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Opportunities and challenges for extended-range predictions of tropical cyclone impacts on hydrological predictions

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SUMMARY

An opportunity exists to extend support to the decision-making processes of water resource management and hydrological operations by providing extended-range tropical cyclone (TC) formation and track forecasts in the western North Pacific from the 51-member ECMWF 32-day ensemble. A new objective verification technique demonstrates that the ECMWF ensemble can predict most of the formations and tracks of the TCs during July 2009 to December 2010, even for most of the tropical depressions. Due to the relatively large number of false-alarm TCs in the ECMWF ensemble forecasts that would cause problems for support of hydrological operations, characteristics of these false alarms are discussed. Special attention is given to the ability of the ECMWF ensemble to predict periods of no-TCs in the Taiwan area, since water resource management decisions also depend on the absence of typhoon-related rainfall. A three-tier approach is proposed to provide support for hydrological operations via extended-range forecasts twice weekly on the 30-day timescale, twice-daily on the 15-day timescale, and up to four times a day with a consensus of high-resolution deterministic models.

1. Introduction

1.1. Background

Especially in the mountainous terrain of Taiwan, floods, debris flows, and landslides are usually induced by the heavy rainfall associated with tropical cyclones (TCs) (Wu and Kuo, 1999; Wu et al., 2002; Tsai and Lee, 2009; Lee et al., 2011). In August 2009, Typhoon Morakot produced almost 3000 mm rainfall over three days as it approached and slowly passed by Taiwan. The rainfall-induced hazards caused 619 deaths and over USD 500 million agriculture losses (Lee et al., 2011).

Despite these destructive effects, TC rainfall is a major water resource in Taiwan. Over 50% of the water resources in southwestern Taiwan come from TC rainfall. Whereas the annual average rainfall in Taiwan is more than 2000 mm, the non-uniform spatial and temporal rainfall distribution and limited reservoir capacity may lead to serious shortages in agricultural water supplies (Huang and Yuan, 2004; Chen et al., 2009). If deficient rainfall occurs during the Mei-yu season, the water storage in the reservoirs in summer can be very low if the typhoon-related rainfall is also deficient, and the Water Resources Agency in Taiwan may need to limit water usage. By contrast, abundant rainfall during Mei-yu plus multiple typhoons may lead to dangerously high water levels during the typhoon season. Thus, predicting both the typhoon-related rainfall and the absence of such rainfall is a challenging issue for water resource management and reservoir operations (Chang and Chang, 2001).

As indicated by the Joint Typhoon Warning Center (JTWC) best-tracks from 1980 to 2010 in the western North Pacific basin (Fig. 1), the Taiwan area (here defined as 21–26°N and 119–125°E) is one of the most active TC regions in the basin. However, large interannual variations in the numbers of TCs exist, with a maximum of nine in 2004 and a minimum of one in 1983 (Fig. 2a). Whereas about 29% of the years during 1980–2010 have the average (and median) five TCs in the Taiwan area, the distribution about the average is rather uniform (Fig. 2b). Even in an active year, the occurrence of a tropical cyclone in the immediate Taiwan area must be considered a rare event.

In addition to the total number of TCs during a season, the first TC that would pass or form in the vicinity of Taiwan after the end of Mei-yu season is also an important factor for water resource management. Broadly defining the Mei-yu season as 15 May to 30 June, the length (days) after 30 June of the first TC gap (i.e., no TC track passing or forming in the Taiwan area) during 1980–2010 is shown in Fig. 3a. While the average first TC gap is 25.2 days and the median is 17 days, the distribution of first TC gaps is highly skewed. About 55% of the years have a TC passing by or forming in the Taiwan area within 20 days after the end of the Mei-yu season. If the Mei-yu rainfall has been plentiful and the water levels in the

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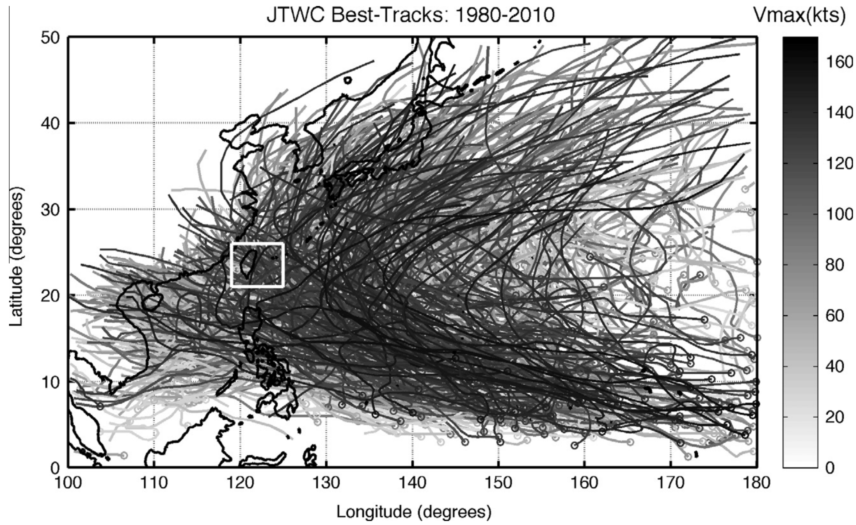

Fig. 1. JTWC best-tracks during 1980–2010. The white box (21–26°N, 119–125°E) is defined as the Taiwan area in this study.

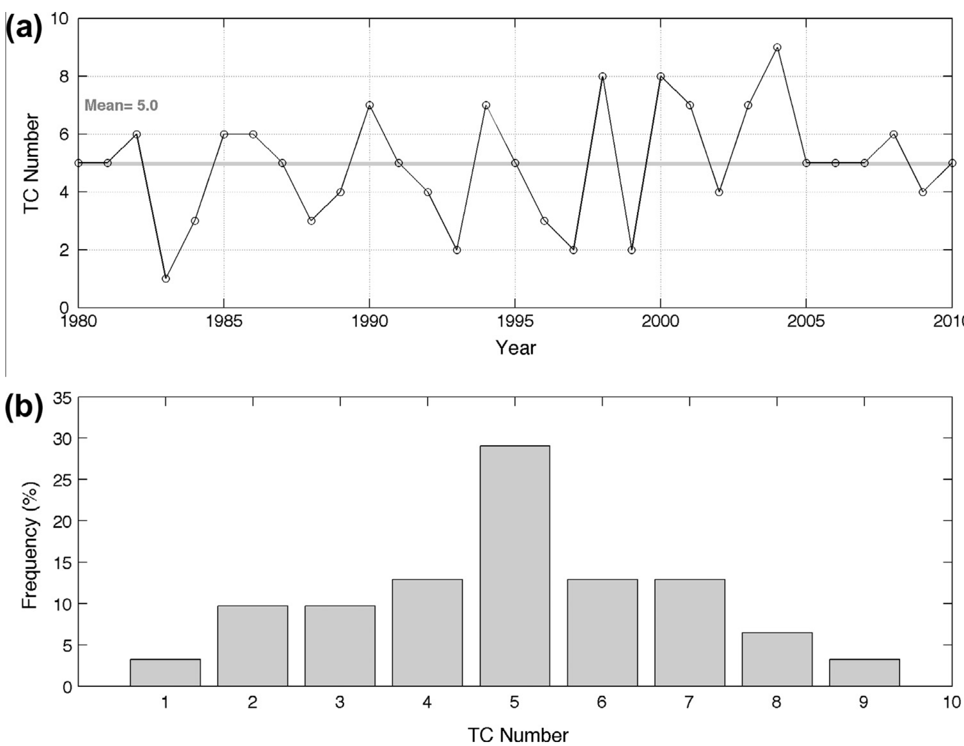

Fig. 2. (a) Annual variations in the number of TCs with maximum intensity ⩾25 kt in the Taiwan area (21–26°N, 119–125°E) during 1980–2010. (b) Frequency (%) distribution of annual number of TCs in which both the mean and median number of TCs is five.

reservoirs are high, the threat of flooding may be raised. By contrast, in 30% (15%) of the years, the first gap was longer than 30 (50) days.

These analyses indicate that using the average numbers of TC in the season is not sufficient in estimating the potential TC-related rainfall impacts for water resource management decisions. As indicated above, the distribution in time is also an important factor for water resource management. Although a drought event is a combination of water resources, water usages, and water management problems, the major drought events are usually related to the amount of typhoon rainfall and its major locations (Hsu et al., 2011). For example, a serious drought event occurred in Taiwan during 1993 (the first TC gap was about 75 days; Fig. 3a) due to the lack of typhoon (only two TCs in the Taiwan area; Fig. 2a) rainfall in the major reservoir catchment areas during that summer. The government limited the agricultural water supplies to support the domestic use, and the drought event was not relieved until April 1994 with heavy spring rainfall (Hsu et al., 2011).

1.2. Present typhoon forecast products

Hydrological predictions for hazards such as flooding, debris flows, and landslides first of all require an accurate typhoon track forecast both for the location of the rainfall and for the duration, which crucially depends on the translation speed. Forecasting the track is particularly difficult as the typhoon circulation interacts

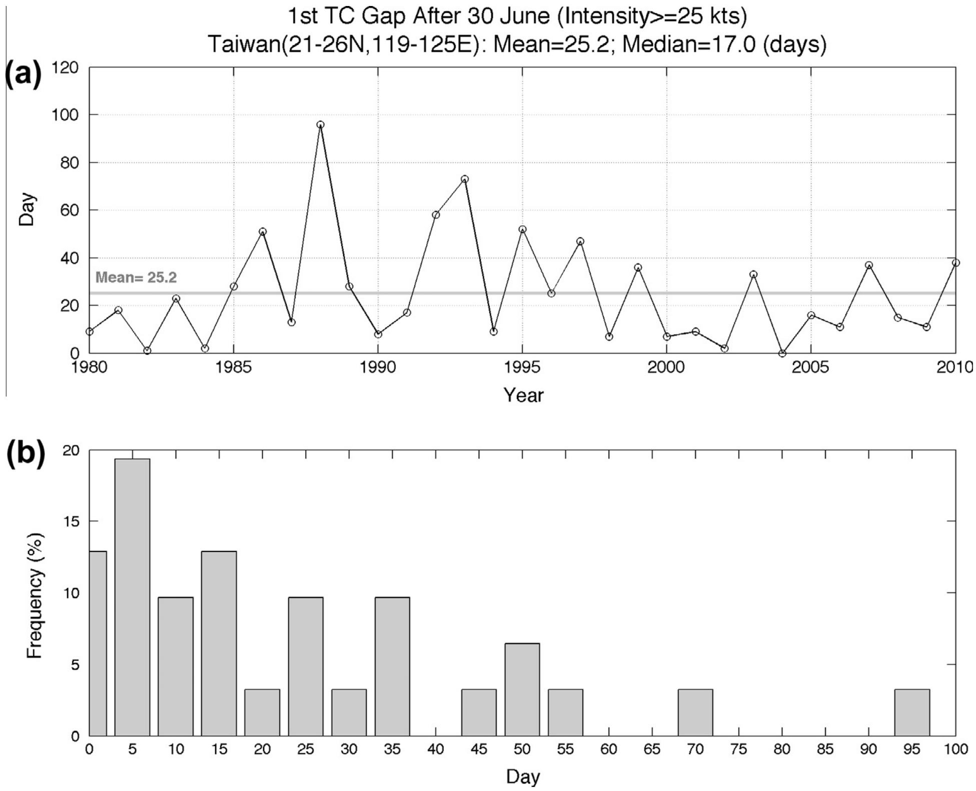

Fig. 3. (a) Time in days after the end of the Mei-yu season on 30 June of gap before the first TC will pass or form in the Taiwan area during 1980–2010. (b) Frequency (%) of the years between 1980 and 2010 for which a gap period (days) before the first TC passes by or forms in the Taiwan area.

with high mountainous terrain such as the Central Mountain Range (CMR) in Taiwan. Recent studies of Morakot (e.g., Chien and Kuo, 2011; Wang et al., 2012) suggest the asymmetric distribution of rainfall may have decreased the translation speed and thus contributed to the extreme rainfall accumulations.

The numerical weather prediction (NWP) model guidance for tropical cyclone track forecasts and warnings has improved over the last 15 years (Elsberry, 2007). With the improvement in the numerical model guidance, and with utilization of consensus of deterministic model tracks, several tropical cyclone warning centers have been able to extend the length of the track forecasts to five days. Indeed, the accuracy of the five-day track forecasts is of the same order of the three-day forecasts of a decade ago. It is emphasized that very highly accurate TC tracks are required to predict the precipitation amounts in narrow river watersheds in the Taiwan CMR that hydrologists may require for flood forecasting. Wang et al. (submitted for publication) have made high-resolution (3 km) simulations of the extreme rainfall in Typhoon Morakot for up to 4 days in advance using the Cloud-Resolving Storm Simulator (CReSS). The key question for hydrological model inputs is the limit of predictability for such deterministic models. Improved ensemble prediction systems are now providing information on the uncertainty of the track forecasts (Elsberry, 2010; Majumdar and Finocchio, 2010), which will be required for probabilistic hydrological forecasts when the accuracy of the deterministic models is not sufficient.

To support the water resource management decision-making process, longer-term TC event outlooks may be needed for the evaluation of possible TC-rainfall impacts. On much longer (seasonal) lead times, the TC forecast approach is generally statistically based and the objective is to predict activity for the entire season (Gray et al., 1992; Chan et al., 2001; Camargo et al., 2007; Klotzbach, 2007; Leroy and Wheeler, 2008; Chu et al., 2010; Lu et al., 2010). Camargo et al. (2007) have indicated that the skill of the seasonal statistical forecasts is related to the prediction of the El Niño Southern Oscillation (ENSO). Among the statistical approaches that have been recently developed, Lu et al. (2010) have applied a Bayesian framework statistical regression model to forecast the seasonal TC counts in the Taiwan area. Three large-scale climate variables are selected as predictors: relative vorticity at 850 hPa, vertical wind shear, and sea-level pressure over the western and central North Pacific. Based on the TC track types, Chu et al. (2010) have developed a probabilistic model to forecast the seasonal TC activity in the vicinity of Taiwan during June to October. These studies found that skillful seasonal TC forecasts may be provided by the statistical models.

Several approaches utilizing NWP models to forecast the seasonal TC activity have also been developed (Vitart et al., 1997; Camargo and Zebiak, 2002; Camargo et al., 2007; Chen and Lin, 2011). However, neither the statistical nor the dynamical seasonal TC activity forecasts provide the tracks and timing necessary for the hydrological-related operations.

1.3. New tropical cyclone forecast products

The question addressed in this study is whether tropical cyclone events (formations and track types) that would be useful for hydrological-related operations can be predicted on timescales longer than five days using ensemble prediction systems. Tsai et al. (2011) have developed an automated technique for the detection and tracking of tropical cyclone-like vortices (TCLVs) in numerical weather prediction models, and especially for ensemble-based models. Tsai et al. (2011) demonstrated that this algorithm efficiently extracts western North Pacific TCLV information from the vast amount of ensemble data from the 16-day National Centers of Environmental Prediction (NCEP) Global Ensemble Forecast System (GEFS). The predictability of typhoon formation and activity during June–December 2008 was also evaluated. The TCLV track numbers and TC signal averages around the formation locations during the 0–96 h period were more skillful than for the 102–384 h forecasts. Compared to weak tropical cyclones (maximum intensity ⩽50 kt), the storms that eventually became stronger TCs did have larger TC signals.

Belanger et al. (2010) used the 32-day ECMWF ensemble forecasts during the 2008 and 2009 seasons to examine the predictability of the North Atlantic tropical cyclones. Predictability to 15–21 days was indicated in the Main Development Region for Atlantic tropical cyclones, and the model skill was related to the Madden-Julian Oscillation as indicated by Vitart (2009). Belanger et al. (2012) have studied the tropical cyclone formation and regional outlooks of tropical cyclone activity for the Arabian Sea and the Bay of Bengal. They found similar levels of predictability as in the North Atlantic.

Elsberry et al. (2010, 2011) have provided evidence of predictability on extended time scales (5–30 days) for western North Pacific tropical cyclone formation and subsequent tracks using the 51-member ECMWF 32-day forecasts made once a week during the 2008 and 2009 seasons. Instead of just considering the number of TC formations, this research has further examined the predictability of the overall tracks. 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 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 (WMVM; Elsberry et al., 2008) in which the weighting factor is inversely proportional to the distance from the endpoint of the previous 12-h motion vector. A two-step objective plus subjective approach was applied for verifying the ensemble storm tracks relative to the JTWC best-tracks. Their approach was to first treat the JTWC track as another storm and compare all of the applicable forecast ensemble storms at each 12 h forecast time to determine if at least one point on the ensemble storm track was matched within a separation distance with the JTWC position at exactly that 12 h time. Second, a subjective assessment was made to assign a quality measure (Excellent, Above Average, Good, Below Average, and Poor) of the match of the ensemble storm to the JTWC track. This assessment focused more on the entire JTWC and ensemble storm tracks to avoid incidental agreement either early or late in the track. However, a certain degree of arbitrariness and person-dependency was involved in this assessment in terms of an Excellent quality measure versus an Above Average, etc.

1.4. Purposes of the study

The first purpose of this study is to examine how the hydrological community might utilize probabilistic forecasts of TC formations and potential tracks on 5–30 day time scales. The second purpose is to explore the capability of the ECMWF 32-day ensemble prediction system in forecasting that no tropical cyclones will exist within a specific area (specifically the Taiwan area) over certain time periods. It is asserted that both types of forecasts may be useful for water-related hazard prediction and water resource management planning. The ECMWF 32-day ensemble model will be described in Section 2, and the verification method is described in Section 3. The evaluations for the western North Pacific TCs during 2009 and 2010 are described in Section 4, with a special focus on no-TC gaps. The proposed hydrological applications and challenges will be discussed in Section 5. Finally the opportunity for an extended-range hydrological alert-to-forecast system is proposed in Section 6.

2. ECMWF 32-day ensemble

The focus of this study is the extended-range forecasts of western North Pacific tropical cyclone formations and tracks with the ECMWF 32-day ensemble forecasts during 2 July 2009 to 30 December 2010. The ECMWF 32-day ensemble forecast model has 50 ensemble members plus one control that are integrated from slightly different initial conditions to represent the uncertainties in the operational control forecast (Buizza and Palmer, 1995; Vitart et al., 2008, 2012). A singular vector method is used to create the 50 perturbations from the control, and stochastic physics are applied during the integration. Also, an ocean model is coupled with the atmospheric model starting at day 10 with two wind stress perturbations to create additional spread in the oceanic initial conditions. The 51-member ECMWF 32-day forecasts are made each week from the conditions at 0000 UTC on Thursdays (a second weekly run of the ECMWF 32-day ensemble forecast on Monday has been added since 10 October 2011). The horizontal resolution is T399 (∼60 km) with 62 levels during the first 10 days. During days 10–32, the resolution decreases to T255 (∼80 km).

A TC tracking routine (Vitart et al., 1997, 2012) was used by ECMWF to obtain the 12-h TC-like vortex positions and intensities predicted by the 51 ensemble members in the western North Pacific. A TC-like vortex is detected by the routine when selected dynamic and thermodynamic fields meet specified criteria. Then the WMVM technique was applied to form the ensemble storm tracks. The JTWC best-tracks are used for the forecast performance evaluations in this study.

Elsberry et al. (2010, 2011) have extensively analyzed the performance of the ECMWF 32-day ensemble in predicting the strong typhoons, moderate typhoons, tropical storms, and even many tropical depressions during the 2008 and 2009 seasons. Two examples of the performance of the ECMWF ensemble will be presented here that illustrate the ensemble storms corresponding to TY Morakot (2009) and Supertyphoon Megi (2010), which both had serious hydrological impacts on Taiwan. An overall summary of the performance throughout 2 July 2009 to 30 December 2010 will be provided in Section 4.1.

The Week 1 through Week 4 forecasts of Typhoon Morakot are shown in Fig. 4. Three aspects of the Morakot track are difficult to predict: (i) A relatively far north formation; (ii) Short initial motion to the north followed by a sharp turn to the west; and (iii) A period of slow motion in the northern Taiwan Strait (when some of the most extreme rainfall occurred over southern Taiwan) followed by a sharp turn to the north. While the ensemble storm in the Week 1 forecast (Fig. 4a) initiated 8 days before Morakot struck Taiwan has a fairly accurate formation location, the predicted track actually does not cross Taiwan. At this time range, the forecaster should consider the uncertainty in the prediction given the large spread of the individual vortex tracks about the ensemble storm track, which includes both westward-moving and recurving vortices.

The Week 2 forecast (Fig. 4b) initiated on 23 July 2009 has an ensemble storm track that begins south of the formation position of Morakot and moves steadily to the northwest. Although this ensemble storm track crosses the Morakot track, it does not represent the sharp turns or slow movement period of Morakot. The meteorologist or hydrologist should utilize this forecast as an alert that a TC may pass by Taiwan in approximately 15 days. However, the spread of the ensemble vortex tracks indicates considerable uncertainty as to whether the track will be north or south of Taiwan.

The ensemble storm in the Week 3 forecast (Fig. 4c) that most closely matches the Morakot track begins well to the southeast of the actual formation location. The steady northwestward track

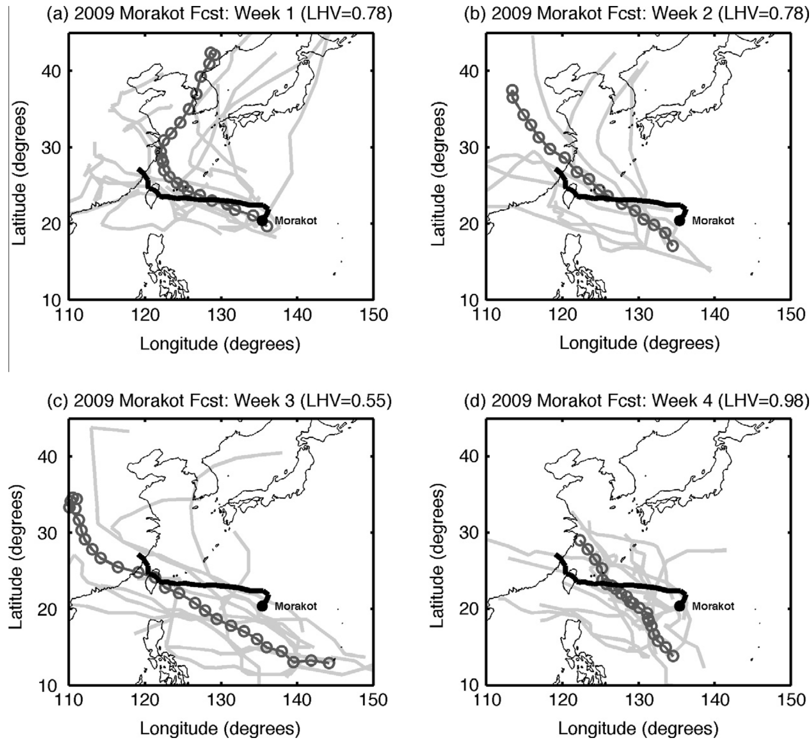

Fig. 4. ECMWF 32-day ensemble forecasts of ensemble storm tracks (12-h positions in open circles) that are matched with the track of TY Morakot (solid black line) starting from Thursdays at 0000 UTC on: (a) Week 1, 30 July; (b) Week 2, 23 July; (c) Week 3, 16 July; and (d) Week 4, 9 July 2009. Individual ensemble member vortex tracks that have been matched to form the ensemble storm are indicated by the gray lines.

then strikes Taiwan at almost the perfect landfall position, but then crosses the Taiwan Strait and continues for a long period over southern China. Although the spread of the individual vortex locations and tracks is quite large in the early stages, the spread of the tracks while crossing Taiwan is somewhat smaller, and again should be considered as the uncertainty to be expected three weeks in advance.

Finally, the initial location and track of the ensemble storm in the Week 4 forecast (Fig. 4d) resemble those of the Week 2 forecast (Fig. 4b), except with a wider spread. Consequently, beginning from this Week 4 forecast and continuing through to the Week 1 forecast, the meteorological forecaster and the hydrologist would be first given an alert that a long-lived TC will approach Taiwan and each weekly forecast would then confirm that Taiwan will be threatened. However, the shorter-term (5-day) deterministic models would need to be consulted to forecast the location of landfall and specific river basins that would be impacted.

The key features in the Supertyphoon Megi track (Fig. 5) are the south-of-west segment that led to landfall on Luzon, Philippines and the sharp turn over the South China Sea that led to a northward path for a second landfall on China. The ECMWF Week 1 forecast (Fig. 5a) initiated 7 October has an ensemble storm that began to the south of the Megi formation location and has a somewhat similar track that is displaced to the south, but has a landfall on Luzon Island. However, the predicted ensemble storm track is then across the South China Sea to a landfall on Hainan Island. Since the spread of the ensemble vortex tracks across the South China Sea is small, no indication of uncertainty that included a possible northward turn was provided by the ECMWF ensemble in this case.

The ECMWF Week 2 forecast (Fig. 5b) initiated on 30 September also has an ensemble storm track that is well displaced to the south, but again has a correct landfall position on Luzon and then continues westward across the South China Sea. Although nearly all of the ensemble vortex tracks favor this westward track, several vortex tracks do indicate the possibility of a northward turn.

The ECMWF Week 3 forecast (Fig. 5c) initiated on 23 September resembles the Week 1 and Week 2 forecasts of a westward track to landfall on Luzon but then terminates over the South China Sea rather than turning north. The ECMWF Week 4 forecast (Fig. 5d) has an ensemble storm that most closely matches the Megi track in that the formation location is excellent, the predicted track twice intersects the Megi track, and although a landfall on Luzon is not predicted, a turn to the north is predicted. Thus, the potential of a TC approaching Taiwan from the south is predicted four weeks in advance. While week-to-week consistency in the forecasts of a TC to form near Guam and move westward to impact Luzon is demonstrated in this case, the critical northward turn that led to hydrological impacts on Taiwan is not consistently predicted. Such a northward turn late in season depends on an interaction with synoptic-scale systems that is not predictable on extended-range timescales. Even though the guidance from the ECMWF ensemble was for a westward track, the Taiwan Central Weather Bureau forecasters would be alert for a northward turn and would be aware of the potential hydrological impacts if such a turn was to occur.

The ECMWF 15-day forecasts of Megi from "Day 0 (i.e., formation day)" to "Day -13" are also examined for consistency and a reduction in track uncertainty with decreasing forecast lead-times beginning after the Week 2 forecast by the ECMWF 32-day ensemble (Fig. 5b). As shown in Fig. 6 (bottom row), the ECMWF 15-day ensemble model forecasts initiated 12 and 13 days prior to the formation day of Megi indicated a good formation location and a track with landfall on Luzon. While the forecasts initiated 9 to 11 days (next-to-bottom row in Fig. 6) have more variability in the initial locations, the westward track to landfall on Luzon is consistently predicted. Notice also that the number of ensemble members predicting this storm increases on "Day -9". Although a few of the ensemble members on "Day -9" begin to indicate a possible northward turn toward Taiwan, only on "Day -7" does a majority of the ensemble members indicate a turn toward Taiwan. Indeed, a potential landfall that would lead to heavy precipitation that is being

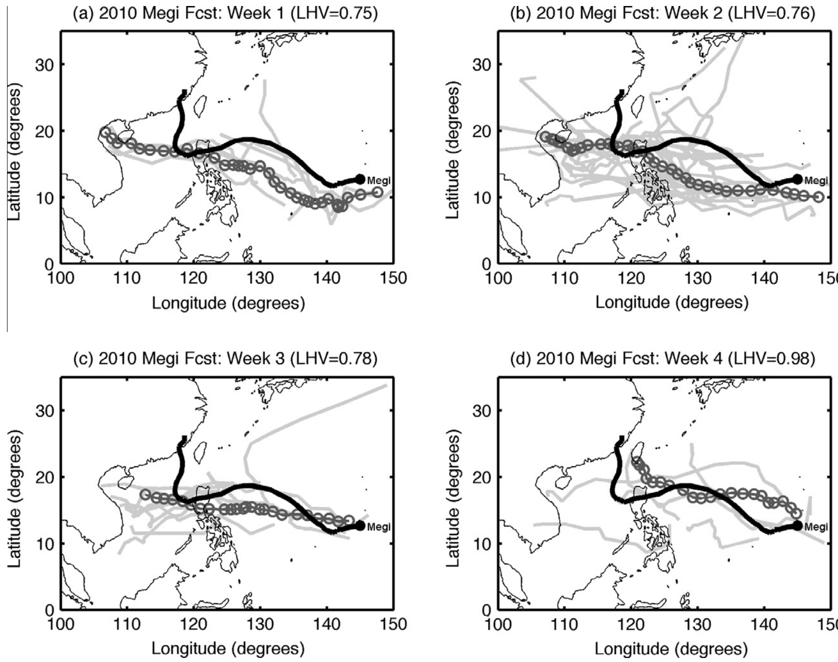

Fig. 5. ECMWF-32 day ensemble forecasts as in Fig. 4, except for TY Megi and started from initial conditions on: (a) 7 October, (b) 30 September, (c) 23 September, and (d) 16 September 2010.

indicated within 20 days should serve as an alert to the hydrology community. On "Day -6" through "Day -2" before Megi has even formed, TC tracks in the near proximity of Taiwan are being forecast with increasing numbers of ensemble members, which should be the basis for a higher alert status to the hydrological community. Thus, these 15-day forecasts can provide daily confirmation of a potential TC-related hydrological hazard event from Megi for two-week periods even before it forms, and confirm the earlier indications at three and four week lead-times from the ECMWF 32-day ensemble forecasts.

3. Verification method

While the Megi forecasts in Figs. 5 and 6 demonstrate the capability of the ECMWF 32-day ensemble to provide useful extended-range forecasts of TC formations and tracks in the western North Pacific, an objective verification technique is desirable to quantify the performance (and failures). Since a detailed description of a new objective track matching procedure is available in Tsai et al. (in press), only a few key features will be described here. First, the data base of ensemble storms for the season are searched to find all ensemble storms within allowable time differences at any time in the JTWC track: ±3 days for Week 1, ±4 days for Week 2, and ±5 days for Weeks 3 and 4 forecasts. Both the shortest distance between any matched points and the average distance between all matched points are calculated. For an ensemble storm to be considered as a match to the JTWC storm that formed in Week 1 of the forecast, the average distance (D_{avg}) must be less 10° and the shortest distance (D_{short}) must be less than 7°. In addition, the formation distance (D_{form}) and ending distance (D_{end}) must less than 7°. To allow for greater uncertainty in Weeks 2–4, these distance criteria were relaxed to 12° and 8°. These criteria ensure that all reasonably likely ensemble storms were considered as possible matches for the JTWC storm.

To objectively determine the similarity between the ensemble storms matched by this typhoon analog approach, a likelihood value (LHV) is calculated:

$$\mathrm{LHV} = 0.3 \times \mathrm{MF}_{avg}(D_{avg}) + 0.25 \times \mathrm{MF}_{short}(D_{short}) + 0.23 \times \mathrm{MF}_{form}(D_{form}) + 0.22 \times \mathrm{MF}_{end}(D_{end}), \quad (1)$$

where the MFs are the membership functions (Fig. 7) for the D_{short}, D_{avg}, D_{form}, and D_{end} between the ensemble storm and the verifying JTWC storm. Notice that larger weighting factors are assigned to the average distance and the shortest distance to emphasize the similarities with the overall JTWC track. In addition, a smaller weighting factor is given to the distance between the formation position of the ensemble storm versus that for the JTWC storm (i.e., max. intensity $\geqslant$25 kt). Finally, a weighting factor is assigned to the ending position difference to minimize matches of recurving and westward tracks between the ensemble storm and the verifying JTWC storm.

The LHVs in Eq. (1) are then used to assign a quality measure for each potential matching ensemble storm depending on its similarity to a particular JTWC storm. The weighting functions for the various terms in Eq. (1) were varied over a range of values to achieve similar quality measures as were subjectively determined by Elsberry et al. (2011) for the 2009 season (see Tsai et al., in press for details). The five quality measures ranging from Excellent to Poor are assigned as a linear function of the LHV values from 1 with an interval of 0.2. A LHV <0.2 (i.e., Poor) is considered to not be a real match of the ensemble storm with that JTWC storm.

4. ECMWF 32-day ensemble tropical cyclone forecasts in 2009 and 2010

4.1. Forecast skill evaluation results

Since the forecast skill of the ECMWF 32-day ensemble forecasts during the 2009 and 20 W seasons is discussed in some detail in Tsai et al. (in press), only those results that have implications for the usefulness in extended-range water resource management and hydrological operations will be highlighted. Table 1 is the summary of the ECMWF 32-day ensemble forecast performance during 2 July to 31 December 2009. The most important result is that the ECMWF 32-day ensemble was able to predict nearly all of the 23 TCs during the study period – even during Weeks 3 and 4 with

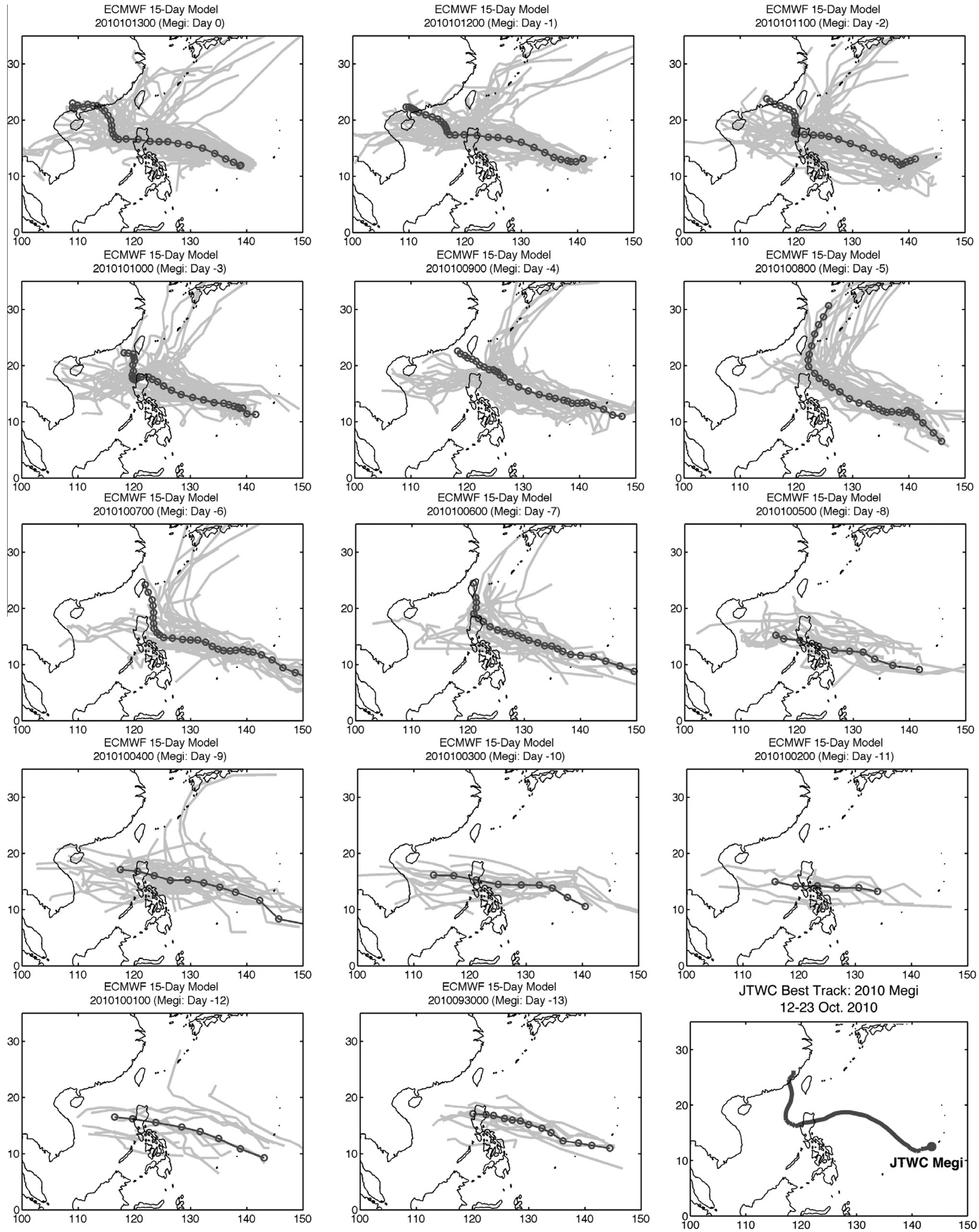

Fig. 6. ECMWF 15-day ensemble forecasts of TY Megi starting from 30 September (Day -13) to its formation (Day 0) on 13 October 2010. The JTWC best track of Megi is again shown in the bottom-right panel.

20 Hits and only 1 Miss. Similar distributions of Hits with 19 TCs, and only one to three Misses, were found for the 2010 season (Table 2). This success in predicting all of the significant tropical cyclone events during two seasons that had very different numbers of events and track characteristics means that the hydrological community can have confidence that a long-lasting, strong tropical

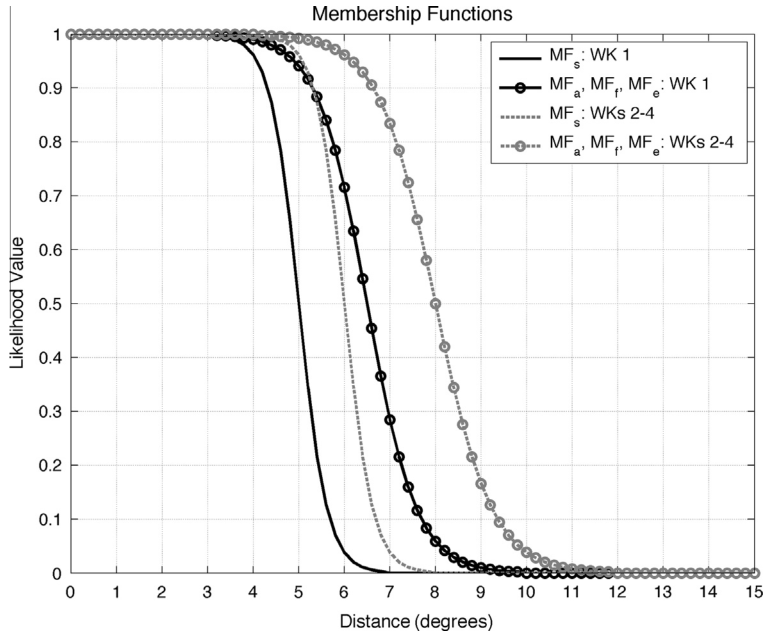

Fig. 7. The membership functions used in this study.

Table 1
Contingency table of the ECMWF 32-day ensemble forecasts in 2009 season (2 July to 31 December 2009). The definition of Hits is LHV $\geqslant 0.2$. (FAs: false alarms; CNs: correct negatives).

	Hits	FAs	Misses	CNs
Week 1	22	38	2	2
Week 2	24	20	0	8
Week 3	20	39	1	2
Week 4	20	72	1	2

Table 2
Contingency table as in Table 1, except for the ECMWF 32-day ensemble forecasts in 2010.

	Hits	FAs	Misses	CNs
Week 1	19	65	1	13
Week 2	17	24	2	27
Week 3	18	54	0	18
Week 4	15	60	3	18

cyclone will not be missed and may be detected as long as four weeks in advance.

Another important result during 2010 (Table 2) was the large number of (CN) forecasts, which means no TCs formed in the week and correspondingly the ECMWF ensemble did not forecast any formations. Because the 2010 season had one of the fewest TCs in recent history, it is considered important for support of hydrological operations that the ECMWF ensemble model be able to predict the no-TC periods as well. The capability to forecast no TCs in the Taiwan area will be examined in Section 4.3.

However, the numbers of false alarms, which are defined as all ensemble storms (as defined in Section 2) that could not be matched with any JTWC storm or had a match LHV <0.20, would be a major issue for hydrological operations. As shown in Tables 1 and 2, a minimum number of FAs with no Misses is found in Week 2 forecasts. Week 1 forecasts have more FAs than in Week 2 and the FAs steadily increase from Week 2 to Week 4. The characteristics of these FAs will be described in Section 4.2.

4.2. Characteristics of false alarms

One of the surprising characteristics of FAs is that 50% of the total number of FAs during Week 1 in Tables 1 and 2 exist in the initial conditions of the ECMWF ensemble model or form during the first 24 h of the forecast. Since these FAs exist in the initial conditions, the cause of the FAs may be related to issues in the data assimilation or in the model physical processes. A tentative explanation for the FAs from Elsberry and Chollet (2010) is that very small but intense vortices are sometimes present in the short-term forecasts that are used in the ECMWF data assimilation. Park et al. (in press) have shown that the ECMWF deterministic model analyses have small intense vortices that when used in regional models also lead to false-alarm systems. Regardless of the cause of the 50% of the false alarms that form during Week 1, it is highly likely that an experienced tropical cyclone forecaster will be able to disregard these formations/tracks by simply comparing the predicted systems with the meteorological satellite imagery at the initial time. Indeed, we had considerable success in detecting many of the false alarms in the initial conditions in a real-time test with the ECMWF 32-day forecasts during the 2012 season using the characteristics of the false alarms from the 2009 and 2010 seasons.

The second characteristic of the FA distribution in time is the almost uniformly increasing number of formations with increasing forecast interval after Week 2 (detailed discussion in Tsai et al., in press). This characteristic is tentatively attributed to the too-active tropical convective over-turning in the ECMWF model, and must be considered by the meteorological forecaster in terms of increasing probabilities that a predicted system may be a FA and thus degrade the reliability of the product. This increasing uncertainty will be conveyed to the hydrological community in terms of the probability that a predicted track is likely to be a real tropical cyclone. As indicated in Figs. 4–6, the week-to-week or day-to-day consistency in the predictions will provide the hydrological community a measure of the reliability.

The formation locations and the tracks of the FAs in 2010 are shown in Fig. 8. Three types of FA tracks are indicated. First, the majority of the FAs begin at latitudes less than 10°N and have westward tracks. As indicated by the centroids (triangles) and

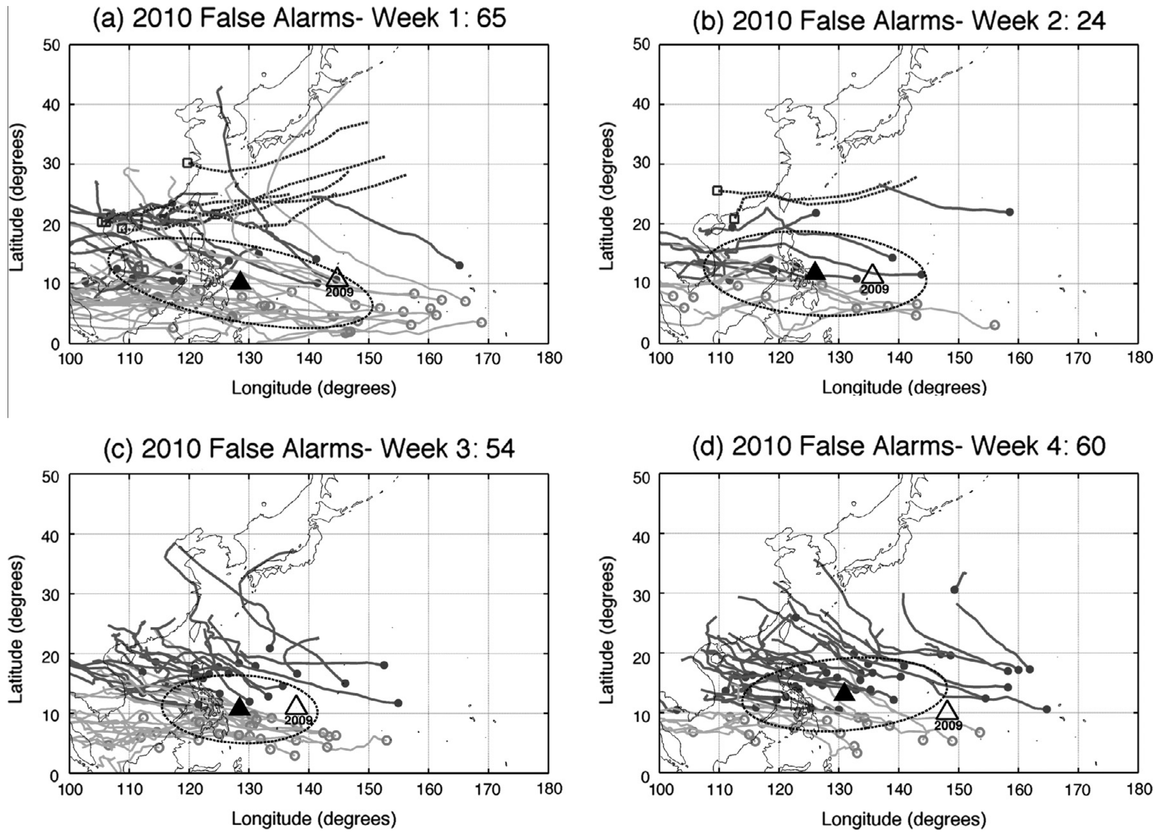

Fig. 8. Formation locations and the tracks of the false alarms as forecast by the weekly ECMWF 32-day ensemble prediction system during 2010: (a) Week 1, (b) Week 2, (c) Week 3, and (d) Week 4 forecasts. The light gray lines starting with open circles are the FAs begin at less than 10°N. The dotted lines starting with open rectangles are the FAs begin along the southern China Coast. The solid lines starting with dots are the FAs begin north of 10°N. The black triangles are the mean formation locations, and the dashed ellipses are the 2-D Gaussian fit of the formation locations outlined at one standard deviation (~68.26%) probability. The mean formation locations of the false alarms in 2009 (open triangles) are also shown in the figures.

ellipses in Fig. 8, these most-frequent FAs form east of the Philippines and would certainly have severe hydrological impacts on the Philippines, but not on Taiwan. Compared to the FAs in 2009, which was an El Niño year, the mean formation locations of all the FAs in 2010 (a La Niña year) began farther westward (Fig. 8). The difference of the average formation locations between the FAs in 2009 and 2010 is 13.16° long. Notice also the frequencies of the FA tracks in 2009 and 2010 are higher in the southern South China Sea (SCS) than in the other regions. These results indicate that better TC activity forecast skill can be expected in the Taiwan area than in the SCS, while higher chances of the FAs may be found during the La Niña years due to the westward shift of the TC formation locations (Chan, 2000; Wang and Chan, 2002).

A second type of FA track in the Week 1 (Fig. 8a) and to a lesser degree in Week 2 (Fig. 8b) begins along the southern China coast and has an eastward motion that would lead to hydrological impacts on Taiwan. Because these forecast tracks occur during the Mei-yu season, the forecaster will be able to easily determine that these systems are not tropical cyclones. On a positive note, knowledge of these Mei-yu systems may be of interest to the hydrological community.

The third type of FA tracks in Fig. 8 begin north of 10°N and have northwestward and recurving tracks that may pass near Taiwan. Because of the potential hydrological impacts associated with this type of FA track, these FAs are of most concern. Since these tracks resemble those of the real TCs that affect the Taiwan area (Fig. 1), Tsai et al. (in press) have compared the predicted characteristics of these FAs with the characteristics of the forecast "Hits" in an attempt to assist the forecaster in identifying the FAs.

4.3. Capability to forecast no-TC gaps

During the Impact of Typhoons on the Ocean in the Pacific (ITOP) field experiment (Elsberry and Harr, 2008), the weekly ECMWF 32-day ensemble forecasts were able to predict no Tropical Storms or greater intensity would exist within 1000 km of the aircraft operations center in Guam during a critical three-week period following TY Malakas and before the formation of TY Megi. The situation was that the final oceanographic instrument deployment was awaiting the occurrence of a typhoon with at least 100 kt intensity before the aircraft had to depart on 20 October. A three-week gap with no TCs in the western North Pacific during late September and early October is relatively rare.

A summary of the Week 0 (i.e., the TC already existed at the time of the Thursday ECMWF forecast) through Weeks 1 to Week 4 predictions is given in Table 3. For the first week in the no-TC gap beginning on 23 September, two FAs existed in the Week 0 initial conditions to the southeast of TY Malakas that may be attributed to Rossby wave dispersion creating new cyclonic vortices that did not intensify beyond 30 kt. Similarly, weak FAs in the Week-1 and Week-2 forecasts initiated on 16 September and 9 September would have been easily disregarded. No TC formations anywhere in the western North Pacific during 23–29 September were correctly predicted in the Week-3 and Week-4 ECMWF forecasts initiated on 2 September and 26 August, respectively.

For the forecast period verifying during 30 September to 7 October, correct forecasts that no TC would be present were made from initial conditions on 30 September (Week 0) and 16 September (Week-2). One weak FA was predicted during that verification per-

Table 3
Assessment of the capability of the ECMWF 32-day ensemble to predict the non-formation of any Tropical Storm or greater intensity within three weekly periods beginning 23 September, 30 September, and 7 October 2010. Week 0 is defined as the Thursday (first day) of the period and Week-1 through Week-4 are one through four weeks prior to that time. Dates (month/day) of the False Alarm development and maximum intensity are indicated, and the number of days in advance of the actual formation of Typhoon Megi during the 7 October forecast are indicated.

Non-formation periods	Week 0	Week-1	Week-2	Week-3	Week-4
9/23–9/29	False 9/24(27 kt) False 9/30(30 kt)	False 9/22(21 kt) False 9/22(27 kt)	False 9/25(23 kt)	None	None
9/30–10/7	None	False 9/30(30 kt)	None	False 9/26(32 kt) False 9/27(27 kt)	Missing
10/7–10/12	Megi −5d(24 kt) False 10/10(24 kt)	Megi −2d(21 kt)	Megi −4d(30 kt)	Megi −4d(22 kt)	None

iod for the forecast initiated 23 September (Week-1) and two weak FAs were predicted for the forecast initiated 9 September (Week-3). Finally, forecasts for the third week (7 October – 12 October) in the no-TC gap did include a FA during the Week 0 and also too-early indications of the development of Typhoon Megi by 2–5 days in Week-1 through Week-4. This tendency for the ECMWF ensemble to predict ensemble storm development too early was noted during the 2008 and 2009 seasons as well (Elsberry et al., 2010, 2011).

For support of hydrological planning and operations specifically for Taiwan, a similar evaluation was made of the capability of the ECMWF ensemble to predict no TCs forming in or moving through the Taiwan area (illustrated in Fig. 1) during weekly periods throughout 2010. This evaluation (Table 4) is different from previous contingency tables that applied throughout the western North Pacific and South China Sea because it applies only to weekly verification periods in which a TC either existed (total of five) or did not exist (total of 47) in the Taiwan area. This test is more stringent because of the limited region in which the track must fall, so in Week 2 (Week 3) only three (two) of the five ensemble storms meet this track requirement. That is, an ensemble storm corresponding to the actual TC was predicted, but its track was not within the box, so these are regarded as Misses for the purposes of this Taiwan area evaluation. Notice also in Table 4 that FAs do occur in the Taiwan area, but the ratio of FAs to Hits is not as large as in the overall 2010 summary in Table 2. If the FAs that are clearly identified as Mei-yu systems rather than TCs are excluded, the number of FAs in Week 1 and Week 2 are reduced to zero and four.

The important result of this Taiwan area evaluation is the CNs in Table 4, which indicates that the ECMWF 32-day ensemble was able to predict weekly no-TC gaps with considerable accuracy. Perfect support of hydrological planning and operations would require both all Hits and all CNs. For Week 1, the CN success rate is 45 (or 47 if the two Mei-yu FAs are eliminated) of the 47 weeks during 2010 that had no TC within the Taiwan area. Larger numbers of FAs then result in smaller numbers of CNs, but 41 CNs of the 47 possible weeks for the Week 2 and Week 3 forecasts is still a favorable result. As indicated in Section 4.2, it appears that many of the false alarms may be identifiable, and some of these false alarms may be weak and not pose a real threat.

Table 4
Contingency table as in Table 1, except for the 52 weekly ECMWF 32-day ensemble forecasts during 2010 of any TCs forming in or any TC track passing through the Taiwan area. The numbers in parentheses indicate the performance if the easily identified Mei-yu system FAs are excluded.

	Hits	FAs	Misses	CNs
Week 1	5	2 (0)	0	45 (47)
Week 2	3	6 (4)	2	41 (43)
Week 3	2	6	3	41
Week 4	4	8	1	39

5. Proposed hydrological applications and challenges

5.1. Proposed rainfall forecast applications

As shown in Section 4, most of the TC formations and tracks can be predicted by the ECMWF 32-day ensemble forecast model. Therefore an opportunity exists to use these extended-range numerical forecasts to assist the hydrological decision-making processes during the typhoon season. For the hydrological operation and simulation, such as the reservoir operation, water resource management, rainfall-runoff model, and river routing model, the most important factor is the total rainfall amount of a TC, or more specifically, the time series of the rainfall amounts. Although the numerical models also predict the rainfall at each time step, the rainfall amount predicted by the global model is much less than observed due to the rather coarse horizontal resolution and this rainfall deficiency is much greater for complex and steep terrain as in Taiwan (Wu and Kuo, 1999; Wu et al., 2002; Fang et al., 2011). Fang et al. (2011) found a horizontal resolution of 4 km was required to realistically predict the Typhoon Morakot rainfall over the Taiwan topography.

Since the ECMWF 32-day ensemble has a more coarse horizontal resolution, some indirect methods exist for inferring what rainfall might occur from the tracks of the TCs that are predicted to approach Taiwan during Week 1 through Week 4. For example, the typhoon climatological rainfall model of Wang (1992) assumes a "phase-lock effect" of the TC-terrain interaction (Chang et al., 1993). Thus, the predicted typhoon center positions could be the predictors for the corresponding rainfall in Taiwan. Similar statistical typhoon rainfall forecast models are still being used as a forecast guidance/benchmark in Taiwan Central Weather Bureau, Taiwan Water Resources Agency, Taiwan Typhoon Flood Research Institute (TTFRI), and Taiwan National Science and Technology Center for Disaster Reduction (NCDR), albeit with some improvements by using the advanced methods (Yeh, 2002; Lee et al., 2006; Hsu and Wei, 2007; Lin and Wu, 2009; Tsai and Lee, 2009). The impact of the spread in the ensemble forecast track on the possible rainfall amounts could also be rapidly calculated by applying the indirect method to the individual ensemble member tracks.

Dynamical downscaling by integrating a higher-resolution numerical model initialized from the coarse-resolution model outputs is skillful and could also be considered (Díez et al., 2005; Spak et al., 2007; Caldwell et al., 2009; Kanamitsu et al., 2010). An analog technique might also be used to define the rainfall forecast patterns that occurred for historical TCs that had similar tracks as in the ECMWF 32-day ensemble forecasts. Thus, probabilistic rainfall forecasts could be obtained by utilizing the rainfall observations corresponding to those analogs.

5.2. Challenges for the operational forecasts

Wang (1992), Chang et al. (1993), and Wu and Kuo (1999) have demonstrated that relatively small track displacements may lead to significant differences on the rainfall amounts on the CMR. As shown in the Weeks 1 to 3 forecasts of Typhoon Megi (Fig. 5), the westward track forecasts would lead to underestimates of the distant rain event on the northeast side of Taiwan. The typhoon warning centers (e.g., JTWC, Taiwan Central Weather Bureau, and Regional Specialized Meteorological Center-Tokyo) issued official forecasts with a westward-moving track when Megi formed east of the Philippines, but some centers did not forecast a northward track even after Megi passed the Philippines on 19 October. Therefore, it should not be expected that the ECMWF 32-day ensemble will be able to forecast such sharp turns.

Because forecasting TC-related rainfall at a specific location and at a specific time is very challenging, typhoon rainfall forecasting could benefit by a probabilistic prediction provided by the ensemble forecast model. Therefore, it is suggested that the tracks of the ensemble member vortices within the ensemble storm might be used to estimate the uncertainties/spread of the track forecasts, and then the associated rainfall forecasts can be obtained by the indirect methods described in Section 5.1.

6. Opportunity for an extended-range hydrological alert-to-forecast system

The viability of a probabilistic forecast of typhoon formations and track types on 5–30 day timescales provides an opportunity for more tightly coupled meteorological support of a hydrological alert-to-forecast system. This support would become more focused in space and in time as the threat of a typhoon becomes progressively higher and guidance becomes more reliable as to the specific location at risk.

As indicated in the Introduction, seasonal forecasts of tropical cyclone activity in the Taiwan area are now available. Although interannual variability (El Niño versus La Niña) clearly affects the formation locations and thus the likelihood of more recurvature tracks to the east of Taiwan, intraseasonal variability (e.g., Madden-Julian Oscillation) can shift the formation location to the west and raise the threat. It is on the extended-range time scale that the 30-day probabilistic forecasts may provide more specific timing and location information as to a TC threat, or to the absence of any threat (no-TC gap).

The proposed meteorological support for hydrological operations is illustrated in Fig. 9. It would begin with twice-weekly outlooks (i.e., Tier 1) as to the existence (or non-existence) of a TC forming or moving into the Taiwan area within the next 30 days based on the ECMWF 32-day ensemble forecasts. At this time, the ECMWF is the only center that is providing such extended-range guidance. The primary beneficiary of this 30-day guidance would be the Taiwan Water Resources Agency for management of the reservoirs. If the Mei-yu rainfall and/or prior typhoons have led to high water levels, the primary concern will be whether approach of a typhoon will raise the threat of dangerous water levels and severe flooding. If the Mei-yu rain and the absence of prior typhoons have led to low water levels, the primary focus will be whether agricultural water supplies may have to be restricted.

Because typhoons are rare events, and the probability associated with any specific ensemble storm in the Week 4 ECMWF forecasts may be ~10–15%, forecast-to-forecast consistency in the formation location and track type will be a critical factor in assessing the reliability of the guidance. That is, if the ECMWF forecast issued on Thursday has (does not have) a similar depiction of a TC forming or moving into the Taiwan area as was depicted in the previous forecast issued on Monday, then more (less) confidence may be given to the forecast. Thus, a TC event in the Week 4 forecast would be a reason for an "alert" that would be monitored through the subsequent twice-weekly forecasts. In low water

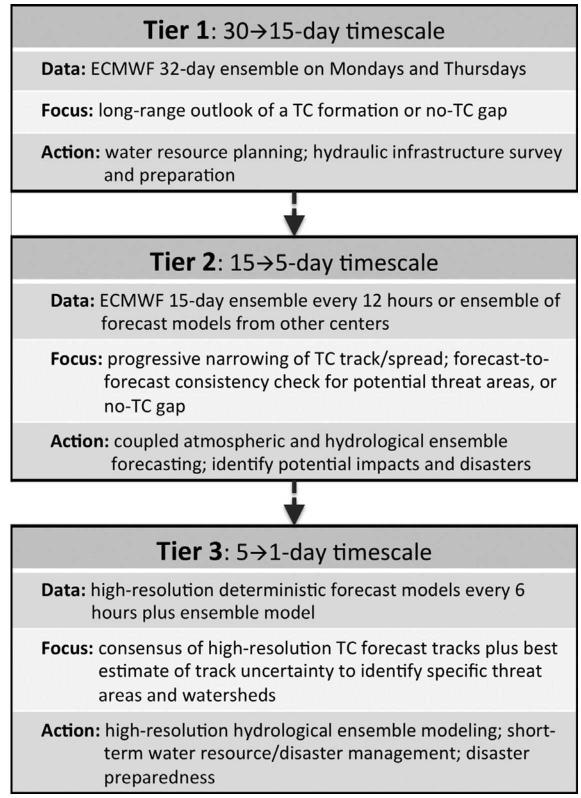

Fig. 9. Schematic diagram of the proposed three-tier approach to a seamless warning system for hydrological hazards related to TCs.

level situations, the consistent continued absence of TC events in the Week 4 into the Week 3 forecasts and then into the Week 2 forecasts would raise the level of concern for agricultural water supplies. A length-of-gap product might be developed that, given the length of the existing gap plus the model forecast of another 30 days without a TC in the Taiwan area, predicts the likelihood of no-TC persistence compared to historical gap period lengths.

On the 15-day time scales (i.e., Tier 2), more numerical weather forecast centers are (or soon will be) producing ensemble forecasts of TC events. The ECMWF produces such forecasts twice daily (00 UTC and 12 UTC) to 15 days. The 21-member NCEP global ensemble will be upgraded in resolution during 2012 and will be available four times a day out to 16 days. Although presently intended only for existing storms, the capability of inclusion of the pre-formation period is being considered. The UK Meteorological Office already detects TC-like vortices in their ensemble system, which would provide additional guidance as to TC events. The Japan Meteorological Agency has installed a new computer in June 2012 and will be testing a higher resolution ensemble that will be extended from 9 days to 13.5 days.

While most of these ensemble forecasts on 15-day timescales will be available twice a day, the opportunity for multi-model ensemble products is expected to greatly improve the reliability of the guidance as to TC formations and track types. Again, forecast-to-forecast consistency will also lead to greater confidence, and this reliability may be quantified by lagged-average products combining information from a sequence of 12-h forecasts.

With more specific and more frequent forecasts on 15-day timescales, the support for hydrological operations can become progressively more specific. Although Taiwan is a relatively small island, consistent forecasts of an approaching TC from the south or southeast versus from the east might be utilized in anticipating which river systems would be threatened as the TC comes closer.

Because TC formation and track type are governed by large-scale environmental conditions, forecast-to-forecast consistency in the TC event will indicate that the large-scale environment is not changing. Conversely, a large spread in the ensemble tracks will indicate larger uncertainty, and alert the forecaster to monitor how the large-scale environment changes might affect this tropical cyclone.

The third tier of guidance is the five-day deterministic model guidance that is available from many centers. Most TC forecast centers use a consensus of deterministic model guidance in preparing warnings. Ensemble forecasts are becoming more useful in estimating the uncertainty in the five-day forecast. The ECMWF is now issuing track probability swath products to 10 days. Although the consensus track guidance is highly accurate, certain scenarios still lead to inaccurate guidance from the models when sharp track changes occur. It is proposed that these scenarios are more likely to be recognized if the forecaster has been consistently monitoring the 15-day ensemble guidance for periods in which such track changes are indicated as being possible based on the ensemble track spread.

With this third tier of guidance, the river basins most likely to be impacted by the TC may be identified. Although the TC motion may be altered by the interaction with the CMR, the track type will be determined by the large-scale environment and any influence of an adjacent synoptic system. With this guidance, short-term disaster management decisions can be made on potential flooding, assessment of landslide hazards, and road closures in mountainous areas that are being threatened.

The benefit of such an extended-range hydrological alert-to-forecast system is to provide the longest possible seamless warning system for hydrological hazards related to TCs affecting regions with complex topography. While recognizing the limits of predictability for TC track and rainfall, reliable probability forecasts at extended range can lead to monitoring of TC formations and tracks so that attention becomes increasingly focused in time and space on the specific area that will have hydrological impacts. If disaster or hazard monitoring officials are alerted at the proper times with progressively more specific information, the warning system will become more effective and decisions can be made to minimize damage, and also maximize the beneficial effects of TC-related rainfall.

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