will be applied at 18 UTC 16 October. The resulting combined WAIP intensity forecast and intensity spread are shown in Fig. 2c. Note that the pre-formation stage WAIP intensity forecast merges smoothly with the Khanun intensity trace beginning at 06 UTC 12 October and has very small errors until 12 UTC 14 October when Khanun intensified 25 kt in just 12 h. However, the peak intensity of 85 kt is within the WAIP intensity spread. The rapid decay of Khanun due to its landfall on Hainan Island is not predicted by the combined WAIP based on the GEFS track forecast in Fig. 2a, which has a path to the south of Hainan Island. Thus, from 18 UTC 15 October to the end of Khanun at 06 UTC 16 October the combined WAIP intensity forecast would have increasingly larger over-forecast errors. The JTWC forecaster would need to remind its customers that uncertainty in the timing of landfall in the GEFS track forecast can contribute to large intensity uncertainty. Since the WAIP requires only 1-2 minutes on a desktop computer, the forecaster could quickly test other options for the T2F timing and magnitude and/or landfall timing to further explore whether a typhoon intensity circulation may occur along this WMVM track. The major conclusion is that a T2F diagnosed from a GEFS forecast initiated 114 h prior to the first entry of Khanun in the JTWC best-track file led to an extended intensity prediction from the combined WAIP.

3b. *Case study of WCM evolution for TY Damrey (2017)*

The GEFS WCM diagram (Fig. 3) at the first time (06 UTC 28 October) that the GEFS had four consecutive forecasts with WMVM track forecasts matching the TY Damrey (28W) best-track and having WCM diagrams indicating a potential TC formation. This GEFS forecast was initiated 90 h prior to the first entry in the JTWC best-track, and the WMVM ensemble storm track starts at 18 UTC 30 October near 10°N, 133°E (Fig. 3a, red line). Although the WMVM track starts with only four ensemble members, a maximum of 19 of a possible 21 members are included later in the track forecast, which crosses the central Philippines and later threatens countries in Southeast Asia. Damrey actually starts at 00 UTC 3 November near 10°N, 120°E and within 12 h (24 h) intensified to 25 kt (35 kt).

The first indication of a warm core (WCM ~ 15) in this GEFS WCM diagram (Fig. 3b, red dots) is at 12 UTC 31 October, and then (with some early gaps) a clear indication is given that this circulation has a potential (WCM ~ 180) to at least become a typhoon by 12 UTC 4 November. Note that the previous GEFS forecast initiated at 00 UTC 28 October (Fig. 3b, green dots) also has a similar WCM evolution, and both have WCM ~ 50 at the time that they cross the 35 kt intensity (horizontal dashed line). Although both of these forecasts indicate a potential intensification, the timing is about 18 h late compared to the actual intensification of Damrey. At the time (00 UTC 2 November) Damrey first attained 35 kt, the WCM ~ 35 and the WCM values had not strongly indicated an intensification, as was better indicated after the WCM had reached a value ~50 for both this (red dots) and the previous (green dots) GEFS forecast.

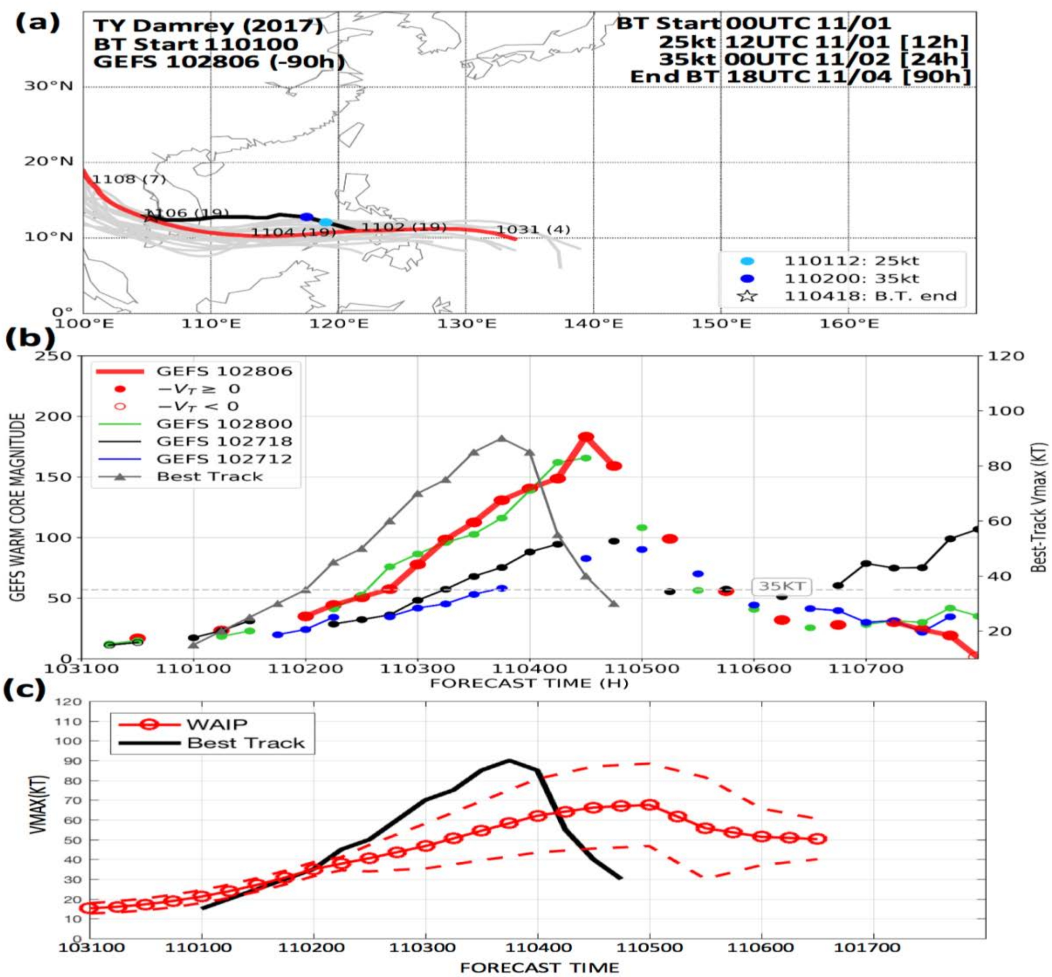

Fig. 3. Warm Core Magnitude (WCM) diagram as in Fig. 1a and Fig. 1c, except for TY Damrey (2017) matching the 06 UTC 28 October forecast GEFS (a) track and (b) WCMs with the JTWC best-track and V_{max} (kt, right ordinate).(c) WAIP intensity (kt, red circles) forecast and intensity spread (red dashed lines) from 00 UTC 31 October with an initial intensity of 15 kt and a T2F (35 kt) at 00 UTC 2 November, and with an ending storm condition applied at 12 UTC 6 October, compared with the JTWC best-track intensity.

Based on the WCMs in Fig. 3b, a combined WAIP intensity and intensity spread forecast (Fig. 3c) is initiated at 00 UTC 31 October with an initial intensity of 15 kt and a T2F (35 kt) at 00 UTC 2 November. The intensification-stage WAIP then begins at this T2F time along the WMVM track in Fig. 3a (red line), which would be over the South China Sea just west of the central Philippines. An ending storm constraint of 50 kt intensity for the selection of 16 analogs for the combined WAIP is set at 12 UTC 6 November based on the GEFS track forecast (Fig. 3a). This WAIP pre-formation intensity forecast beginning 24 h before the first entry in the JTWC files is quite good with an over-forecast of 5 kt at 00 UTC 1 November. Note that Damrey intensified more rapidly (55 kt in 42 h) than in the WAIP forecast, which did indicate a typhoon-stage storm would exist over the South China Sea. Furthermore, Damrey translated more rapidly than in the GEFS track forecast (Fig. 3a), and made landfall on the east coast of Vietnam about 24 h earlier than indicated in the GEFS forecast. Consequently, the WAIP intensity was an under-forecast during the rapid intensification and an over-forecast during the rapid decay (fortunately, the verification would end at 18 UTC 4 October!). Issuing a watch/alert based on this WAIP forecast 24 h before the first entry in the JTWC best-track would have been justified in this Damrey case because the WAIP forecast provided a strong indication of intensification as had been suggested by the WCM evolution.

3c. *Case study of WCM evolution for TS Merbok (2017)*

The GEFS forecast from 00 UTC 6 June predicted a pre-TC circulation would begin 48 h prior to the first JTWC best-track entry (Fig. 4), which is 84 h prior to Merbok becoming a Tropical Storm. Note that the GEFS WMVM track forecast (with a maximum of only 6 of 21 members) started near 8°N, 130°E and traveled along the Philippine islands and recurved at 20°N, 120°E (Fig. 4a, red line). Perhaps due to this track over the islands, the GEFS-predicted WCMs (Fig. 4b, red line) are very small from 06 UTC 8 June to 00 UTC 10 June (beginning of the JTWC best-track) and then only slowly increased to a peak WCM ~ 70 at 06 UTC 12 June. It is noteworthy that this rate of increase in WCM is very similar to the rate of increase in the JTWC intensities (Fig. 4b, grey dashed line) from 15 kt at 00 UTC 10 June to 45 kt at 00 UTC 12 June. Furthermore, the timing of the WCM decreases agrees well with the decrease in intensities of Merbok even though it was due to recurvature and extratropical transition rather than landfall. The earlier GEFS-predicted WCMs from 12 UTC (Fig. 4b, black line) and 06 UTC (Fig. 4b, blue line) 7 June have a similar evolution with very small WCMs until 00 UTC 11 June (rather than 00 UTC 10 June) and then increasing WCMs to peak WCM ~ 50 at 00 UTC 12 June.

Although this GEFS ensemble storm only has a maximum of 6 members out of 21, the GEFS forecast from 00 UTC 6 June 2017 (4 days before first entry in JTWC best-track file) included a maximum of 15 members out of 21 and had a long path over warm water including the Kuroshio ocean current just east of the Philippines (not shown), so a combined WAIP intensity forecast for this storm in Fig. 4a would be of considerable interest to the JTWC forecasters. Since at the starting time of 06 UTC 8 June the WCM is near zero, the initial intensity for the pre-formation stage of the combined WAIP intensity forecast is set at 15 kt. Since the largest WCM value is only 60 at 00 UTC 12 June, it is expected this system will at most become a TS and the more appropriate time to be selected as the T2F is 12 UTC 10 June with an intensity of 25 kt rather than 35 kt. Thus, the pre-formation stage in the combined WAIP with an initial intensity of 15 kt would start at 06 UTC 8 June and the squared function intensity would end with an intensity of 25 kt at 12 UTC 10 June. The intensification stage WAIP would then begin at 12 UTC 10 June with selection of analogs that have similar tracks starting at that time in Fig. 4a and intensities within +/- 5 kt of 25 kt. However, an ending storm constraint on those analog selections will be applied at 12 UTC 13 June (to meet the WAIP requirement for at least a 72 h target track forecast), since by this time the open circles around the WCMs at 12 UTC 13 June in Fig. 4b clearly indicate cold cores and thus an extratropical transition. Here, the ending storm constraint intensity should be no more than 35 kt (rather than 50 kt as in Tsai and Elsberry 2017). This combined WAIP intensity forecast and intensity spread guidance is indicated in Fig. 4c and compared with the JTWC best-track intensities after the first time they are first available (00 UTC 10 June). Note that the intensity spreads are very small prior to the T2F and yet include the verifying intensities over the entire forecast interval, which clearly indicates that this storm will be at most a tropical storm.

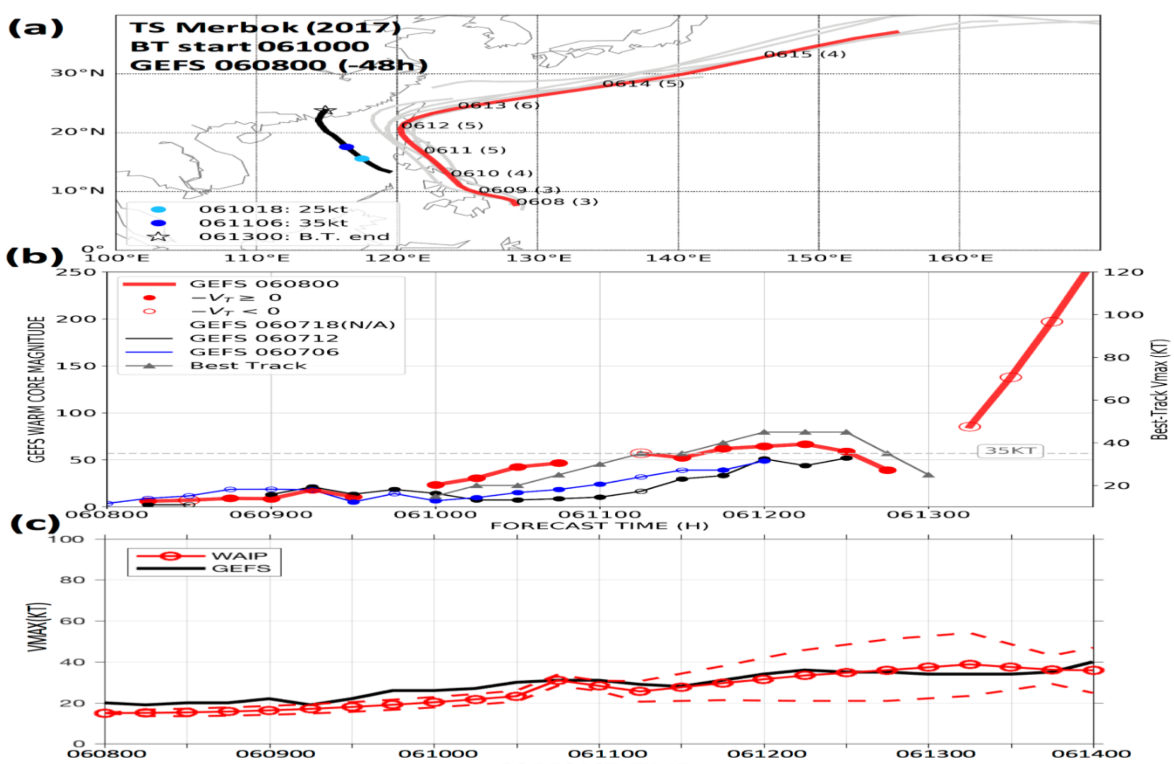

Fig. 4. Warm Core Magnitude (WCM) diagram as in Fig. 1a and Fig. 1c except for TS Merbok (2017) matching the 00 UTC 6 June forecast GEFS (a) track and (b) WCMs with the JTWC best-track and V_{max} (kt, right ordinate). Combined WAIP intensity (red circles) and intensity spread (red dashed lines) from 00 UTC 8 June with initial intensity of 15 kt and a T2F (25 kt) of 12 UTC 10 June versus the JTWC intensities (black line).

In summary, the GEFS-predicted WCM evolution from 00 UTC 10 June (and for only three consecutive forecast times) has a more rapid increase to peak value than might have been expected from the JTWC intensity values that steadily increase from 15 kt to 45 kt at 00 UTC 12 June. Indeed, the WCMs from the four forecasts are all nearly constant in the range of 70 to 80 during the 24-h period that the JTWC intensities increase from 30 kt at 00 UTC 11 June to 45 kt at 00 UTC 12 June. However, it is important that these GEFS forecasts later have decreasing WCMs that are generally consistent with the rapid decrease in JTWC intensities. Thus, the diagnosed T2F to be input in the WAIP will be 00 UTC 11 June and a squared function intensity evolution 00 UTC 10 June to that time starting at 15 kt will be the pre-formation WAIP intensity forecast. Then the basic WAIP will start at 00 UTC 11 June with an intensity of 35 kt and analog selection to match the WMVM ensemble track forecast in Fig. 4a. Note that the ending storm constraint will be enforced in that analog selection due to the landfall. Rather than an analog intensity ending storm constraint of 50 kt, in this case the intensity may be 35 kt. With the short track before landfall, and the initial intensity of 35 kt, there may not be 16 analog tracks available, and especially with the ending storm constraint of 35 kt.

3d. *Case study of TD number 2*

The GEFS WMVM track forecast from 06 UTC 13 April (78 h prior to first best-track entry) has a maximum of 10 ensemble members that are quite compact (Fig. 5a, red line). Although this is an early season pre-TC circulation, the track across the southern Philippines and then poleward over the eastern South China Sea would be of considerable interest to JTWC customers. Whereas the track forecast begins near 8°N, 132°E over a warm ocean region and is translating slowly, this circulation might pose a threat to the southern Philippines, but then the interaction with the other islands adjacent to its poleward track might be an inhibiting factor.

In this GEFS forecast, the initial WCM at 00 UTC 14 April was already at ~50 (Fig. 5b, red dots), which in many of the typhoons and tropical storms described above was an indication of a tropical storm intensity circulation. Two prior GEFS forecasts at 12 UTC 12 April (blue dots) and 00 UTC 13 April (green dots) also had WCM ~ 50 at that time, which indicates that the GEFS has consistently over-forecast this circulation, and this could be easily substantiated with satellite imagery. Whereas the two prior GEFS forecasts continue to intensify (WCM increases) this circulation, this GEFS forecast indicates a slow WCM decrease to a value around 35 at the time of the first entry in the JTWC best-track with an intensity of 15 kt (Fig. 5b, triangles). By this time, the two prior GEFS forecasts had decreasing WCMs to around 50. While TD 02W then slowly increased to 25 kt at 00 UTC 18 April and maintained that intensity until 06 UTC 19 April, in this GEFS forecast the WCM slowly decreased from 45 at 00 UTC 18 April to 30 at 18 UTC 18 April, and then rapidly decreased to become near-zero at 06 UTC 19 April (post-recurvature in Fig. 5a). It was 24 h later that the last entry in the JTWC best-track was posted with an intensity of 15 kt.

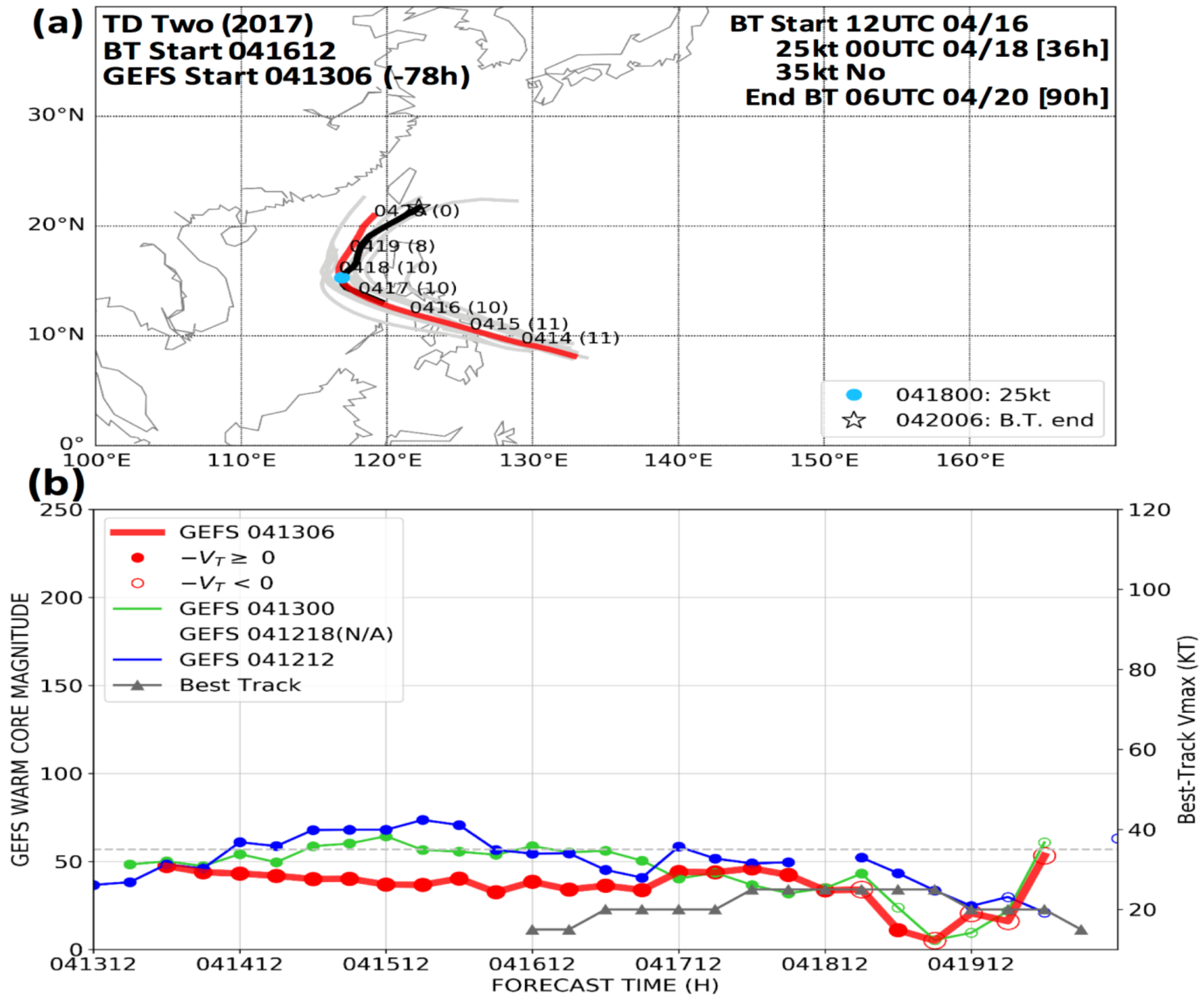

Fig. 5. Warm Core Magnitude (WCM) diagram as in Fig. 4a and Fig. 4b except for TD 02W (2017) matching the 06 UTC 13 April forecast GEFS (a) track and (b) WCMs with the JTWC best-track and V_{max} (kt, right ordinate).

The positive aspect of this WCM diagram is the almost continuous decrease in WCM values, which would indicate a non-development if the satellite imagery at the initial time had indicated that the circulation in the GEFS was not valid. The negative aspect is that it might be difficult to disregard this WCM diagram when the WMVM ensemble storm track is headed to the central Philippines. It would also be misleading to start a WAIP with this track and an initial intensity of even 20 kt since almost all of the historical analogs in the JTWC intensify to at least 35 kt. Thus, it would be advisable to delay any WAIP forecasts until a satellite-validated circulation existed and a more reasonable initial WCM was diagnosed in a subsequent GEFS forecast.

In summary, the WCM evolutions have been produced along the GEFS track forecasts that have been matched with all of the WPAC TCs during the 2017 season. Two examples of Typhoons Khanun and Damrey demonstrate that the GEFS forecasts as early as 114 h before the first entry in the JTWC best-track file can provide the T2F that is required for the WAIP intensity and intensity spread forecast. In both of these typhoons, an ending storm (landfall) time could have been provided for the WAIP from the GEFS track forecast and WCM evolution as well, albeit with a landfall forecast that is a day late. The key point is that these WCM evolutions and the WAIP predictions would have provided an alert/watch at least 5 days in advance of the likelihood that a typhoon would be crossing the South China Sea and making landfall. Furthermore, the WCM evolutions from GEFS track forecasts indicated that the circulation matched with TS Marbok would only achieve an intensity less than typhoon stage, and that TD Two would not in the next 6 days intensify to tropical storm stage. We thus expect that the GEFS-based WCM evolutions will help identify any false alarm circulations in the GEFSs.

2. PRODUCTS

My keynote address at the 9th International Workshop on Tropical Cyclones in Honolulu during 3-7 December 2018 included a discussion of this work. This was an opportunity for discussions with JTWC personnel and planning for an operational test for the WPAC later this year. Discussions were also held with NHC and CPHC personnel. A manuscript entitled "Combined three-stage 7-day weighted analog intensity prediction technique for western North tropical cyclones" was submitted and is being revised. An implementation plan for operational testing at JTWC has been produced.

1. Incorporating the GEFS WCM evolution in JTWC forecast operations

The JTWC has a new Two-week Tropical Cyclone Formation Outlook that highlights geographic areas and time frames that forecasters consider a significant tropical cyclone may form during the next 14 days. As illustrated in Fig. 1, these "Potential Formation Areas" (PFAs) are indicated by colored boxes with yellow, orange, and red for Low (< 40%), Medium (40%-60%), and High (> 60%) probability of formation subjectively estimated by the JTWC forecaster. If JTWC already has an Invest area for that PFA, the box will be labeled with an Invest number P7xW in the western North Pacific. Also indicated at the bottom of Fig. 1 are the time intervals between which the TC formation is expected to occur. An example of the PFA for a particular Invest 99W is given in Fig. 2. Note that the area within which the TC is expected to form is fairly large (10° lat. x 10° long.), and no indication of a track is provided. In this example of an update at 2219 UTC 27 June 2018, the estimated time to formation (1200 UTC 29 June) is provided at the end of the timeline dates from Invest through the Low, Medium, and High probability times plus the expected first warning time. These Formation Outlooks are issued twice daily at 0000 UTC and 1200 UTC, but as illustrated in Fig. 2, they can be updated at any time.

The T2F from the GEFS (and/or ECMWF ensemble) WCM analysis will be blended into the PFAs at 0000 UTC and 1200 UTC. Tim Marchok's vortex tracker files for the 6-h GEFS (twice daily ECMWF ensemble) arrive at JTWC about 7 hours (10-11 hours) after the synoptic times. Since these arrival times are after JTWC has issued its track, intensity, and structure forecasts at the synoptic time + 6 h, but prior to beginning their t + 12 h forecast, the JTWC forecasters can use this time gap for interpretation of the GEFS and ECMWF ensemble storm track forecasts, the WCM-based T2F and the ending storm time along those ensemble storm tracks, plus the WAIP intensity and intensity spread guidance. The earlier the forecasters can monitor the performance (and time consistency) of these products in predicting the formation, track, and intensity for a circulation, the more confidence they will have in issuing their first warnings.

We envision that a close synergy with the JTWC satellite analysis branch will be a benefit. These satellite analysts have access to Himawari-8 imagery as frequent as every 10 minutes to be monitoring circulations that have the potential to form a TC. Thus, the JTWC forecaster interpreting the GEFS-based WCM evolution should begin with knowledge of suspect areas being detected in satellite imagery. Then the forecaster should attempt to match the GEFS ensemble storm track forecasts with the satellite suspect areas (including existing Invest areas). Where a match can be made, the forecaster should examine the WCM evolution for that ensemble storm track forecast, and estimate the T2F based on the examples provided above. In addition to updating the PFA graphic product, the forecaster should coordinate with the satellite analyst and request special attention be given to all circulations in the GEFS forecast that are indicated to form a TC. Specifically, the forecaster should indicate where and when along the GEFS track that formation is predicted, and even provide the satellite analyst the WAIP intensity prediction. This concept of operations with a close synergy with the satellite analysis branch is

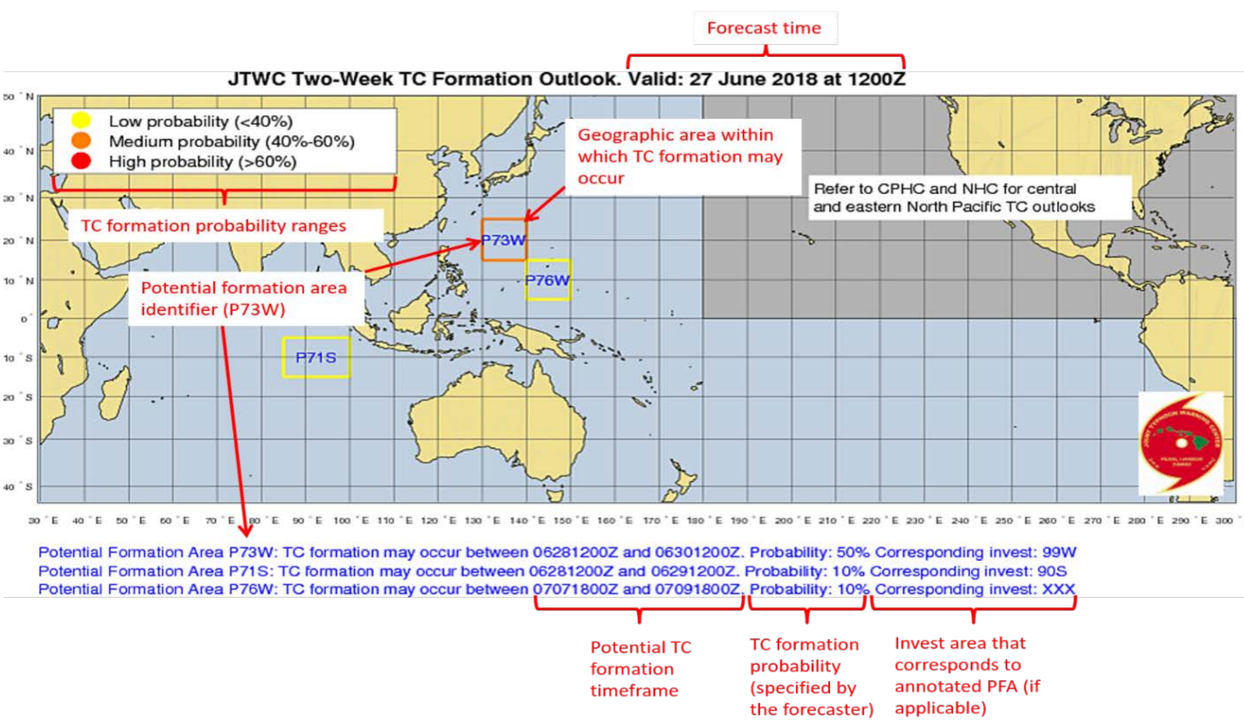

Fig. 1. Two-week tropical cyclone formation outlook provided by JTWC. Potential Formation Areas (PFAs) are indicated by colored boxes (see inset in upper left) [provided by Matt Kucas, JTWC].

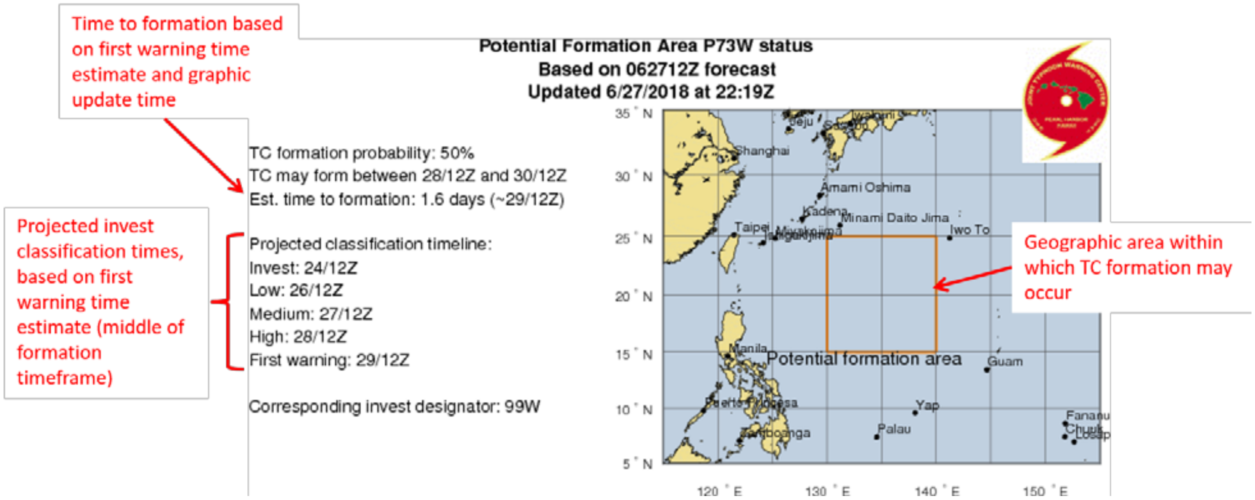

Fig. 2. Example of a PFA that has been updated at 2219 UTC 27 June for an Invest, which indicates the detailed information that is provided when a first warning is expected to be issued [provided by Matt Kucas, JTWC].

expected to contribute to improved timing and accuracy of TC formation, and its subsequent track and intensity.

2. Procedure for diagnosing T2F from WCM evolution

As indicated above, it is suggested that the JTWC forecaster should begin the procedure for diagnosing the T2F as soon as Tim Marchok's vortex tracker files for the latest 6-h GEFS forecast have arrived at JTWC (synoptic time + 7 hours). For this discussion, we will return to the first example of a WCM diagram for TY Talim in Fig. 3c. This case was selected to illustrate a classic recurvature case with a long enough existence that a 7-day WAIP forecast after T2F could be illustrated (very few of the 2017 WPAC TCs had such a long existence). While the GEFS forecast track (Fig. 3a, red line) appears to be excellent, the along-track translation speed was slow. Whereas the end of the JTWC best track at 18 UTC 17 September (Fig. 3a., star at end of black line) is over northern Japan, the GEFS forecast track at that time is just approaching recurvature 10° lat. and 10° long. to the southwest. The WCM diagram (Fig. 3b.) corresponding to this GEFS track forecast was discussed in detail in conjunction with Fig. 1c. Specifically, it was noted that this is the fourth consecutive time that the GEFS has predicted a circulation with a warm core, so that the JTWC forecaster can have some confidence in the WCM evolution (Fig. 3b, red dots) indicating a peak WCM of 250, which according to the schematic in Fig. Z likely corresponds to an intense typhoon. However, this peak WCM at 00 UTC 16 September (Day 10 in the GEFS forecast) is delayed by 48 h from the actual peak intensity of TY Talim at 00 UTC 14 September (Fig. 3b., triangles). Note also the TY Talim had rapidly intensified from 80 kt to 120 kt in the previous 24 h.

In diagnosing the T2F from this WCM diagram, the forecaster should note that the WCM rapidly increased from a value of ~ 10 at 00 UTC 8 September (Day 2 in GEFS forecast) to ~ 50 at 18 UTC 9 September. With the peak WCM indicating a typhoon as in the schematic in Fig. 4, which also implies a more rapid increase in WCM in the early pre-formation stage for typhoons, the JTWC forecaster would be well-advised to designate the T2F as 18 UTC 9 September (which in retrospect would have been correct). By contrast, if the forecaster waits to designate the T2F until the WCMs again rapidly increase following 18 UTC 11 September, this would in retrospect lead to a 2 day delay in starting the combined WAIP intensification stage forecast. Whether this delay is associated with the slow translation speed or the environmental variable prediction in the GEFS forecast is uncertain.

The combined WAIP prediction with the pre-formation stage beginning at 00 UTC 8 September with an intensity of 15 kt (because the vortex was slightly cold core as indicated by the open red circle) and at T2F (35 kt) at 18 UTC 9 September is shown in Fig. T1c. During this pre-formation stage of Talim, the simple squared function intensity forecast is very accurate, and the intensity spread is very small. The combined WAIP intensification stage intensity forecast is less than the actual intensification, but during the first three days after the T2F the verifying intensities are within the combined WAIP intensity spread. However, the rapid intensification from 00 UTC 13 September to 00 UTC 14 September is not forecast by this statistical intensity technique. Since this combined WAIP intensity forecast is based on a GEFS forecast initiated at 00 UTC 6 September, this rapid intensification occurred on Day 6 to Day 7 of that forecast.

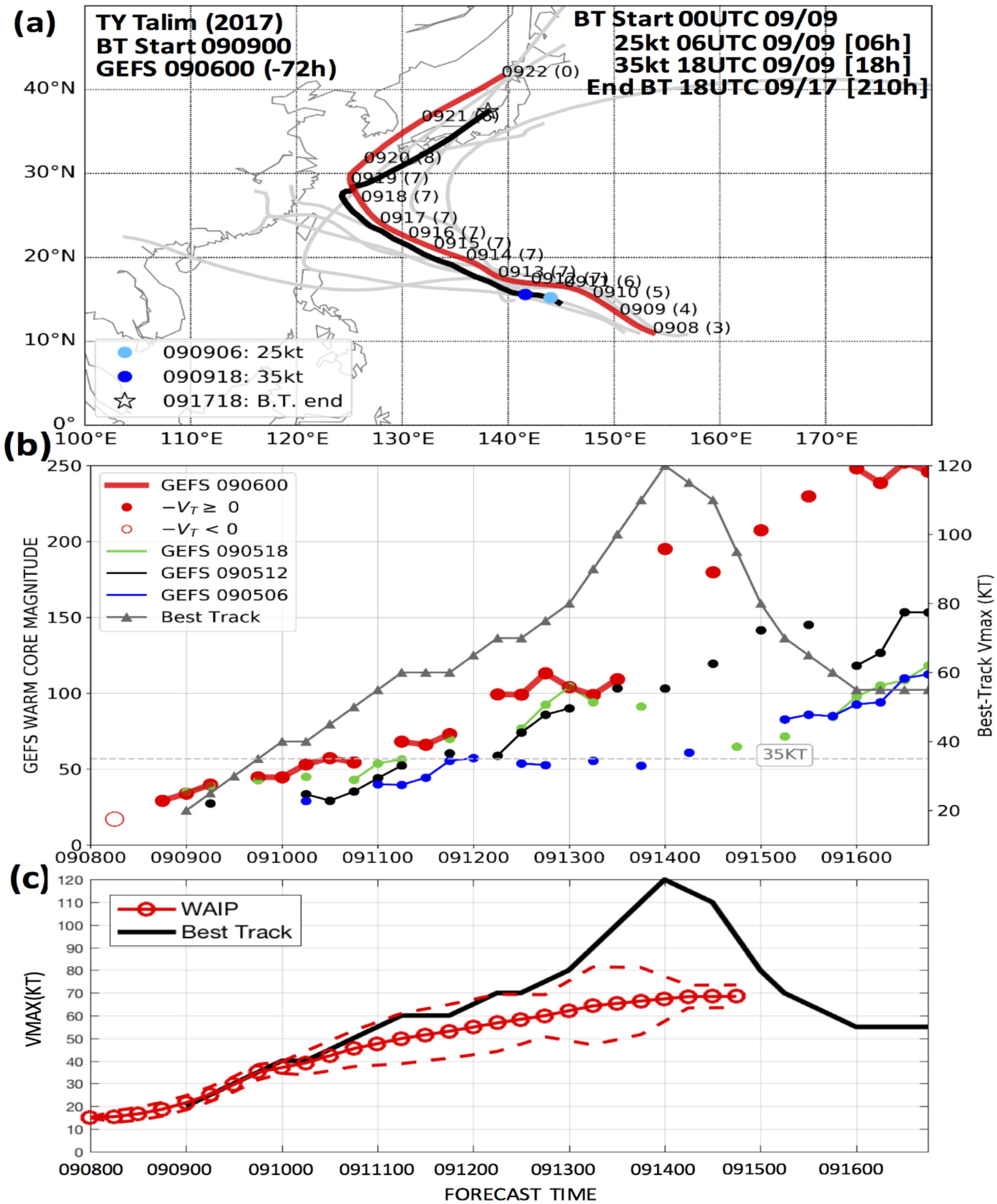

Fig. 3. (a) GEFS-based Weighted Mean Vector Motion (WMVM) ensemble storm track forecast (red line, labeled with month/day and number of ensemble member tracks in gray) matched with the TY Talim track (black line). (b) Warm Core Magnitude diagram for four times (see insert in upper left) and best-track intensity (black triangles), and (c) Combined WAIP intensity (red circles) and intensity spread (red dashed line) versus best-track intensity (black line).

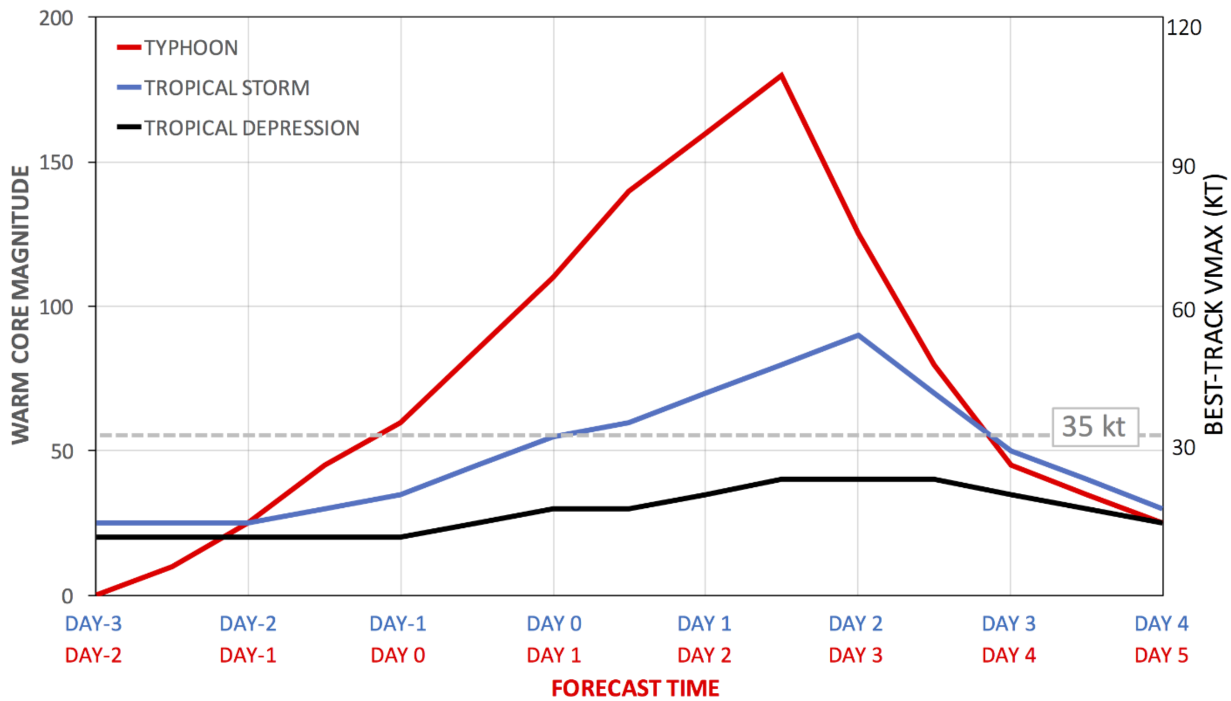

Fig. 4. Schematic of the types of warm core magnitude (WCM) evolutions that would be indicative of a typhoon (red line), a Tropical Storm (blue line), or a Tropical Depression (black line). Day 0 in red numbers (blue) on the abscissa indicates a Time to Formation at 35 kt for the typhoon or a (T2F- 25 kt) when the WCM time evolution has an increased slope in the case of a Tropical Storm.

In real time, and with the suggested procedure to diagnose the T2F after four consecutive times, the forecaster would actually have started by reviewing the WCM diagram from 24 h earlier (06 UTC 5 September, blue dots in Fig. 3b.). The forecaster would have noted that a circulation in the GEFS would begin with a WCM ~ 25 (first blue dot at 06 UTC 5 September), and from 18 UTC 11 September until 06 UTC 14 September the WCM values would have magnitudes of 50 - 55 that indicate the potential for at least a Tropical Depression. Thus, the forecaster would have hypothetically consulted with the JTWC satellite analyst on duty at that 06 UTC 5 September time. Since it was not until 00 UTC 9 September (90 hours later) that the JTWC best-track has the first entry for Talim, and the first position in the GEFS track forecast (Fig. 3a.) is not until 06 UTC 8 September, it is not likely the satellite analyst would have been able to identify a cloud system that might correspond to the feature in the WCM diagram. Therefore, the forecaster would have concluded it was too early to consider this pre-TC circulation in the 06 UTC 5 September GEFS forecast to become a tropical storm. Since the complete combined three-stage WAIP is not executed if the circulation is likely to remain below 35 kt, no intensity and intensity spread plot as in Fig. 3c. would be prepared.

Looking back just 12 h from the time of Fig. 3, the GEFS track forecast (Fig. 5a) initiated at 12 UTC 5 September (84 h prior to first entry in the JTWC best track) has a pre-TC circulation

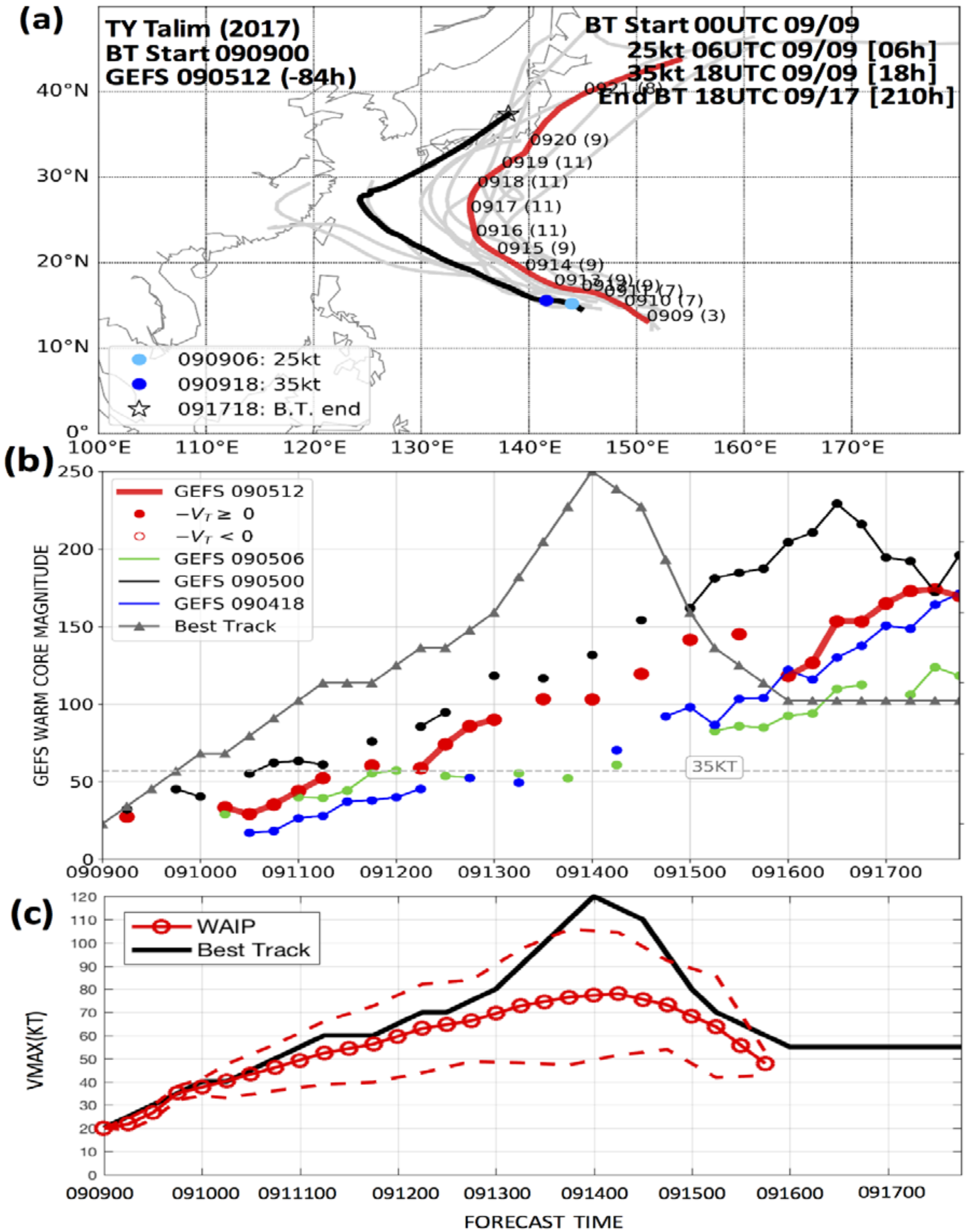

Fig. 5. GEFS ensemble storm track forecast, WCM diagram, and combined WAIP intensity and intensity spread forecast as in Fig. 3 except 12 h earlier at 12 UTC 5 September (84 h before the start of Talim in the JTWC best-track file.

beginning at 06 UTC 9 September (Day 3.75) near (13°N, 150°E). Although the WMVM ensemble storm starts with only three members, it later includes 11 of the 21 GEFS members. Furthermore, the starting time is late (already a TD at 06 UTC 9 September, and a TS at 18 UTC 9 September) and the location to the east, so that it is not surprising that the recurvature point near 26°N, 134°E is also well to the east. Of course, the forecaster would not know this deficiency, but that the WMVM track forecast in Fig. 5a passes just to the east of mainland Japan – and not until 15 days after the initial time of the GEFS forecast.

The WCM diagram for the GEFS forecast at 12 UTC 5 September (red dots in Fig. 5b) again indicates a circulation with an initial WCM ~ 25 has been predicted at 06 UTC 9 September. Although there are some gaps (due to issue with the WCM calculation when a new ensemble member joins the ensemble storm), this circulation is predicted by the GEFS to have increasing WCM values after about 00 UTC 10 September that peak at WCM ~ 175 at 12 UTC 17 September. According to the schematic in Fig. 4, such large WCM values indicate the potential for a typhoon. Even though a consultation with the satellite analyst would probably not find early evidence (t – 84 h from first best-track entry) in the satellite imagery, a heightened interest in this system would be warranted. As mentioned above, the track forecast does not indicate an immediate threat.

Based on the WCM diagram in Fig. 5b, the forecaster should note that at the initial time of 06 UTC 9 September the initial intensity would likely be 20 kt. Although there are some gaps, the WCM values begin to increase by around 18 UTC 10 September. This time/day may then be recorded as the T2F, which is 36 h since the initial time and would be consistent with a likely typhoon. It is also consistent with the combined WCM timing from the 00 UTC 5 September GEFS forecast (black dots in Fig. 5b). Since the ensemble storm track in Fig. 5a is indicating an extratropical transition by 18 UTC 17 September, an ending storm time may also be entered. The WAIP intensity and intensity spread forecast for these inputs is presented in Fig. 5c (red line and red dashed lines). The agreement with the best-track (black line) is quite good through 00 UTC 13 September. However, the rapid intensification during the next 24 h was not forecast, although the peak Vmax of 120 kt was only about 15 kt beyond the upper intensity spread value. Considering that the rapid intensification occurred on Day 8 to Day 9 of the GEFS forecast, the WAIP intensity forecast of at least a typhoon would have been useful guidance.

In another 6 h (18 UTC 5 September, Fig. 6b.), the initial WCM ~35 is at 00 UTC 9 September (third consecutive initial WCM near that time), but the WCM values slowly increase to ~ 50 on 11 September but the peak WCM ~ 100 is at 00 UTC 13 September. Similarly, the WCM evolution from the GEFS forecast 12 h ago (black dots) only indicate a likely tropical storm based on the schematic in Fig. 4. Here it would be important for the duty forecaster would consult with the satellite analyst because the previous GEFS forecast WCM evolution (green dots) as described above had indicated a possible typhoon with a peak WCM value of 150. Furthermore, the GEFS forecast from 18 h ago (blue dots in Fig. 6b) had indicated a possibly strong typhoon. Since the track forecast in Fig. 6a has the pre-TC circulation starting at low latitudes with a long (and slow) track over a warm ocean prior to recurvature, the forecaster should assume a likely typhoon and go with an earlier intensification than in Fig. 6b.

Thus, an initial intensity of 20 kt at 18 UTC 8 September is specified for the combined WAIP forecast. Following the above interpretation of Fig. 6b, an early T2F of 18 UTC 9 September is specified. Furthermore, an ending storm time of 18 UTC 15 September (7 days) is assumed in anticipation that the time to recurvature is being under-forecast. The combined WAIP intensity and intensity spread forecast (Fig. 6c) is highly accurate again until the rapid intensification begins on 00 UTC 13 September. The intensity spread is quite large in this case, which indicates a large uncertainty for this type of track. Because of this large spread, the peak Vmax is only 10 kt beyond the upper intensity value.

After having reviewed these three previous WCM diagrams and the WAIP forecasts, the forecaster would return to the current WCM diagram in Fig. 3b. (00 UTC 6 September GEFS forecast) to diagnose a T2F. First, an open red circle indicating a slightly cold core is predicted at 06 UTC 8 September, and then the WCMs are constant at ~ 50 during 10 September and constant at ~ 60 on 11 September. However, the WCMs then irregularly increase to ~ 100 from 06 UTC 12 September through 12 UTC 13 September, and ~ 200 on 14 September with a peak WCM value of 250 at 00 UTC 16 September. These WCMs from 00 UTC 14 September to 00 UTC 16 September clearly indicate a potential for a typhoon according to the schematic in Fig. Z. The GEFS track forecast (Fig. T1a) along which these WCM values from 8 – 16 September apply is for a long path over a warm ocean that would be consistent with formation and intensification to a typhoon. Furthermore, this ensemble storm track indicates a potential threat for a landfall anywhere between Taiwan to mainland Japan. Now a consultation with the satellite analyst given the initial track position on 8 September, which is Day 2 in the forecast and ~ 24 h before first entry in best track, would likely detect a cloud system within the monsoon trough that could be associated with this GEFS ensemble storm.

Recall that the WCM diagram in Fig. 3b is the fourth consecutive GEFS forecast with a WCM evolution that now indicates that the potential for a strong typhoon, and the GEFS track forecast in Fig. 3a indicates that the typhoon will be a threat to maritime activities and to islands off the east coast of Asia. Consequently, JTWC may well decide to at least issue an alert/watch based on this GEFS forecast initiated 72 h before the first entry in the JTWC best-track file. To also provide a WAIP intensity and intensity spread forecast, a T2F is required. Based on the WCM evolution in Fig. 3b, if the open red circle at 06 UTC 8 September (and with the track forecast position in Fig. 3a) taken as the start of the pre-formation period (at 15 kt because it was slightly cold core), the T2F (35 kt) might be the first time the WCM ~ 50, which would be 18 UTC 9 September. Thus, the pre-formation stage would be 36 h in length, which is rather long for the WPAC when the track is over a warm ocean region as in Fig. 3a.

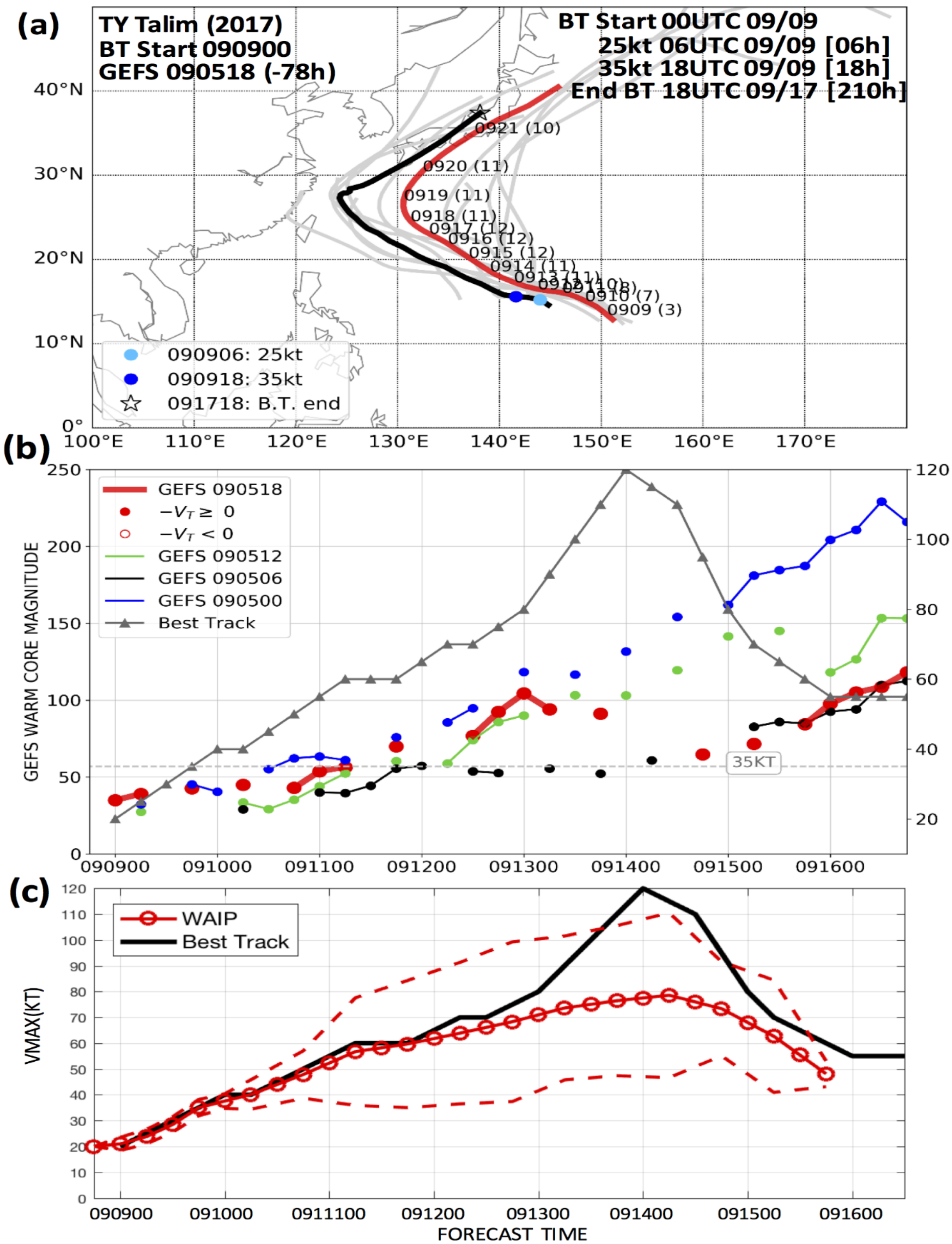

Fig. 6. GEFS ensemble storm track forecast, WCM diagram, and combined WAIP intensity and intensity spread forecast as in Fig. 3, except 6 h earlier at 18 UTC 5 September (78 h before the start of Talim in the JTWC best-track file).

3. Decision tree for diagnosis by JTWC forecaster of T2F from WCM evolution

1. At approximate synoptic time (t) plus 7.5 h, JTWC forecaster checks that Tim Marchok's vortex tracker files for the latest GEFS forecast have arrived and have been automatically processed for all pre-formation circulations in the WPAC Area of Responsibility (AOR).
    a. Track forecasts of circulations have been matched to be within 300 km weighted-mean distance of any similar pre-formation circulation track forecasts from the previous (or the t - 12 h forecast if the t - 6 h forecast was missed) GEFS forecast in order to identify a sequence of Warm Core Magnitude (WCM) time evolutions. Even if this is now only the second consecutive GEFS forecast, a WCM diagram as in Fig. 3b will have been prepared for the forecaster to evaluate.
    b. If no match with a similar pre-formation circulation in the previous GEFS forecast has been established, the circulation will next have been considered to be a potential false alarm. That is, the WCM values in this forecast will have been checked to determine if the peak WCM < 25, which would indicate lack of development. If a match of its track forecast with the false alarm track forecasts from the previous GEFS forecast, had confirmed that this was a persistent false alarm, this pre-circulation would have also been added to the false alarm file.
    c. If neither check (a) nor the false alarm check (b) applied, this pre-TC circulation would have been recognized as a candidate for TC formation. While this "first-time" to formation candidate will be presented to the forecaster, we suggest that a sequence of three or more consecutive GEFS forecasts have WCM evolutions that also indicate a TC formation. However, and especially if the GEFS track forecast indicates a threat of landfall or impacts on maritime activities, the forecaster will have the option to proceed to Step 2 to get an early determination of the T2F and other inputs to produce a WAIP forecast of the peak intensity and the intensity spread.

2. Given that one or more pre-TC circulations in the GEFS forecast have been confirmed to be the third or fourth consecutive forecast to have a WCM evolution (as in Fig. 3b) indicating the possibility of a formation of either a typhoon or a tropical storm along the GEFS track forecast (as in Fig. 3a):
    a. The initial date/time of WCM evolution, and a preliminary estimate of the initial intensity (15, 20, or 25 kt), will be recorded.
    b. The peak WCM will be compared with the schematic in Fig. 4 to determine whether the pre-TC circulation will likely become a typhoon, a tropical storm, or a tropical depression at peak intensity.
    c. If a likely typhoon, then determine and record the T2F (35 kt) with a beginning as in Fig. 4 that emphasizes an early formation time as the WCM begins to increase.
    d. If a likely TS, then determine and record the timing of T2F (25 kt) with a beginning as in Fig. 4 that anticipates a too slow increase in the WCM in the GEFS forecast.

e. The forecaster should also examine the track forecast and the WCM evolution and record (if applicable) the timing of an ending storm due to landfall or an extratropical transition that would be reflected as decreasing WCM values after the peak WCM.

3. Based on the analysis in Step 2, the forecaster enters in the combined three stage WAIP the initial time and the initial intensity, the T2F either as a 35 kt for a likely typhoon or a 25 kt for a likely tropical storm, and an ending storm time if applicable. In the execution of the WAIP, the forecaster will be provided two cluster intensity forecasts with separate intensity spreads whenever a bifurcation situation is objectively determined to exist. The forecaster should select Cluster 1 with the larger peak V_{max} if at least 5 of the ensemble members are indicating the possibility of a more rapid intensification, and if the sequence of four consecutive WCM diagrams is also indicating further intensification.

Here the role of the forecaster is critical because there are possible cross-track or (likely slow) along-track errors, and there is uncertainty in the GEFS-based T2F derived from the WCM diagram. The limitation of the WAIP to predict rapid intensification timing or magnitude will leave to under-forecasts for any major typhoon. Depending on the level of threat to the JTWC customers, the forecaster must decide if an early alert/watch or even a warning is appropriate, or whether to wait for more conclusive forecast guidance from the next GEFS forecast.

3. PARTICIPANTS

Dr. Hsiao-Chung Tsai of Tamkang University, New Taipei City, Taiwan and Tim Marchok, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey.

4. IMPACTS

Approximately 25% of the budget has been spent in a foreign country (Taiwan).

5. CHANGES/PROBLEMS

Due to the delayed arrival of the first-year funding of my JHT project, the re-assignment of my NOAA collaborator Tim Marchok to other duties that delayed a critical research task in the project, and an opportunity at the JTWC to proceed directly to operational implementation in the WPAC during the 2019 season, the summary of progress below focuses on the WPAC. We could take advantage of the JTWC opportunity because I had an Office of Naval Research (ONR) project that could be used to develop and test the critical Time-to-Formation (T2F) research task. That is, our ONR research team was developing a combined three-stage WAIP intensity and intensity spread prediction technique that included the pre-formation stage so that the new combined WAIP could be used in this JHT project. To take advantage of this common requirement to provide the T2F values in the WPAC, we were able to utilize these ONR funds to complete the development and testing of the combined WAIP with best-track data to specify the T2F. Unfortunately, the test of Tim Marchok’s scheme to specify the T2F in the WPAC was not successful, which was attributed to the number of WPAC TCs that develop from monsoon depressions that already have a lower-tropospheric warm core and are vertically stacked. Furthermore, these WPAC monsoon depressions may already have 35 kt winds in outer bands. Transition to a TC then occurs when the associated outer band of deep convection either contracts or separate deep convection forms near a vorticity maximum typically at the eastern end of the monsoon depression, but occasionally at the western end (Beattie and Elsberry 2016).

Plans for remainder of 2017-2019 JHT project

A methodology to create WCM plots from the GEFS forecasts in the WP\AC has been developed and tested, and the approach for determining the T2F and the ending storm timing has been established for implementing the combined, three stage WAIP. Thus, the complete package will be delivered to JTWC in early February for operational testing during the 2019 WPAC season. This transition to operational testing at JTWC will be straight-forward as they are already operationally running the GEFS and the ECMWF ensemble. The JTWC already has a two-week TC formation outlook into which we will merge our T2F and WAIP intensity and intensity spread forecast for the pre-formation stage.

For the Atlantic, we have a similar intensity and intensity spread technique called WAIA that includes an ending storm stage, but does not include an option for bifurcation situations, or the pre-formation stage. The JHT liaison team has implemented that WAIA version, which is in MATLAB, so implementing the new, combined three stage WAIA version should be straight-forward. The first task will be to transition to the Atlantic the WPAC code to calculate the WCM evolutions from the GEFS and test the WPAC approach for estimating the T2Fs and the ending storm times along the WMVM track forecasts. We will again examine the 2017 season, which was quite active with hurricanes that made landfall. Addition of the pre-formation stage for the combined WAIA will be identical to the WAIP. The second task will be to add the bifurcation option in the new combined WAIA intensification stage. The final transition for the Atlantic will be to implement the GEFS WMVM track forecasts (again in MATLAB) on the local NHC computer if the entire process is going to be run onsite (vice run offsite and provided to NHC in near-real time) during the 2019 season. The target delivery date for the Atlantic is May 1.

For the combined eastern and central North Pacific, we first have to develop the intensity and intensity spread technique (tentatively called WIEC) as an adaptation of the WAIA, and then include a similar pre-formation stage in the combined three stage WIEC. Since this MATLAB code will also be executed on a local NHC computer as for the Atlantic WAIA version, this transition is expected to be straight-forward. Similarly, time can be saved as the transition of the GEFS WMVM track forecast for the eastern and central Pacific storms will be implemented on the local NHC computer at the same time as for the Atlantic WAIA application. The most time-consuming procedure will be to generate and evaluate the WCM evolutions to determine the T2Fs and the ending storm times, because almost all of these hurricanes die over the open ocean rather than make landfall, and few of the storms undergo extratropical transition. Thus, the target delivery date for the entire procedure for the eastern and central North Pacific is June 30.

6. SPECIAL REPORTING REQUIREMENTS

The initial Readiness Level (RL) in the three tropical cyclone basins to be studied (WPAC, ATL, and combined EPAC/CPAC) was RL 3. At the 12/31/ 2018 reporting date, the WPAC was at RL 6, ATL was at RL 4, and the combined EPAC/CPAC was at RL 3.

7. BUDGETARY INFORMATION

The project is on budget and no changes are planned.

8. PROJECT OUTCOMES

No project outcomes this early in the project.

REFERENCES

Tsai, H.-C., and R. L. Elsberry, 2015: Seven-day intensity and intensity spread predictions for western North Pacific tropical cyclones. *Asia-Pacific Journal Atmospheric Sciences*, **51**, 331-342.

Tsai, H.-C., and R. L. Elsberry, 2017a: Seven-day intensity and intensity spread predictions for Atlantic tropical cyclones. *Weather and Forecasting*, **32**, 141-147.

Tsai, H.-C., and R. L. Elsberry, 2017b: Ending storm version of the 7-day weighted analog intensity prediction technique for western North Pacific tropical cyclones. *Weather and Forecasting*, **32**, 2229-2235.

Tsai, H.-C., and R. L. Elsberry, 2018a: Seven-day intensity and intensity spread predictions in bifurcation situations with guidance-on-guidance for western North Pacific tropical cyclones. *Asia-Pacific Journal Atmospheric Sciences*, **54**, in press (August issue)

Tsai, H.-C., and R. L. Elsberry, 2018b: Combined three-stage, 7-day weighted-analog intensity prediction technique for western North Pacific tropical cyclones: Combined pre-formation, bifurcation intensification, and ending storm version. *Weather and Forecasting*, Manuscript submitted.

Conference Presentations

Elsberry, R. L. and H.-C. Tsai, 2018a: Improvement of seven-day weighted analog intensity prediction technique: Addressing pre-formation and ending storm stages. 2018 PACOM Joint Tropical Cyclone Forecasting Program Assembly, Honolulu, Hawaii, 20-23 February 2018

Elsberry, R. L., H.-C. Tsai, and T. Marchok, 2018b: JHT project 7: Ensemble-based pre-genesis watches and warnings for Atlantic and North Pacific tropical cyclones. 2018 Interdepartmental Hurricane Conference, Miami, Florida, 13-15 March 2018

Tsai, H.-C., and R. L. Elsberry, 2018a: Improved weighted-analog intensity and intensity spread predictions for western North Pacific tropical cyclones in pre-formation and ending stages. Presentation 16C.6, AMS Hurricane and Tropical Meteorology Conference, Ponte Verda, Florida, 16-20 April 2018

Tsai, H.-C., and R. L. Elsberry, 2018b: Improvement of weighted analog intensity prediction for different stages of the western North Pacific tropical cyclones. Presentation AS31-028, Asia Oceanic Geophysical Society meeting, Honolulu, Hawaii, 3-8 June 2018