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Predictability of Tropical Cyclone Events on Intraseasonal Timescales with the ECMWF Monthly Forecast Model

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Abstract: The objective of this study is to provide evidence of predictability on intraseasonal time scales (10-30 days) for western North Pacific tropical cyclone formation and subsequent tracks using the 51-member ECMWF 32-day forecasts made once a week from 5 June through 25 December 2008. Ensemble storms are defined by grouping ensemble member vortices whose positions are within a specified separation distance that is equal to 180 n mi at the initial forecast time *t* and increases linearly to 420 n mi at Day 14 and then is constant. The 12-h track segments are calculated with a Weighted-Mean Vector Motion technique in which the weighting factor is inversely proportional to the distance from the endpoint of the previous 12-h motion vector. Seventy-six percent of the ensemble storms had five or fewer member vortices. On average, the ensemble storms begin 2.5 days before the first entry of the Joint Typhoon Warning Center (JTWC) best-track file, tend to translate too slowly in the deep tropics, and persist for longer periods over land. A strict objective matching technique with the JTWC storms is combined with a second subjective procedure that is then applied to identify nearby ensemble storms that would indicate a greater likelihood of a tropical cyclone developing in that region with that track orientation. The ensemble storms identified in the ECMWF 32-day forecasts provided guidance on intraseasonal timescales of the formations and tracks of the three strongest typhoons and two other typhoons, but not for two early season typhoons and the late season Dolphin. Four strong tropical storms were predicted consistently over Week-1 through Week-4, as was one weak tropical storm. Two other weak tropical storms, three tropical cyclones that developed from precursor baroclinic systems, and three other tropical depressions were not predicted on intraseasonal timescales. At least for the strongest tropical cyclones during the peak season, the ECMWF 32-day ensemble provides guidance of formation and tracks on 10-30 day timescales.

Key words: Tropical cyclone formation prediction, intraseasonal predictability of tropical cyclone events, ECMWF monthly forecast model

1. Introduction

The operational forecasts of tropical cyclone tracks out to five days have been greatly improved during the past decade as a result of improved numerical model guidance and the use of consensus forecasting with multiple skillful deterministic models (Elsberry, 2007). Whereas formation of a tropical cyclone close to an island or a coastline has always been a serious forecast problem, formation forecasts have increased in importance with the issuing of five-day track forecasts since a pre-tropical cyclone seedling can intensify to a typhoon stage within five days.

Elsberry *et al.* (2009) have suggested that a consensus of four deterministic global models as interpreted by a skilled analyst might provide a Likely or Unlikely decision as to whether and when a pre-tropical seedling in the western North Pacific would become a Tropical Depression according to the Joint Typhoon Warning Center (JTWC). Furthermore, a conditional consensus technique also produced 72-h track forecast errors of the order of 300 n mi for a sample of pre-tropical cyclone seedlings and Tropical Depressions, which would have been considered skillful track forecasts for a typhoon a decade ago. The caveats are that study was conducted only on the pre-tropical cyclone seedlings during the combined Tropical Cyclone Structure (TCS08)/THORPEX Pacific Asian Regional Campaign (T-PARC) field experiment and the consensus formation technique was only successful for cases in which the pre-tropical cyclone seedling later became a strong Tropical Storm or Typhoon. These global models did not consistently predict the formation from a mesoscale (midget) seedling or a baroclinic system, or when the seedling would only become a Tropical Depression or weak Tropical Storm.

Because the environmental conditions must be favorable over a relatively large area to provide time for the circulation to become a typhoon, Elsberry *et al.* (2009) proposed that the present global models have some skill in predicting these formation cases with anomalous conditions over large areas. It follows that the track of these pre-tropical cyclone seedlings or Tropical Depressions that later become strong Tropical Storms or Typhoons may also be predicted since the first-order effect in tropical cyclone motion is the environmental flow.

Seasonal forecasts of tropical cyclone activity over a basin

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have also become more skillful (Camargo *et al.,* 2007). Whereas these seasonal forecasts were previously statistically based, Vitart *et al.* (2007) have demonstrated that a dynamical model ensemble has skill equal or better than the statistical technique. Most of this skill for seasonal tropical cyclone activity for both the statistical and the dynamical model techniques depends on predicting the environmental conditions associated with El Niño Southern Oscillation (ENSO). Although a seasonal forecast does not necessarily require a correct distribution of formation locations, one objective is to now make basin-specific and landfall prediction, which also implies track prediction skill. This is a challenge for the statistical techniques in part because the sample sizes for smaller areas or landfall cases are reduced. In principle, a dynamical model of the appropriate resolution could predict both the formation locations and tracks if the external forcing of the ocean and land surfaces was also predicted and the physical processes were properly represented in the model.

The focus of this study is the intraseasonal prediction of western North Pacific tropical cyclone formation and tracks with a dynamical model, and specifically the experimental European Center for Medium-range Weather Forecast (ECMWF) 32-day ensemble forecasts of tropical cyclones that is made each week from the conditions at 0000 UTC on Thursdays. The original motivation was to examine the feasibility of anticipating when and where tropical cyclone formation might (or might not) occur during the August-September period of the combined TCS08/T-PARC field experiment. Because limited aircraft flight hours were available for formation-objective missions, and the months leading up to the experiment had relatively few formations, any guidance on when and where formations might occur would be useful. The ECMWF kindly provided the experimental forecasts, which did appear to indicate a "dry period" of formations in late August and then an active period of formations. In retrospect, the tracks of the major typhoons during TCS08/T-PARC predicted on 10-30 day leadtimes were also quite reasonable. Thus, a more detailed study of the formations and tracks of the ECMWF 32-day ensemble predictions has been carried out. To obtain a more representative sample, the sample was expanded to include 30 weekly forecasts beginning 5 June 2008 through 25 December 2008.

In contrast to statistical approaches that indirectly predict tropical cyclone formations by associations with environment conditions such as vertical wind shear, these dynamical model integrations directly predict the formations and tracks of vortices in each ensemble member. The objective of this study is to determine the predictability of the ensemble storms by comparison with actual storm tracks during the period.

2. ECMWF new VarEPS-monthly forecasting system

The source of the western North Pacific tropical cyclone-like vortices for this study is the variable resolution ensemble prediction system (VarEPS-monthly) that is an extension to 32 days once a week of the 15-day VarEPS that was implemented in November 2006 (Buizza *et al.,* 2007). Vitart *et al.* (2008) provide a complete description of VarEPS-monthly prediction system and its improvements over the previous monthly forecast system.

Some key features for tropical cyclone prediction are that during Days 0 to 10 (leg 1) the horizontal resolution of the 51 member ensemble is T399 (~ 50 km) with 62 levels. During Days 10-32 (leg 2), the resolution decreases to T255 (~ 80 km). As in the VarEPS, the initial perturbations for the ensemble are based on singular vectors and stochastic physics perturbations are applied during the model integration. From Day 0 to Day 10, the sea-surface temperatures (SST) are the seasonal values plus the SST anomalies that existed at Day 0. From Day 10, the atmosphere is coupled to the Hamburg Ocean Primitive Equation model, which has 29 vertical levels and has higher horizontal resolution in equatorial regions. The oceanic initial conditions include a control and four perturbed ocean analyses. Each of these five ocean assimilations is used as the initial condition for 10 (or 11 for the control assimilation) of the 51 atmospheric ensemble members (Vitart *et al.,* 2008).

Vitart (2009) explains the importance of inclusion of the coupled ocean in the VarEPS-monthly for tropical cyclone activity prediction. Until recently the ECMWF atmospheric model predicted well the propagation of the Madden-Julian Oscillation (MJO) but the amplitude was significantly reduced after only a few days (Bechtold *et al.*, 2008). Mostly due to changes in the convective parameterization, the model is able to maintain the amplitude of the MJO for more than 30 days, and the representation of tropical storms has also improved.

Vitart (2009) demonstrated the impact of the MJO on tropical storms in the ECMWF model with a series of 15-member ensemble hindcasts that begin on the 15th of each month and extend 45 days. This model version reproduces well the main characteristics of the observed distribution of tropical cyclones, although the activity in the model tends to be higher than observed. Differences between the tropical cyclone activity during active and inactive phases of the MJO also seem to be well-predicted in the model. Because of the ability of the model to predict the MJO up to 20 days, and the relationship of MJO to tropical storm activity, Vitart (2009) proposes that the tropical storm activity including the risk of landfall may be predicted on intraseasonal timescales.

3. Methodology

Each of 51 ensemble members (control plus 50 perturbed members) may have several predicted vortex tracks during the 32-day model integration. For example, member 15 formed four vortices beginning at Day 1, Day 7.5, Day 13, and Day 24.5 during the 0000 UTC 28 August integration (Fig. 1). Thus, a total of 120-150 individual vortex tracks are predicted that begin at various times during the 32-day integration. The approach Vitart (2009) adopted is to consider each vortex as a tropical cyclone and then calculate a strike probability that the vortex center would pass within 220 km of each point during the month.

The first objective in the procedure here is to match vortices from different ensemble members to form "ensemble storms" that will then be compared with the list of tropical cyclones from JTWC. When a tropical cyclone already exists at the initial time, the procedure is straight-forward as multiple members (many times all 51) will have a vortex with a similar position. All ensemble member vortices within a time-dependent separation distance ε (t) are grouped in an ensemble storm and a number is assigned. Each of these vortices then stays as a storm member throughout its existence. The allowable separation distance between vortex centers was set at 180 n mi for time t = Day 1, but then was increased linearly to a value of 420 n mi at Day 14 to account for growing uncertainty in the model solutions for the initial vortex location. After Day 14, the separation distance is held constant at 420 n mi to avoid combining vortices that are of a different origin.

At the end of the first pass through all ensemble member vortices that exist on Day 1, perhaps three ensemble storms with multiple vortices will be identified and any remaining vortices that are separated by more than 180 n mi will also be labeled as an ensemble storm. In the second time step of 12 h, and subsequent 12-h steps until Day 32, any new ensemble member vortex that begins at that time step will either be matched with an existing ensemble storm [i.e., be within ε (t) distance] or will become a new ensemble storm. Note the importance that is being given to the first position in the member vortex track.

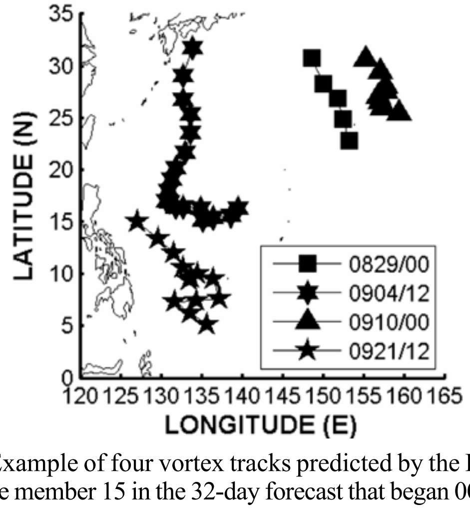

Fig. 1. Example of four vortex tracks predicted by the ECMWF ensemble member 15 in the 32-day forecast that began 0000 UTC 28 August 2008. The start time (MMDDHH) for each vortex track is indicated in the inset, and positions are indicated each 12 h.

The track of an ensemble storm begins at the mean latitude and longitude of all member vortices that belong to that storm. A Weighted-Mean Vector Motion (WMVM) technique (Elsberry *et al.,* 2008) is used to calculate the next 12-h position. The principle is that those vectors with origins that are closest to the mean position should be given the greatest weight in calculating the consensus motion vector. Thus, an inverse distance weighting factor is calculated for each ensemble member 12-h vector (Fig. 2). This WMVM approach is particularly useful when the number of member vortices begins to decrease. Whereas a simple average latitude and longitude may result in discontinuous track directions when a vortex track drops out, the WMVM results in a smooth track because the remaining vortex 12-h vector motions are being added to the most recent position.

Particularly at the beginning of a member vortex, considerable uncertainty in the initial position may exist when the circulation is weak. After the matching of new member vortices has been completed and a new position has been determined from the WMVM, the separation distances between all existing ensemble storms are calculated. Any storms within 180 n mi are considered to instantaneously merge to become a storm that retains the storm number that is smaller (existed the longest and may be the largest). This merger separate distance is based on observations. The new position is the average position of all vortices in the merged ensemble storm, and the next 12-h WMVM will originate from that point. In addition, a "backward" WMVM is calculated from that merged storm position to find an origin point for the new ensemble storm (Fig. 3a).

In the Typhoon Jangmi example in Fig. 3a, Storm 1 with 28

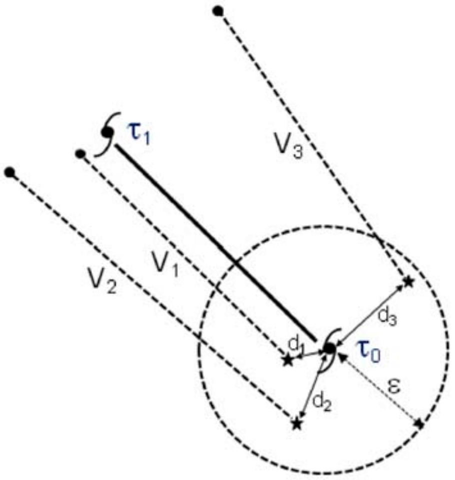

Fig. 2. Illustration of the Weighted-Mean Vector Motion (WMVM) calculation with three 12-h vectors, V_1, V_2, and V_3 that are within separation distance ε and originate at distances d_1, d_2, and d_3 from the ensemble storm position at time τ_0. The WMVM position at $\tau_1 = \tau_0 + 12$ h is the weighted-mean of the three vectors in which the largest (smallest) weight is given to the vector V_1 (Vector V_3) that is closest (farthest) from the origin point at τ_0.

members began just east of the Philippines and Storm 2 with 24 members began as a separate system as it was more than 180 n mi to the east. However, the two storms then approached and a new merged storm track continued with 52 members. In addition, a backward WMVM calculation creates a continuous track from an origin point between the two original storm initial positions (Fig. 3b). Notice the spread among the ensemble vortex tracks between a track toward South China and a recurvature near Taiwan and then a northeastward track toward Japan. The WMVM track is in the middle of the vortex tracks when the storm is predicted to move northwestward, and then favors the recurvature and northeastward track, especially when the tracks into South China terminate over land.

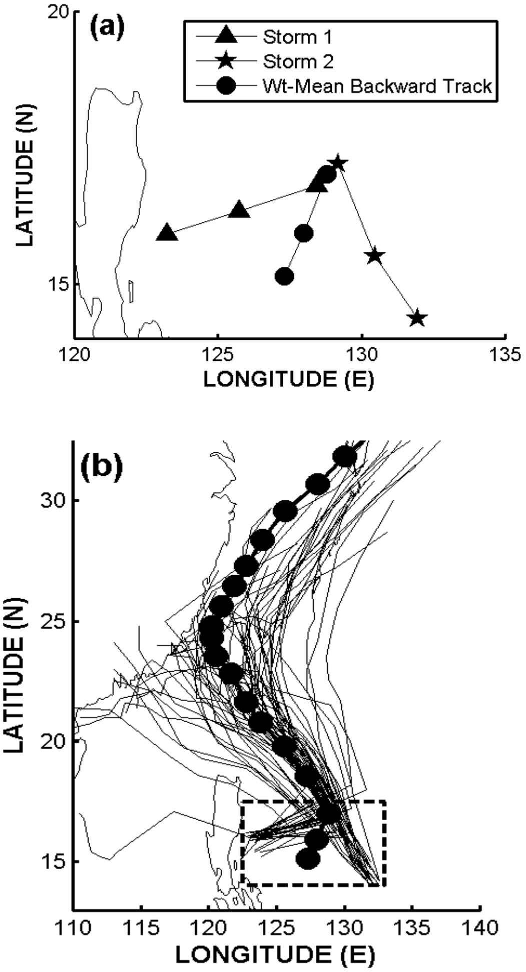

Fig. 3. (a) Illustration of the merging of ensemble storm 1 with 28 members that began at 1200 UTC 25 September (triangles, 12-h positions) and ensemble storm 2 with 24 members that also began at that time (stars). A backward WMVM is calculated from the merged storm position at 1200 UTC 26 September to determine the merged storm positions over the two previous 12-h time periods (circles). (b) Complete ensemble storm track (positions each 12 h) for the merged storms as indicated in panel (a). All of the vortex tracks that make up this merged ensemble storm are also indicated (thin lines), which corresponds to Typhoon Jangmi.

4. Some characteristics of the ECMWF 32-day ensemble storm tracks

The methodology in section 3 was applied to match the 51 ensemble member vortex tracks to form ensemble storm tracks during each of the 30 weekly forecasts of 32-day length from 5 June 2008 through 25 December 2008. A total of 826 ECMWF ensemble storms were analyzed during the 30 weekly forecasts (note that these are overlapping periods). The minimum number of ensemble storms identified during a 32-day forecast was 14 during the forecast initiated at 0000 UTC 5 June 2008 and the maximum number was 44 for the forecast from 0000 UTC 31 July 2008. Similarly, the number of the Tropical Depression and stronger tropical cyclones according to the JTWC was counted in each corresponding 32-day period. The minimum (maximum) number of JTWC storms was zero (nine) for the 32-day forecast period beginning 25 December 2008 (18 September).

Vitart (2009) indicated this VarEPS-monthly model tends to have too many tropical cyclone-like vortices. One of the objectives of this analysis is to match the ECMWF ensemble storms as defined by the methodology in section 3 with the observed storms and identify those ensemble storms that are

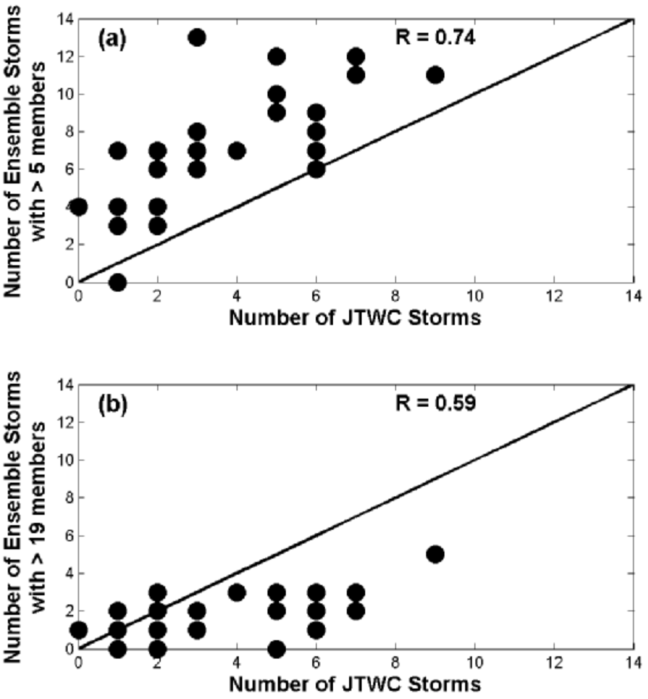

Fig. 4. Correlations and scatter-plots of ECMWF ensemble storms with (a) greater than five member vortex tracks or (b) greater than 19 member vortex tracks versus the corresponding number of JTWC storms during the 30 weekly forecasts initiating between 5 June and 25 December 2008.

likely to be spurious. As a first consideration, 626 (76%) of the identified ensemble storms had five or fewer member vortices. Excluding these ensemble storms, correlations of the number of ECMWF ensemble storms with > 5 vortex members (> 9 vortex members, > 19 vortex members) with the JTWC total number of storms during each of the 30 weekly 32-day forecasts led to an 0.74 (0.58, 0.59) correlation value. The scatter plots of the number of ECMWF ensemble storms with > 5 member vortices (Fig. 4a) indicates some co-variability with the JTWC number of storms, but with too many ensemble storms. By contrast, the co-variability with the number of ensemble storms with > 19 vortex members (Fig. 4b) is less and indicates that setting the threshold at 19 members will under-estimate the storm variability.

Another notable characteristic of the ECMWF ensemble member vortices and storms is that the tracks in most cases start before the first entry in the JTWC best-track (positions based on a post-storm analysis) file each 6 h (Fig. 5a). That is, the lead times range from 11.5 days for the Tropical Depression 11W to a lag time of 5.5 days for pre-Dolphin, with an average of 2.49 days lead time for the 21 JTWC storms. As shown in Fig. 5b, the first entry in the JTWC best-track file is frequently 15 kt, which indicates the ECMWF vortices are beginning at a very early stage in most cases. Clearly, the first entry in the ECMWF ensemble storm file should not be interpreted as being a formation time of a Tropical Depression.

Those ECMWF ensemble storm tracks that cross land, especially in Southeast Asia, have much longer tracks than are represented

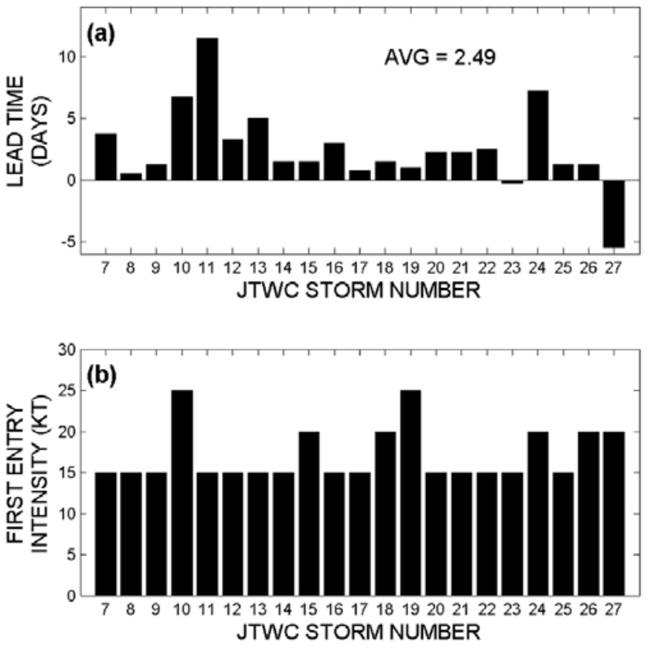

Fig. 5. Histograms of (a) the lead-time (days) of the ECMWF ensemble storm first position and the corresponding first position in the JTWC best-track file, and (b) the intensity (kt) of the JTWC storm on the first entry for the 21 JTWC tropical depressions and stronger storms that existed between 5 June and 25 December 2008.

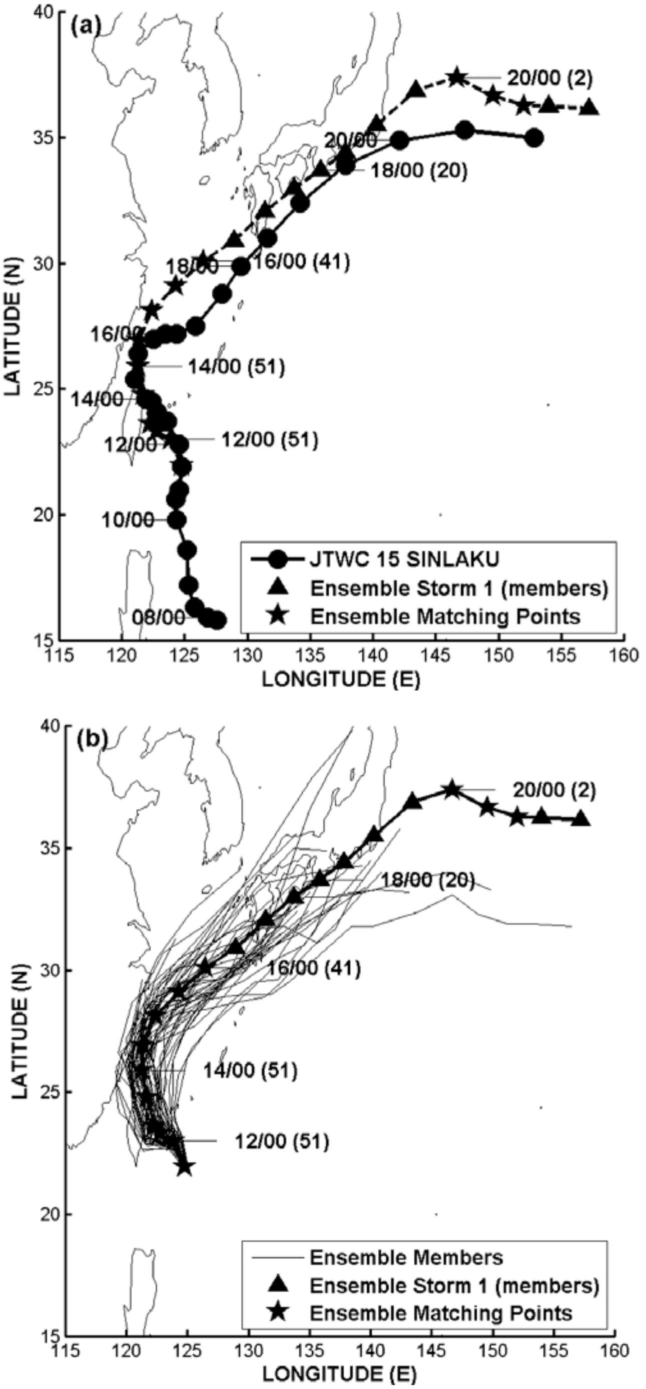

Fig. 6. (a) Best-track positions (circles, selected dates/times on left) each 12 h from JTWC for 15 W (Sinlaku) and ECMWF ensemble storm 1 in the 11 September 32-day forecast with numbers of members in parentheses and matched points within ε (t) distance indicated by star symbols. (b) Ensemble storm 1 track as in panel (a) with individual ensemble vortex tracks indicated by thin lines.

in the JTWC best tracks (not shown). This difference may arise from JTWC more rapidly decaying the storm over land to less than 25 kt and thereby justifying dropping the storm. Since the ensemble storms begin earlier and are carried farther over the land, the durations are clearly longer for the ensemble storms.

Another characteristic of the ensemble storms is a tendency for slow movement while in the deep tropics. This slow bias was more obvious when the consensus track was calculated as the mean latitude and longitude, but also continues with the WMVM tracks. Examples of the translation speeds in the deep tropics will be given later in Figs. 7-9. This slow bias has implications for storm activity calculations (or storm risk calculations expressed as the times the position is within 200 km of a point), since the ensemble storm will tend to be near a given point longer than in nature.

5 . Validation procedures for the ensemble storm tracks

The validation of the ensemble storm tracks derived from the matching methodology in section 4 is done in two steps. First, an objective and strict matching track procedure is applied that is analogous to the matching of ensemble member vortices to define the ensemble storms. A second subjective matching of objectively-determined tracks that are judged to be nearby in space or in time are combined to indicate a greater likelihood of belonging to the same storm event than might be determined from the objective technique only.

a. Objective matching of ensemble storm and JTWC storm tracks

The first step in the objective validation procedure is to create a file of JTWC tracks that existed during the 5 June 2008 through 25 January 2009 period. Although the extension into January 2009 was necessary to cover the 32-day forecast interval from the 25 December ECMWF forecast, no western North Pacific tropical cyclones occurred during that period. Each of the JTWC best-track (post-storm analysis versus the real-time warning) positions was put in the same format as for the ECMWF vortex track.

The matching methodology in section 4 is applied by comparing the JTWC storm positions with all ensemble storm positions that existed at that time. If the two positions were within the allowable separation distance ε (t), where t is the forecast time for the ensemble member, then a match is defined. Notice that this is a strict matching criterion since no time deviation is allowed, e.g., as in some statistical techniques in which time deviations of up to one week are allowed. Rather, the two positions may vary only within the spatial interval ε (t) that varies from 180 n mi at the initial time to 420 n mi at Day 14 and beyond in the 32-day forecast. Examples of these objective ensemble storm matches will be given in conjunction with the following discussion.

Whereas this objective matching methodology ensures a highly likely match of the ensemble storm with the JTWC storms, three characteristics of the member vortices and ensemble storms affect the matching. First, the early stages of the ensemble storms will not be matched with the JTWC storms because the first position of an ensemble storm is on average 2.5 days prior to the first entry in the JTWC best-track file (Fig. 5a), and this first JTWC entry is nearly always before the 25 kt threshold (Tropical Depression) is analyzed (Fig. 5b). Notice also that convective systems that do not later achieve Tropical Depression or stronger status do not appear in the JTWC best-track file. Thus, the validation of the ensemble storm tracks will focus on period after the JTWC best-track storm file begins, even though the early portion of the ensemble storm track will also be displayed.

The second characteristic of the ensemble storms that affects the matching with the JTWC storms is the slow translation speed bias. Even with the WMVM technique, many of the ensemble storms translate more slowly than the corresponding JTWC storm. Thus, even with a JTWC storm moving in roughly the same direction, the matching will then fail when the separation distance ε (t) is exceeded. These cases of shortened matches may be flagged with a notation “only good early,” although the failure may be due to other causes as well.

The third characteristic of the ensemble storms is that these tracks continue longer over land than in the JTWC best-track file (e.g., see Fig. 7a). Thus, these persisting over-land positions will not be matched in the objective technique. However, the last JTWC positions near the coast or farther inland tend to correspond to a slower translation or even stalling. Thus, the ensemble storm, which may have been moving too slowly, may then overtake the JTWC storm. This somewhat coincidental matching from the objective technique will be flagged with a notation “only good late.”

In summary, the validation of the ensemble storms with the JTWC storms will not focus on either the early positions or the late ensemble storm positions over land, and will take into account shortened matching periods associated with a slow bias. It is emphasized that the entire ensemble storm is considered to be an “event” with a track forecast rather than just a tropical cyclone formation forecast.

b. Quality of match measures

The overall philosophy behind this matching procedure is that success is likely to be achieved in identifying the relatively few ensemble storms that correspond to actual storms versus attempting to identify which of the large number of ensemble storms, especially the 76% that contain less than five vortex tracks, are actually real storms. That is, greater success in matching is likely with those ensemble storms that contain a larger fraction of the 51 ensemble member vortices. Notice that the track of an ensemble storm with only one member may resemble an actual storm track for some distance just by chance.

The quality of the objective matching of the ensemble storms with the JTWC storms is assessed in five categories ranging from Excellent to Poor. The choice of only five categories is guided by the likely precision that might be expected at this stage of dynamical model forecasting of CCEWs and the MJO. That is, it seems unlikely that a precise probability should be attempted for an event that involves some uncertainty in both formation and in track. Furthermore, five categories of the likelihood of such a tropical cyclone event is probably sufficient guidance for many tropical cyclone impacts planning purposes on intraseasonal time scales of 10-30 days.

An assessment of an Excellent match of the ensemble storm with the JTWC storm is assigned when the paths are nearly coincident over a considerable number of days. The vast majority of the Excellent assignments are for the weekly forecasts in which the tropical cyclone already exists, which is labeled as Week 0 (see example in Fig. 6a). The forecast track of such cyclones is typically highly skillful, and the spread of the ensemble tracks is typically quite small (Figs. 3b and 6b), especially when a good initial position exists and the tropical cyclone structure is defined well. Because the ECMWF does not insert synthetic observations (bogus vortex), these conditions do not always apply, especially during the Tropical Depression or weak Tropical Storm stages. An Excellent assignment will also be assigned later in the 32-day forecast period when the orientation of the ensemble track is quite similar to the JTWC track and the space and time displacements are well within the ε (*t*) matching threshold.

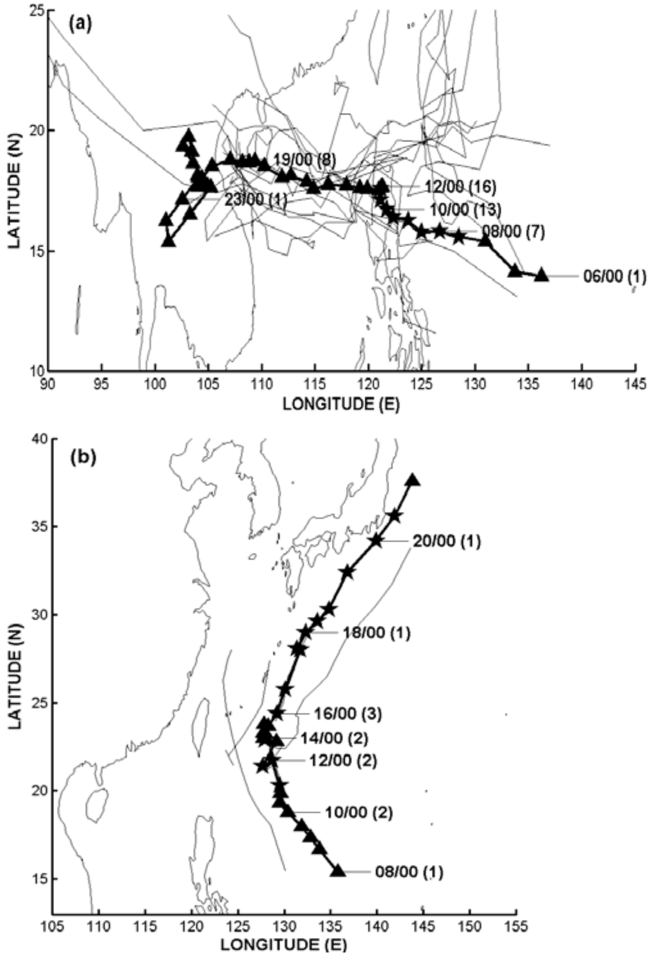

Fig. 7. As in Fig. 6b, except for (a) ensemble storm 4 with 23 members and (b) ensemble storm 8 with 4 members in the 4 September 2008 forecast (Week-1) of Sinlaku.

An assessment of Above Average (see example in Fig. 7b) is assigned when the path of the ensemble storm closely resembles the JTWC storm path, but the overall track is displaced to the left or right, or is shifted in time, too much to be assessed as Excellent. This is an intermediate condition between an Excellent assignment and a Good assignment that has a match with the JTWC track only for a shorter period (usually early or late in the JTWC track) and then has a larger path deviation (see example in Fig. 7a). A Good assignment in the forecasts initiated two, three, four weeks before Week 0 indicates that the general location and orientation of the track of the ensemble storm agree well enough with the JTWC track that this would indicate a reasonable likelihood that such an event will occur. However, qualifying notations will generally be provided to indicate what the limitations are that prevent a higher assessment.

The assessment of Poor is given when a match with the JTWC storm position has been calculated, but this match is coincidental. That is, it is clear that the ensemble storm path and evolution are different from the JTWC storm. This is particularly evident when the matched points are near the end of tracks that have evolved from different regions, or when the ensemble storm position was in the subtropics and the track of a recurving storm happened to be within a distance ε (*t*). Finally, the assessment of Below Average is then an intermediate condition between a Poor and a Good assignment. That is, the matched points between the ensemble storm and the JTWC track are more than for the Poor assessment, but the path orientations do not agree as well as in the Good assignment. Thus, the Below Average assignment for the ensemble storm would indicate enough of a possibility that such an event would occur that an alert would be given and the region should be monitored for further indications in the next weekly forecast that the event might occur.

In summary, the procedure for assessing the quality of the ensemble storm predictions has three easily recognizable categories of Excellent, Good, and Poor plus two intermediate categories of Above Average and Below Average to account for less recognizable or clear-cut situations. When the assessment procedure was repeated during the technique development

Table 1a. Evaluations of the quality (Excellent, Above average, Good, Below average, Poor) for those ECMWF ensemble storms that had at least one 12-h position that met the matching criterion ε (t) with the JTWC position at the same time. In the first column, the storm number (according to JTWC) and name, maximum wind speed (kt) at any time in the lifecycle and the date at 0000 UTC of the experimental ECMWF 32-day ensemble forecast. Columns 2-6 are for the Week 0 (corresponding to date in column 1) through the preceding four week evaluations that might have forecast that JTWC storm. In the first line of each entry, the ensemble storm number for that weekly forecast in parentheses, the number of days between the model start and the ensemble storm start where 0 days indicates the JTWC storm was already in existence at the initial time, and then in brackets the maximum number of ensemble member vortices in the ensemble storm. The quality of the storm forecast is indicated on the second line of each entry, and the qualifier statements are indicated by superscripts that are explained below the table. Italics indicate similar storm tracks that when combined would suggest more confidence (see section 5c). In this table, selected major typhoons during the TCS08/T-PARC field experiment are evaluated.

STORM	WEEK 0	WEEK-1	WEEK-2	WEEK-3	WEEK-4
15W Sinlaku 125 kt 11 September	(1) 0 days [51] Excellent	(4) 2 days [23] Good^{o} (8) 4 days [4] Above (11) 5 days [6] Poor$^{\#}$	*(2) 3.5 days [20]* *Good* *(4) 4 days [18]* *Above* *(13) 12 days [7]* *Above*	*(16) 15.5 days [5]* *Above* *(20) 16 days [5]* *Above* (23) 19 days [6] Good (26) 22 days [5] Good^{e} (31) 27.5 days [1] Poor$^{\#}$	*(21) 17.5 days [10]* *Above* (29) 21.5 days [3] Good^{l} (30) 22 days [6] Above^{e}
18W Hagupit 125 kt 18 September	(1) 0 days [51] Excellent	(5) 5 days [20] Above	*(13) 8.5 days [12]* *Above*^{l} *(17) 10.5 days [12]* *Above* *(18) 12 days [18]* *Above*^{o}	(15) 13 days [24] Good^{l} *(19) 19 days [10]* *Good*^{s} (24) 22 days [4] Above (26) 23 days [8] *Above**	(32) 28 days [3] Excellent
19W Jangmi 140 kt 25 September	(1) 0 days [52] Excellent (10) 4.5 days [1] Excellent	(9) 6.5 days [7] Above^{e}	(7) 6 days [19] Above^{l}	*(20) 15.5 days [11]* *Excellent* *(23) 21 days [9]* *Good*^{e}	(23) 22 days [11] Excellent (30) 27 days [2] Below

Superscripts: o = only good early; e = shifted to east; # = coincidental match; l = only good late; * = several days late; s = shifted to south

stage, it was these intermediate categories that were most subjected to revision (usually lower).

c. Second subjective validation rationale

Especially in validating the matches of the ensemble storms in the predictions during Week-2 through Week-4 with the JTWC storms, it became evident that multiple ensemble storm tracks may resemble the JTWC storm track, but were on opposite sides or shifted in time enough that the storm tracks had not been merged or identified as the same storm due to the strict matching criteria. This situation was particularly evident when two ensemble storms with the same quality indicator and with five or more member vortices in a weekly forecast began within 1-2 days. Thus, a subjective procedure was applied in which a "seed ensemble" with the largest number of member vortices is identified. Other ensemble storm tracks within that weekly forecast were then subjectively compared with the seed ensemble track. If these tracks essentially were providing the same guidance as to the likelihood of the storm event occurring, then the two (or more) ensemble storms were flagged. The implication of such flagged ensemble storms is that their combined number of member vortices indicates a greater likelihood of a tropical cyclone developing in that region with that track orientation.

The objective in this first validation is simply to indicate the existence of these nearly matched ensemble storms and suggest that their existence provides more evidence of intraseasonal predictability of some tropical cyclones in the western North Pacific. In future work, a quantitative evaluation will be made of the increased probability of an event when this subjective matching procedure to increase the number of member vortices in the ensemble storm is incorporated.

6. Evidence for intraseasonal predictability of typhoon events

The eight typhoons that developed during the experimental weekly ECMWF 32-day predictions initiated on Thursdays beginning 5 June 2008 through 25 December 2008 are divided into two groups. The predictions of the three strong typhoons

(Sinlaku, Hagupit, and Jangmi) during the second month of the combined TCS08/T-PARC field experiment are examined separately because they may have benefited from the special observations during the first month.

a. Three strong typhoon events during September 2008

The evaluations of the quality of the ensemble storm predictions relative to these three typhoon events is given in Table 1a. Typhoon Sinlaku was the signature event during the combined TCS08/T-PARC experiment because special observations were made from an early stage with one period on 10-11 September 2008 in which four aircraft were in the storm. Special observations were also made during its re-intensification to a typhoon near Japan after having struck Taiwan and decayed, and finally during the extratropical transition stage.

The Thursday forecast beginning 0000 UTC 11 September 2008 is selected as the Week 0 period for the Sinlaku case. As indicated in Fig. 6a, the ECMWF ensemble storm track matches the JTWC track very well during the landfall on Taiwan and into the recurvature period. However, the ensemble storm is predicted to accelerate too early during the post-recurvature so that it was about 36 h too early as to when Sinlaku would pass near Japan as a typhoon and then turn eastward during the extratropical transition. The spread of the 51 member vortices that are contained in this ensemble storm is quite small and indicates considerable confidence could be placed in the predicted ensemble storm track. Because of this agreement with the JTWC track, this Week 0 forecast for Sinlaku clearly justifies a quality assessment of Excellent (Table 1a).

Two ensemble storms (fourth in Fig. 7a and eighth in Fig. 7b) matched from the vortices predicted in the Week-1 forecast begun on 4 September are assigned quality indicators of Good and Above Average (hereafter just Above), respectively. Notice that Storm 4 has 23 member vortices with a track that begins two days after the model initial time (Table 1a) near 14°N, 136°E and is toward the west because a majority of the vortex tracks are in that direction. However, nine of the vortex tracks are toward the north with a path that is more similar to the actual track of Sinlaku (see Fig. 6a). Because the matches of ensemble storm 4 are limited to early in the track, a qualifier of "only good early" is given to that storm (Table 1a). Ensemble storm 8 begins two days later (Table 1a), which is then 11 days prior to the time of the forecast in Fig. 6a. Although the initial position is near 15°N, 135°E, which is about 9° longitude to the east of the actual position, the objective matching technique indicates agreement within $\varepsilon(t)$ at nearly all positions in ensemble storm 8 (Fig. 7b) from 1200 UTC 11 September to 1200 UTC 20 September when the ensemble storm is just east of Tokyo, Japan. Thus, ensemble storm 8 is assigned a quality indicator of Above (Table 1a), but it is not assigned an indicator of Excellent because of the offset to the east at the beginning and especially when Sinlaku made landfall on Taiwan. Although a smaller number of vortices is contained in ensemble storm 8 relative to ensemble storm 4, it is clearly the more representative forecast track. Although nine northward tracks are included in ensemble 4 (Fig. 7a), application of the subjective evaluation procedure outlined in section 5c should not result in a combination of the two ensemble tracks because they clearly represent two different track scenarios.

During this Week-1 forecast, the ensemble storm 15 track (not shown) began another day later and even farther to the east than ensemble storm 8. Although a few positions were objectively matched late in the forecast, this ensemble storm clearly represents a different scenario and is assigned a quality indicator of Poor (Table 1a) since the matches were coincidental.

During the Week-2 forecast initiated on 28 August, ensemble storm 2 (Fig. 8a) began near 12°N, 145°E on Day 3.5 and eventually had 20 members, ensemble Storm 4 (Fig. 8b) with a maximum of 18 members began on Day 4 but near 10°N, 148°E, and ensemble storm 13 (Fig. 8c) began on Day 12 near 12°N, 135°E with a maximum number of tracks of only seven (Table 1a). When Sinlaku formed around 8 September, ensemble storms 2 and 4 were immediately matched by the objective technique, and ensemble storm 13 was delayed but matched the early track of Sinlaku after 3.5 days. Ensemble storms 2 and 4 are an excellent example of the subjective matching technique described in section 5c in which two ensemble storms that eventually have numerous members begin at nearly the same time from different positions, but then evolve to provide quite similar guidance about the Sinlaku early track. Ensemble storm 13 begins later, but would subjectively be considered to also provide similar guidance with either ensemble members 2 or 4 as the "seed storm." This combination of 45 vortex tracks would then be considered to indicate with high confidence that a tropical cyclone was going to form just east of the Philippines. Although ensemble storm 4 indicates a track over Taiwan, the other two tracks indicate a more westward track to the south of Taiwan. Nevertheless, this subjective combination of the three ensemble storm tracks from a 32-day ensemble forecast that had began about 10 days before Sinlaku existed and about 16 days before Sinlaku struck Taiwan indicates some predictability on intraseasonal time scales.

Similarly, ensemble storms 16 and 20 (not shown) that both began around 16 days into the Week-3 (Table 1a) forecast that began on 21 August might be subjectively combined even though both only contained five members. Since ensemble storm 16 passed over Taiwan and ensemble storm 20 passed over Luzon, Philippines, these storms are classified in the Above category and certainly would have been good guidance at Week-3 with a total of 10 members. Ensemble storms 23 and 26 (not shown) also have six and five members and are assigned in the Good category in the sense that they would provide some

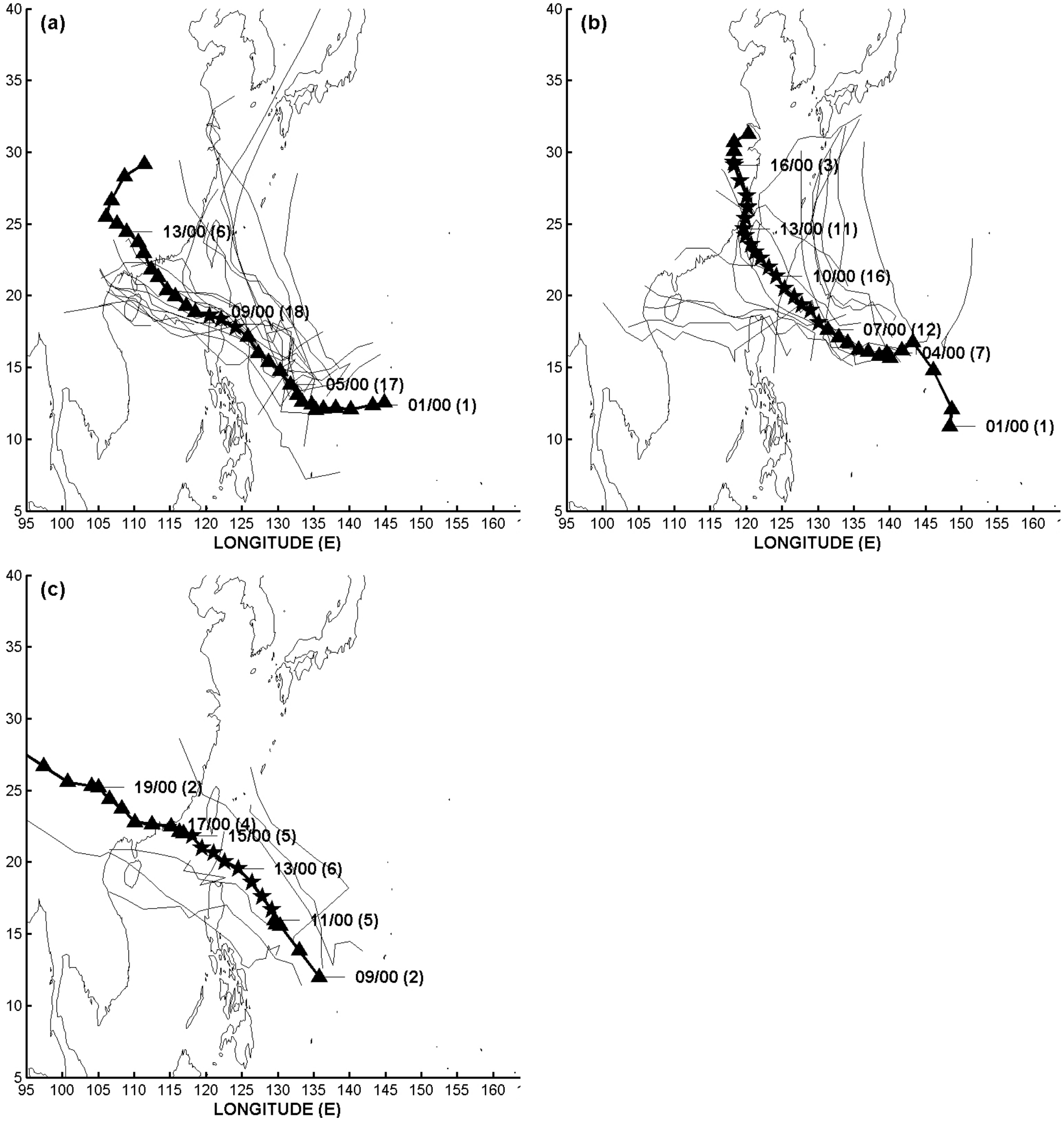

Fig. 8. As in Fig. 7, except for (a) ensemble storm 2 with 20 members, (b) ensemble storm 4 with 18 members, and (c) ensemble storm 13 with 7 members in the 28 August 2008 forecast (Week-2) of Sinlaku.

indication of the Sinlaku event, but were too far to the east (especially ensemble storm 26) to be subjectively combined to add more confidence.

Finally, the Week-4 forecast initiated on 14 August (about a month before Sinlaku struck Taiwan) resulted in a 10-member ensemble storm 21 and 6-member ensemble storm 30 (Fig. 9). These storms began 17.5 days and 22 days into the Week-4 forecast and both were assigned a quality indicator of Above (Table 1a). Ensemble storm 21 is predicted to pass over Taiwan, although the early stage was well to the east of the actual location. Ensemble storm 30 started near the region where Sinlaku formed, but then took a more westward track across the northern

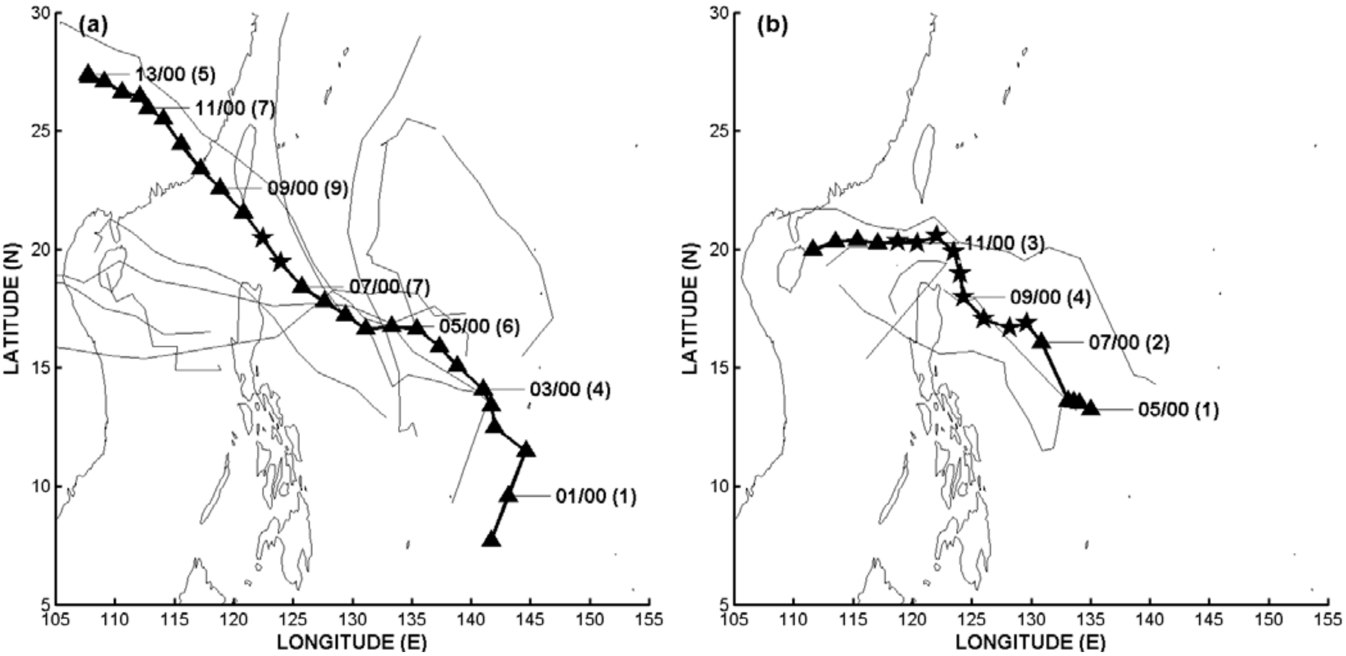

Fig. 9. As in Fig. 7, except for (a) ensemble storm 21 with 10 members and (b) ensemble storm 30 with 6 members in the 14 August 2008 forecast (Week-4) of Sinlaku.

Philippines. If the ten members of ensemble storm 21 are considered sufficient for a "seed storm," then the track of ensemble storm 30 would meet the criteria in section 5c to subjectively combine these two storms. With a total of 16 (i.e., 31% of the 51 possible) members, this case would indicate some intraseasonal predictability at Week-4, at least for this strong Typhoon Sinlaku.

Another consideration in the predictability on intraseasonal time scales is whether consistency exists in location or there is convergence on the track type of an event that is occurring in the predictions from Week-4 (i.e., 28 days before the event is occurring) until the Week-0. In the predictions of the Sinlaku event, the location to the east of the Philippines and two track types (toward Taiwan or a westward track across the northern Philippines) were consistently indicated from Week-4 forward in time. However, it is curious that such a weak indication of the track orientations was predicted in Week-1. This forecast-to-forecast consistency aspect will be able to be applied more effectively when the frequency of the ECMWF monthly forecasts is increased to twice a week (Vitart *et al.,* 2008).

The performance of the ECMWF 32-day ensemble for TY Hagupit (Table 1a) was similar to the Sinlaku event, but illustrates timing issues with the tracks. Even at Week 0 (Fig. 10a), the number of the ensemble vortices that had more northward tracks rather than the correct western tracks around the northern tip of Luzon, Philippines led to a predicted landfall that was farther east along the South China coast. As was the case in the Sinlaku event, the Week-1 forecast identified with Hagupit (Table 1a) had a relatively small number of members. Although the forecast path (not shown) was excellent, the timing was several days late, and thus the assessment was only as Above (Table 1a).

Another similarity in the Hagupit event with the Sinlaku event was that three ensemble storms (13, 17, and 18) predicted in Week-2 (Table 1a) had tracks that could be subjectively evaluated to provide similar guidance and thus be combined to indicate a higher probability (42 of a possible 51 member vortices) that the event would occur. The track of ensemble storm 13 (Fig. 10b) with 12 member vortices practically overlies the actual track, but is early by 5 days. Although the track of ensemble storm 17 (Fig. 10c) with 12 member vortices passes through southern Luzon rather than around northern Luzon, the landfall position in South China is quite good. However, this track is late by several days. Finally, the track of ensemble storm 18 (Fig. 10d) with 18 member vortices overlies the actual northwestward track for three days, but then deviates to the north. However, a large fraction of the vortex tracks for ensemble storm 18 actually had westward tracks (Fig. 10d) that were more correct. The combination of these three ensemble storm tracks with a total of 42 members would provide relatively confident guidance that a tropical cyclone would begin east of the Philippines in about 20 days and have a landfall on the South China coast in about four weeks from the initial time of the 28 August 2008 integration.

The subjective assessment in section 5c applied to the Hagupit Week-3 forecast resulted in the combination of ensemble storms

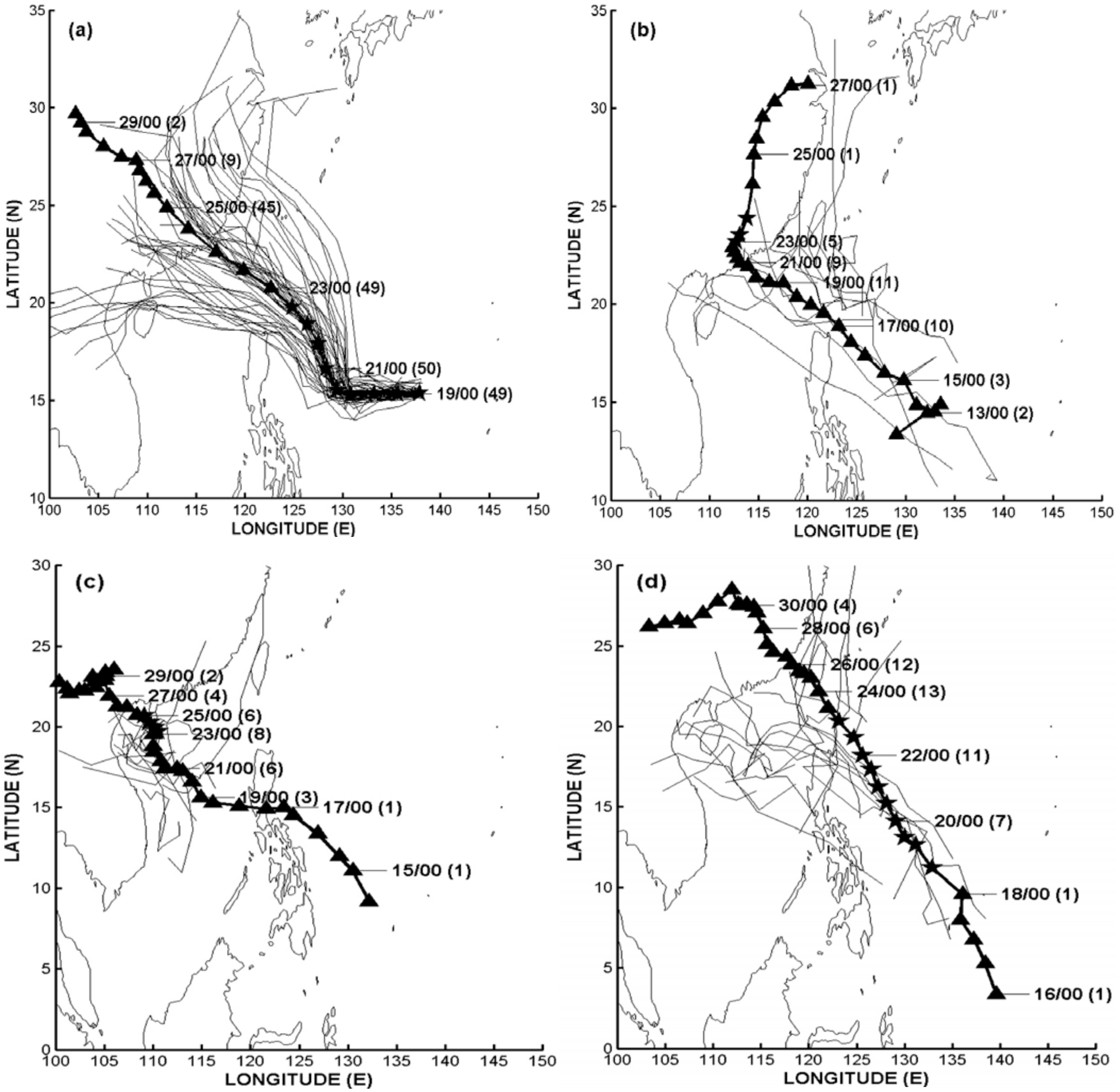

Fig. 10. As in Fig. 7, except for Hagupit and (a) ensemble storm 1 with 51 members in the 18 September 2008 forecast (Week 0), (b) ensemble storm 13 with 12 members, (c) ensemble storm 17 with 12 members, and (d) ensemble storm 18 with 18 members in the 4 September 2008 forecast (Week-2).

19 and 26 for a total of 18 members (Table 1a). Again ensemble storm 26 had an excellent path prediction (not shown) but it was 4 days late. The ensemble storm 19 had a similar shape to the track (not shown) but was to the south by more than 5° latitude. Although one might have subjectively included ensemble storm 15 with 24 members in this group because the path closely resembles the Hagupit track, this storm was more than 5 days early and the only objective matches occurred following predicted landfall when the translation speed was small so the actual storm overtook it.

The Jangmi event (Table 1a) again had similarities with Sinlaku and Hagupit: (i) an excellent Week 0 track; (ii) a low number of members in the Week-1 forecast; (iii) Above guidance with 19 members in Week-2; and (iv) a subjective combination in Week-3 of an Excellent ensemble storm 20 track with 11 members and a Good ensemble storm 23 that was shifted to the

Table 1b. As in Table 1a, except for other typhoons during the 5 June to 25 December integrations.

STORM	WEEK 0	WEEK-1	WEEK-2	WEEK-3	WEEK-4
07 W Fengshen 110 kt 19 June	(1) 0 days [51] Excellent	(1) 1.5 days [12] Good^{o} (6) 10 days [1] Poor$^{\#}$	(4) 14.5 days [5] Below^{o}	Not available	Not available
08 W Kalmaegi 90 kt 17 July	(1) 0 days [23] Excellent	(2) 1.5 days [16] Good*	None	None	None
09 W Fung-Wong 95 kt 24 July	(1) 0 days [49] Excellent	(5) 5.5 days [4] Above^{o} (9) 8.5 days [1] Poor*	(2) 1.5 days [16] Good^{l} (13) 8 days [12] Poor$^{\#}$ (15) 9 days [12] Below^{e} (20) 15 days [2] Below^{e}	*(12) 16 days [3]* *Above*$^{\triangle}$ (16) 18.5 days [24] Below^{e} *(18) 21 days [2]* *Good*^{s}	*(15) 22.5 days [3]* *Above*^{e} *(18) 23 days [6]* *Good*^{e}
13 W Nuri 110 kt 21 August	(1) 0 days [51] Excellent	None	*(9) 4 days [14]* *Above*^{s} *(12) 8 days [6]* *Excellent*	*(23) 12 days [12]* *Excellent* *(25) 15 days [4]* *Excellent*	(30) 24.5 days [4] Good^{s} (34) 26.5 days [1] Good^{e}
27 W Dolphin 85 kt 11 December	(1) 0 days [43] Excellent	None	None	None	None

Superscripts: o = only good early; # = coincidental match; △ = little slow; e = shifted to east; * = several days late; s = shifted to south; l = only good late.

east. Even the Week-4 forecast had an Excellent ensemble storm 23 track with 11 members (Table 1a), which might be considered as a region and track that should be monitored in the next weekly forecast for a potential storm event.

Overall, the ECMWF 32-day forecasts provided guidance on the formation and tracks on intraseasonal time scales for these three strong typhoons during the TCS08/T-PARC field experiment period. The subjective assessment procedure described in section 5c would appear to be useful in increasing the confidence in the Week-2 to Week-4 forecasts when similar tracks can be combined.

b. Five other typhoon events after 5 June 2008

The performance of the ECMWF 32-day forecasts for the other five western North Pacific typhoons after 5 June 2008 is summarized in Table 1b. In the case of Typhoon Fengshen, the Week 0 forecast is from 19 June and this storm can only be validated through the Week-2 (5 June) forecast. Although the Week 0 forecast ensemble storm 1 with 51 members is assessed as an Excellent track (Table 1b) through the first 5 days, the track was displaced well to the east and then to the north after that time (not shown). This northward bias for Fengshen was common to all of the deterministic model guidance available to JTWC and this led to some of the largest track forecast errors of the 2008 season.

The Week-1 forecast ensemble storm 1 with 12 members was only assessed as Good (Table 1b) because it agreed well with the Fengshen track for two days and then was markedly displaced to the east and recurved toward southern Japan (not shown) instead of predicting the landfall near Hong Kong. The Week-2 forecast had no skillful tracks (Table 1b).

The performance of the ECMWF 32-day forecasts for Kalmaegi was very similar to that for Fengshen (Table 1b) . Even though only 23 vortex members were included in the Week 0 (17 July) ensemble storm 1, the track forecast was rated as Excellent. Although the Week-1 path forecast for ensemble storm 2 had a few early positions that were objectively matched with the Kalmaegi positions (not shown), the quasi-stationary period of Kalmaegi was not forecast and the ensemble storm was about 5 days too fast in predicting landfall on the east coast of China.

No objective matches of the ensemble storms with Kalmaegi occurred in the Week-2, Week-3, and Week-4 (Table 1b). Thus, it is clear that no intraseasonal predictability existed for Kalmaegi, and likely also for Fengshen. The reasons for this lack of predictability compared to the three strong typhoons described in section 7a are unclear. Whether this is a characteristic of early season cyclones can only be tested with a larger sample.

By contrast, the performance of the ECMWF 32-day forecasts for Typhoon Fung-Wong and Typhoon Nuri (Table 1b) is similar to that of the three strong typhoons (Table 1a). For both of the typhoons, an Excellent Week 0 forecast ensemble storm 1 is preceded in Week-1 forecasts that have minimal skill. That is, the Week-1 ensemble storm 5 for Fung-Wong was assessed as Above, the matches were only for two days early in the track and then the ensemble storm took a northwestward path instead of a westward track (not shown). In the case of Nuri, no objective matches of the Week-1 ensemble storms exist. The ECMWF (and other deterministic models-Elsberry *et al.,* 2009) model was following a wave in the easterlies that was farther to the north until the first TCS08/T-PARC aircraft flights on 15 August revealed a center developing to the south of Guam. It was the southern circulation that became Nuri, and this likely is the explanation for absence of a match during Week-1.

The Week-2 forecasts for Fung-Wong and Nuri provided better guidance than the Week-1 forecasts (Table 1b). For Fung-Wong, only one of the forecasts was assessed as Good. Although ensemble storm 2 with 16 members is an excellent path forecast for several critical days prior to landfall (not shown), the timing is off by about 5 days (late). Ensemble storm 15 has 12 members and a few matches occur early in the period, but the subsequent track is poleward rather than westward (not shown). For Nuri, the Week-2 ensemble storms 9 and 12 with 14 and 6 vortex members, respectively, are subjectively evaluated to have tracks that provide similar guidance (Table 1b). Whereas the track of ensemble storm 9 is parallel to the Nuri track (not shown), it is displaced to the south and thus is assessed as Above. The ensemble storm 12 has an Excellent track (not shown).

The Week-3 forecast of Nuri has two Excellent tracks (Table 1b) in which the seed ensemble storm 23 with 12 members would be subjectively combined with ensemble storm 24 with an additional four members. For the Week-3 forecast of Fung-Wong (Table 1b), ensemble storms 12 and 18 have tracks that provide similar guidance that would be useful, although this combination would only have five members. By contrast, the 24 members of ensemble storm 16 would indicate a more likely track that is only assessed as Below because it is well to the east of the Fung-Wong track.

Although the Week-4 ensemble storms necessarily have shortened tracks in a 32-day forecast, ensemble storms 15 and 18 for Fung-Wong have tracks with a total of nine members that subjectively appear to provide similar guidance that would be useful (Table 1b). In particular, the ensemble storm 15 track (not shown) is assessed as Above as it has the same shape but is shifted to the east. Ensemble storm 18 is shifted farther to the east but at the end of the 32-day forecast is objectively matched with the Fung-Wong track.

The last typhoon of the season (Dolphin) occurred in mid-December 2008 (Table 1b). The Week 0 forecast initiated on 11 December had an ensemble storm 1 with 43 members that was an Excellent track forecast. However, none of the ensemble storms in the Week-1 through Week-4 forecasts had a single 12-h position match with the Dolphin track. Thus, no intraseasonal predictability exists for this typhoon.

In summary, the two early season typhoons (Fengshen and Kalmaegi) and the late season typhoon (Dolphin) clearly were not predictable on intraseasonal timescales. Two typhoons (Fung-Wong and Nuri) that occurred closer to the peak typhoon months had similar evidence of being predictable on 14-28 day timescales, as was the case with the three strong typhoons discussed in section 6a. However, a disturbing minimum of predictability occurs in the Week-1 forecasts of all five of these typhoons that seem to have predictability at longer timescales. The subjective assessment of track similarity described in section 5c appears to contribute to enhanced probability of an event occurring in Week-2 through Week-4.

7. Evidence for intraseasonal predictability of strong tropical storms

Based on the Elsberry *et al.* (2009) evaluation of the four deterministic global models performance in predicting tropical cyclone formations during the TCS08/T-PARC experiment, one might expect that ensemble predictions of events that resulted in a strong tropical storm would be more predictable on intraseasonal time scales. Thus, the performance of the ECMWF 32-day ensemble forecasts for four strong tropical cyclones that occurred after 5 June and achieved 50-55 kt maximum intensity according to the JTWC is summarized in Table 2.

Even though JTWC did not consider Kammuri had become a Tropical Depression in the northern South China Sea until 4 August, the Week 0 ECMWF forecast is selected to be the one initiated on 31 July 2008 because ensemble storms 2 and 4 began in the first day (Table 2). Ensemble storm 2 with 11 members began east of the Philippines and had a track (not shown) assessed as Excellent (Table 2) although it was a little slow in predicting a landfall on the South China coast. The track of ensemble storm 4 with 14 members was assessed as Above (Table 2) as it began in the central South China Sea but had an excellent timing on position of the landfall point (not shown).

The Week-1 forecast ensemble storm 4 with 42 members had an Excellent (Table 2) track in that it overlayed the actual track from the time of the first entry in the JTWC best-track file through the landfall on the South China Sea. Similarly, the Week-2 forecast provides guidance of the TS Kammuri event. Ensemble storm 12 with 14 members had an Excellent (Table 2) track in terms of both location and timing. Whereas the predicted path of ensemble storm 15 with 18 members was excellent, the timing was delayed by 2-3 days so that the assessment was Above (Table 2). Finally, the Week-3 forecast had two similar tracks that would

Table 2. As in Table 1a, except for strong tropical storms during the 5 June to 25 December integrations.

STORM	WEEK 0	WEEK-1	WEEK-2	WEEK-3	WEEK-4
10 W Kammuri 50 kt 31 July	*(2) 0 days [11]* *Excellent* *(4) 1 days [14]* *Above*	(4) 3.5 days [42] Excellent	*(12) 10 days [14]* *Excellent* *(15) 12 days [18]* *Above*$^{\triangle}$	*(25) 17.5 days [9]* *Above*^{n} *(31) 22.5 days [9]* *Excellent* *(35) 24.5 days [1]* *Good*^{l}	None
12 W Vongfong 55 kt 14 August	(1) 1.25 days [33] Excellent	(6) 2.5 days [15] Above^{o}	(1) 0.5 days [12] Above^{o} (17) 7 days [5] Poor$^{\#}$	(13) 10 days [7] Poor$^{\#}$ *(16) 12 days [12]* *Good* *(18) 13 days [24]* *Above*^{s}	(24) 22 days [5] Poor$^{\#}$ (31) 26.5 days [1] Good
20 W Mekkhala 55 kt 25 September	(6) 0 days [33] Good	(3) 3.5 days [44] Excellent	(5) 5 days [20] Above^{l}	*(17) 10.5 days [12]* *Good** *(22) 20 days [12]* *Above*	None
24 W Maysak 55 kt 6 November	(1) 0 days [56] Above	*(0) 4 days [32]* *Good*^{s} *(3) 3 days [37]* *Above*$^{\triangle}$	(20) 11 days [1] Below^{e} *(21) 11.5 days [11]* *Good** *(22) 14 days [4]* *Good**	*(14) 15 days [15]* *Above** *(18) 21.5 days [16]* *Good** *(23) 24 days [5]* *Good*$^{\triangle}$	(29) 23 days [10] Good^{s} *(32) 25 days [8]* *Above*

Superscripts: n = shifted to north; l = only good late; o = only good early; # = coincidental match; * = several days behind; s = shifted to south; △ = little slow

meet the criteria in section 5c for subjectively combining the tracks. Ensemble storm 25 with nine members was assessed as Above (Table 2) because the track was shifted to the north. En-semble storm 31 with nine members was assessed as Excellent (Table 2) considering the objective matching within ε (t) was perfect for all of the JTWC positions (not shown). Since the ensemble storm 31 track was a little to the south and the ensemble storm 25 was to the north, the composite of the two storms would provide confident evidence of the Kammuri location and timing.

The ECMWF 32-day forecast performance for the strong TS Vongfong event was similar (Table 2): (i) Excellent track forecast in Week 0 by ensemble storm 1 with 33 members; (ii) ensemble storm 6 with 15 members during Week-1 was again more skillful than all of the typhoons in Table 1; (iii) a skillful track was forecast by ensemble storm 1 in Week-2, although with only 12 members versus the combined 32 members in Week-2 for the Kammuri event; and (iv) a combination of a seed storm 18 with 24 members and a similar track of ensemble 16 with 12 members in Week-3 would provide a confident forecast of the Vongfong event.

Likewise, the 32-day forecast for the strong TS Mekkhala was similar to the performance with TS Kammuri. Whereas the Week 0 ensemble storm 6 track with 33 members was only assessed as Good (Table 2) due to poor timing even though the path was quite good, the Week-1 ensemble storm 3 track forecast based on 44 members was assessed as Excellent (Table 2) because it represented well the extended period of quasi-stationary motion in the South China Sea before moving into northern Vietnam. As in the TS Kammuri and TS Vongfong forecasts, the Week-2 forecast was assessed as Above and the seed ensemble storm 17 in Week-3 could be subjectively combined with the nearby ensemble storm 22 to form a more confident forecast of the TS Mekkhala event on intraseasonal timescales.

Finally, the performance of the ECMWF 32-day forecasts for strong TS Maysak (Table 2) is as good or better than for the other three strong tropical storms. Note that a subjective combination in Week-1 of the seed ensemble storm 3 with 37 members and ensemble storm 1 with 32 members would provide highly confident forecast of the Maysak track, although the full loop in the track is not predicted (not shown). A subjective combination of Week-3 ensemble storms 14, 18, and 23 with 15, 16, and 5 members, respectively, would provide a more confident forecast of the Maysak event (Table 2). Even at Week-4, a subjective combination of ensemble storms 29 with 10 members and 32 with 8 members would provide an alert that a tropical cyclone event will occur in the South China Sea in four weeks. Confirmation of such an event in the same area and with a similar track in each subsequent weekly forecast would provide more

Table 3. As in Table 1a, except for weak tropical storms during the 5 June to 25 December integrations.

STORM	WEEK 0	WEEK-1	WEEK-2	WEEK-3	WEEK-4
21 W Higos 40 kt 2 October	(1) 0 days [38] Excellent	*(5) 0 day [28]* *Good*^{o} *(6) 0 day [33]* *Above*^{l}	(3) 3.5 days [44] Good^{l} *(4) 4.5 days [22]* *Good*^{e} *(5) 5 days [25]* *Below*^{e} (9) 6.5 days [7] Good^{l}	(17) 14 days [36] Excellent (23) 20 days [2] Below^{s}	(20) 15.5 days [11] Poor^{l} *(23) 21 days [9]* *Above*^{l} *(27) 23 days [13]* *Excellent*
23 W Bavi 45 kt 16 October	(5) 2 days [5] Excellent	(14) 6.5 days [1] Excellent	None	None	None
26 W Noul 40 kt 13 November	(1) 0 days [33] Excellent	(4) 5.5 days [7] Above^{a}	(14) 14.5 days [1] Poor^{s} (15) 17.5 days [2] Good*	(25) 17.5 days [11] Above	(29) 29 days [4] Below*

Superscripts: o = only good early; l = only good late; e = shifted to east; s = shifted to south; n = shifted to north; * = several days behind; a = a little fast

confidence as to the likely occurrence.

In summary, these four strong tropical storms (Table 2) were forecast by the ECMWF 32-day forecasts more consistently over Week-1 through Week-4 than for the typhoons summarized in Table 1b. Subjective assessments of similar tracks leads to larger numbers of members and thus a higher confidence in the occurrence of these strong tropical storms. Whereas this evaluation suggests an intraseasonal predictability for these strong tropical storms, it is not known whether this result may be biased because three of these four tropical storms formed in the South China Sea where the observation coverage may be better.

8. Lack of intraseasonal predictability of weak tropical cyclones

For completeness, the lack of predictability on intraseasonal timescales for the weaker tropical cyclones during 5 June 2008 through 25 December 2008 is summarized in Tables 3 through 5. This lack of predictability is not surprising as Elsberry *et al.* (2009) concluded that the four deterministic global models did not consistently predict the formations for baroclinic systems or when the tropical cyclone only achieved tropical depression stage during the TCS08/T-PARC experiment.

The only exception is the performance of the ECMWF 32-day forecasts for weak TS Higos (Appendix Table 3), which is quite similar to the performance for the strong tropical storms in Table 2. That is, an Excellent assessment is assigned for ensemble storm 1 with 38 members during Week 0 and a subjective combination of a Week-1 seed ensemble storm 6 with 33 members with ensemble storm 5 that has 28 members would provide rather confident guidance of the occurrence of TS Higos. Similarly, a subjective combination of the Week-2 ensemble storms 4 and 5 both with 22 and 25 members (Table 3) would also provide confident guidance. Whereas Week-2 ensemble storm 3 with 44 members was assessed as a Good match for Higos with the qualifier that the agreement was late in the period, it was an Excellent match for Mekkhala (Table 2). The 36 member ensemble storm 17 in Week-3 was assigned an Excellent quality (Table 3) for the Higos event. Finally, a subjective combination of ensemble storm 27 with 13 members as the seed storm with ensemble storm 23 with nine members provides a confident alert even in Week-4 as to the likely tropical cyclone occurrence. This storm occurred at the end of the TCS08/T-PARC field experiment after a month of intensive observations in Typhoons Sinlaku, Hagupit, and Jangmi, which may be a possible explanation for the better forecasts for weak TS Higos.

By contrast, weak TS Bavi was not predicted well by the ECMWF 32-day forecast even at Week 0 when only five vortex tracks were included in ensemble storm 5 (Table 3). In addition, no objective matches with the Bavi track occurred with any of the ensemble storms during Week-2, Week-3, or Week-4. The performance of the ECMWF 32-day forecasts for weak TS Noul was also not good, except that ensemble storm 1 with 33 members during Week 0 was assigned an Excellent quality (Table 3).

Because the ensemble prediction systems (EPSs) have been developed primarily for midlatitude, baroclinic systems, one might expect that those tropical cyclones that formed from baroclinic systems might be predictable. For example, the first entry for Tropical Depression (TD) 16 W in the JTWC best-track was on 9 September at 29°N, 150°E. The ECMWF 32-day

Table 4. As in Table 1a, except for baroclinic systems during the 5 June through 25 December integrations.

STORM	WEEK 0	WEEK-1	WEEK-2	WEEK-3	WEEK-4
TD 16 W 35 kt 4 September	(5) 2 days [20] Good^{o}	(10) 6 days [2] Above (12) 8.5 days [1] Below	(17) 15.5 days [5] Excellent	(27) 21.5 days [3] Above^{l} (38) 26.5 days [1] Above	None
TD 17 W 35 kt 11 September	(2) 0 days [11] Above*	(5) 2 days [20] Good^{n} (12) 8 days [2] Below*	(14) 13 days [2] Poor	None	(35) 25 days [3] Below$^{\#}$ (41) 27.5 days [1] Below$^{\#}$
25 W Haishen 40 kt 13 November	(20) 0 days [5] Excellent	None	None	None	None

Superscripts: o = only good early; n = shifted to north; * = several days behind; # = coincidental match; l = only good late.

forecast initiated on 4 September did include ensemble storm 5 with 20 members, but the track was only assessed as Good (Table 4) because a rapid poleward motion was predicted rather than a slow drift to the west with a later turn to the north (not shown). However, the Week-1 through Week-4 forecasts, had ensemble storms with only small numbers of vortices that could be objectively matched with the track of TD 16 W. A seemingly favorable indicator for baroclinic system TD 17 W was in the Week-1 forecast in which ensemble storm 5 had 20 members (Table 4). However, the remainder of the Week-2 through Week-4 forecasts for TD 17 W had ensemble storms with either two or fewer members or with no objective matches. Finally, no objective matches with any ensemble storms in Week-1 through Week-4 were found with the track of TS Haishen (Table 4), which formed from a baroclinic system. Thus, evidence is not found for intraseasonal predictability of tropical depressions or weak tropical storms that form from baroclinic systems.

The final group examined was three tropical depressions 11 W, 14 W, and 22 W that according to JTWC achieved wind speeds of 35 kt (one-minute sustained winds), but the RSMC-Tokyo Typhoon Center did not consider these systems to have 35 kt (10-minute sustained winds) and thus did not name them. Tropical Depression 11 W was a midget cyclone that formed from a mesoscale convective system that was off the east coast of Taiwan on 11 September and then moved northward to the south coast of the Republic of Korea. In the Week-1 forecast (Table 5), ensemble storm 8 with seven members was subjectively compared with ensemble storm 16 because both storms start in low latitudes and pass to the east of Taiwan. However, the different origin for the ensemble storms makes this agreement somewhat fortuitous. No substantial evidence of TC 11 W is available in the Week-2, Week-3, and Week-4 forecasts.

In the case of TD 14 W, the ECMWF 32-day forecasts in Week 0 and Week-1 had no ensemble storms that objectively matched the track (Table 5). Although ensemble storms 11 and 17 in the Week-2 and Week-3 had some matches late in the track, they had only four and seven members and had origins well to the east of TD 14 W (not shown).

Finally, the performance of the ECMWF 32-day forecasts for TD 22 W is somewhat better (Table 5). The Week 0 ensemble storm 1 has 44 members, but is only assessed as Good because it is several days behind. Although multiple ensemble storm matches with TD 22 W occur in Week-1, Week-2, and Week-3, application of the subjective evaluation for similarity of tracks does not result in matches that would indicate higher probability. It is possible that the somewhat better performance for TD 22 W in these forecasts may be attributed to the special TCS08/T-PARC observations during the preceding weeks in September in conjunction with the strong Typhoons Sinlaku, Hagupit, and Jangmi. In summary, no substantial evidence of intraseasonal predictability for the tropical depressions is found in this small sample.

9. Conclusions and discussion

The objective of this study has been to provide evidence of predictability on intraseasonal timescales (10-30 days) for western North Pacific tropical cyclone events-not just the formation, but also the tracks. The basic idea is that if the ECMWF monthly ensemble forecast can predict the large-scale environment in the tropics that determine the locations of tropical cyclones, then the overall features of the tracks of those tropical cyclones will also be predicted since the environmental steering is the first-order effect in tropical cyclone motion. Thus, the once-per-week ECMWF 51-member ensemble 32-day forecasts of tropical cyclone-like vortex tracks during the period 5 June through 25 December 2008 have been compared with the JTWC best-track file of storm events.

Several characteristics of these ensemble storm tracks affect the validation relative to the JTWC storms. First, the total of 826

Table 5. As in Table 1a, except for non-baroclinic tropical depressions during the 5 June through 25 December integrations.

STORM	WEEK 0	WEEK-1	WEEK-2	WEEK-3	WEEK-4
TD 11 W 35 kt 31 July	_(1) 0.5 days [12] Below_^{e} _(12) 6.5 days [6] Above_	_(8) 7 days [7] Above_^{l} (13) 10 days [7] Poor$^{\#}$ _(16) 12 days [12] Good*_	(28) 23 days [2] Good* (31) 26.5 days [1] Poor$^{\#}$	None	None
TD 14 W 35 kt 28 August	None	None	(11) 9.5 days [4] Below^{l}	(17) 11 days [7] Below^{l} (23) 19 days [2] Above	_(35) 22 days [2] Good*_ _(37) 23.5 days [6] Above_^{s} (39) 24.5 days [2] Poor$^{\#}$
TD 22 W 35 kt 9 October	(1) 0 day [44] Good*	(7) 4.5 days [5] Good^{e} (10) 8.5 days [2] Poor$^{\#}$	(6) 0 days [33] Good^{l} (18) 13 days [4] Good^{l} (23) 16.5 days [1] Good^{l}	(15) 12.5 days [11] Good^{n} (21) 17.5 days [8] Good^{l} (23) 20 days [6] Below^{e}	None

Superscripts: e = shifted to east; # = coincidental match; * = several days behind; l = only good late; s = shifted to south.

ensemble storms in the 30 overlapping weekly 32-day forecasts is excessive, and 626 (76%) of these storms had five or fewer member vortices. Second, the first position of the ensemble storms is on average 2.5 days before the first entry in the JTWC best-track, which typically corresponds to a satellite-based intensity of 15 kt. Thus, the tropical cyclone-like vortices as defined in the ECMWF tracking routine is identifying circulations well before the JTWC declares a system has become a Tropical Depression (25 kt sustained wind). Third, the ensemble storms that cross land tend to persist much longer than indicated by the JTWC best-track file, which contributes to longer durations. Fourth, the ensemble storm translation speeds in the deep tropics tend to have a slow bias. The effects of the first three characteristics could be ameliorated by a revision of the vortex detection criteria, but this is beyond the scope of this work.

A strict objective matching procedure is applied as a first step in the validation of the ensemble storm tracks. That is, the ensemble storm position at forecast time t must be within the same separation distance ε (t) of the JTWC position as used in the definition of the ensemble storm (180 n mi at Day 1 to 420 n mi at Day 14 and beyond). No time deviation is allowed in this objective matching. Given the four characteristics of the ensemble storms listed above, the early stages will not be matched, the slow bias will lead to premature ending of matched storms, and the long-persisting ensemble storm positions over land will not be matched. The quality of the objective matching of the ensemble storms with the JTWC storms is assessed in five categories ranging from Excellent to Poor. A second subjective procedure then was applied to identify nearby ensemble storms with similar tracks to the left, right, slower, or faster that if combined would indicate a greater likelihood of a tropical cyclone developing in that region with that track orientation.

The first set of ensemble storms compared with the JTWC storms were the three strong typhoons during the second month of the TCS08/T-PARC, noting that the ECMWF forecasts in this month may have benefited from the special observations during the previous month. With the inclusion of the subjective procedure, the ensemble storms identified in the ECMWF 32-day forecasts provided guidance on intraseasonal timescales of the formations and tracks of these three strong typhoons.

The validations of the ensemble storms relative to the other five typhoons in the JTWC best-track file from the 5 June through 25 December periods were more mixed. The two typhoons (Fung-Wong and Nuri) that occurred closer to the peak typhoon months had similar evidence of being predictable on 14-28 day timescales. However, two early season typhoons (Fengshen and Kalmaegi) and the late season typhoon Dolphin clearly were not predictable on intraseasonal timescales.

Four strong tropical storms, including three that developed in the South China Sea, were predicted more consistently over Week-1 through Week-4 than for the five weaker typhoons. The subjective procedure for assessing similar tracks leads to larger numbers of members in the combined ensemble storms, and thus to a higher confidence in the occurrence of these strong tropical storms. A similar conclusion of intraseasonal predictability for weak TS Higos may be because Higos occurred at the end of a month of greatly enhanced TCS08/T-PARC observations. The other two weak tropical storms clearly were not predictable on intraseasonal timescales. Similarly, no substantial evidence of predictability on intraseasonal timescales was found for two weak tropical storms and a tropical depression that formed from precursor baroclinic systems, and three other tropical depressions.

In conclusion, the matching procedure to identify ensemble storms from the once-per-week experimental 51-member ECMWF ensemble 32-day forecasts of tropical cyclone-like vortices results in realistic tracks. Although these tracks begin early, tend to have a slow bias in the deep tropics, and persist longer over land, many of those tracks with more than five members can be objectively matched with the JTWC storm tracks. Except for two early and one late season typhoons, the two-step objective plus subjective validation provides evidence of intraseasonal (10-30 day) predictability for typhoons and strong tropical storms in this sample of 32-day ensemble forecasts initiated once a week on 5 June through 25 December 2008.

Elsberry *et al.* (2009) offered a possible explanation for the success of global models in predicting typhoon and strong tropical storms and not the weaker systems that may depend on mesoscale system processes. The stronger circulation systems require favorable environmental conditions (dynamical and thermodynamical) over large areas not just for formation but also during the time necessary for intensification to strong tropical storm and typhoon stages. Thus, it may be these large-scale regions of favorable environmental conditions that the ECMWF ensemble model members are capable of predicting even on intraseasonal timescales. Since the convective parameterization in the ECMWF model appears to be overly active (i.e., generates too many tropical cyclone-like vortices, and too early), the necessity or the requirement for a mesoscale circulation in the formation process is obviated given the existence of favorable environmental conditions.

Future work will be directed to utilizing the ensemble storm characteristics derived from this analysis to develop a technique to forecast on 10-30 day timescales strong tropical storm and typhoon events that are likely to occur during the peak season. Such a technique will require a calibration step that will identify the true events and exclude the many ensemble storms with few members that do not represent actual events. Success with such a technique based on the ECMWF 32-day ensemble forecasts would provide 10-30 day guidance to forecasters and long-range planners as to the strong typhoon events that are most dangerous and thus pose the greatest threat to people and property.

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