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Applicability of the Superensemble to the Tropical Cyclone Track Forecasts in the Western North Pacific

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Abstract: In this study a superensemble was constructed and assessed to examine its applicability to the tropical cyclone track forecasts in the western North Pacific. The data used for this study were outputs of 20 tropical cyclone forecast models and analyzed tropical cyclone tracks by the Korea Meteorological Administration from 2011 to 2013. The annual mean track errors were analyzed at the 24-, 48-, 72-, 96- and 120-h periods for 2012 and 2013, and the superensemble forecasts showed lower annual errors than the simple mean consensus (using 20 numerical models), ECMWF_TIGG, and GFS. The superensemble track errors for individual tropical cyclone cases were lower than the simple mean consensus over 60% of the total cases, and lower than the best-performing model over 50% of the total cases for the 24-, 48-, and 72-h forecast periods. In the track error distribution, the superensemble had lower density for relatively large errors than the simple mean consensus, and higher density for smaller errors than single models. When the results are combined, the probability of the superensemble yielding lower errors than the simple mean consensus and single models becomes high, which indicates that the superensemble can serve as an objective reference for the tropical cyclone track forecasts.

Key words: Superensemble, tropical cyclone track forecast, consensus, objective reference.

1. Introduction

Tropical cyclones can cause huge social and economic damage, but such losses can be reduced or prevented by increasing the predictability of tropical cyclone tracks and intensities. Track forecast errors have considerably decreased over the last 20 years by using the numerical models and consensus methods (Elsberry, 2014). The consensus technique for tropical cyclone track forecasts has better performance than single model predictions because the former offsets random errors inherent in individual model forecasts (WMO, 2007; Elsberry, 2014). The development and operational application of consensus techniques have become an important factor that can increase the accuracy of short-term tropical cyclone track forecasts (Gall *et al*., 2013).

Cangialosi and Franklin (2013) and National Hurricane Center (NHC, 2009) define a consensus scheme as a combination track that results from an ensemble of one or more models. Burton *et al.* (2006) classified the consensus schemes as single- vs. multi-model, selective vs. non-selective, and weighted vs. non-weighted approaches. The Goerss consensus method (2000) is applied in many operational centers (e.g., Australian Bureau of Meteorology, Joint Typhoon Warning Center, National Hurricane Center, and Japan Meteorological Agency) because of its simplicity and ease of interpretation. In the Goerss approach, a consensus is calculated by taking the arithmetic mean of tropical cyclone track forecasts from multiple models (Burton *et al.*, 2006). However, this approach is limited in that each model forecast is given equal weight regardless of its forecast performance.

In a multimodel superensemble, unequal weights are assigned to individual models based on each model's past performance, and it outperforms a simple mean consensus if the training process is based on the most recent forecast data (Krishnamurti *et al*., 1999; Williford *et al*., 2003). According to the 2012 National Hurricane Center Forecast Verification Report, the Florida State University Super Ensemble (FSSE), a superensemble forecast system, had superior performance to

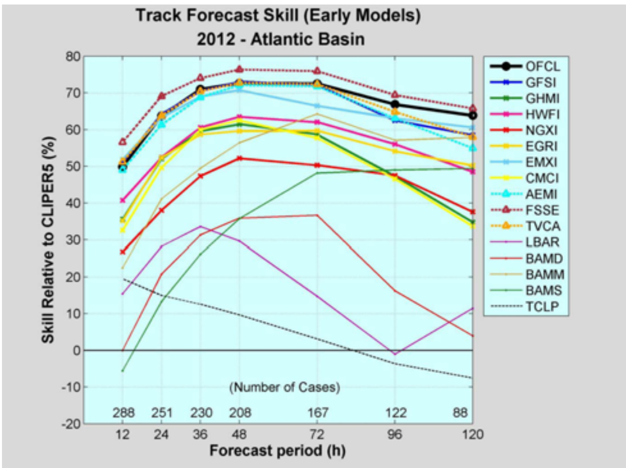

Fig. 1. Homogeneous comparison for selected Atlantic Basin early track models for 2012. This verification includes only the models that were available for at least two-thirds of the forecast times (Cangialosi and Franklin, 2013).

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other NHC numerical models and consensus schemes in hurricane prediction. The FSSE was also the only technique that consistently had better performance than the official forecast (Fig. 1).

The superensemble technique developed by Krishnamurti *et al*. (1999) has been used in many studies such as Williford *et al*. (2003) for real-time hurricane prediction during 1999 and Vijaya Kumar and Krishnamurti (2003) for tropical cyclone prediction over the Pacific Ocean during 1998-2000. Jordan II (2005) used the superensemble method for Eastern Pacific tropical cyclone forecasting with training sets over the Atlantic basin. Kramer (2008) also developed a superensemble of mesoscale models for tropical cyclone track and intensity forecasting to assess operational applicability.

The Korea Meteorological Administration (KMA) uses consensus schemes, a multi-model simple mean method (CONB1) and a weighted method (CONB2). CONB2 differs from superensembles in that the weights are assigned on the basis of empirical evaluations of the forecaster. Because human subjectivity can introduce errors into tropical cyclone track forecasts, adapting an objective superensemble method for operational application is preferred. In this study, a superensemble is constructed and evaluated for applicability in western North Pacific tropical cyclone track forecasts.

Descriptions of the data and the method to construct the superensemble are given in Section 2. In Section 3, the performance results of the superensemble, the simple mean consensus, and individual models are compared. To evaluate the applicability of the method, the annual averages of track errors, mean track errors for individual tropical cyclone cases, and distribution of track errors are analyzed for the years 2012-2013, and then the performance characteristics of the superensemble are discussed with case studies. Concluding remarks with a brief summary of the analysis are given in Section 4.

2. Data and methods

Tropical cyclone analysis positions from the KMA and forecast tracks from 20 numerical models (Table 1) were used to construct the superensemble forecasts. The superensemble forecasts are produced via the training and forecast phases (Fig. 2). In the training phase, a multiple linear regression equation is formulated to generate weights by comparing the tropical cyclone forecast positions with analyzed positions (Krishnamurti *et al*., 2000; Williford *et al*., 2003). The weights of models are determined based on the model performance characteristics of past forecasts, and are set up to produce forecasts as close as possible to the tracks being analyzed (Jordan II, 2005; Kramer, 2008). By contrast, Goerss' (2000) simple mean consensus calculates arithmetic means without

Table 1. List of numerical models used in the study.

Model Name		Operating agency and type	Freq. (daily)
Deterministic Models	CMSC	CMC global dynamical model through TIGGE	2
	DBAR	NTC/KMA Double Fourier series Barotropic typhoon prediction model	4
	ECMWF	ECMWF global dynamical model through GTS	2
	ECMWF_TIGG	ECMWF through TIGGE (higher resolution than ECMWF)	2
	GDAPS	KMA global dynamical model based on UKMO model	4
	GFS	U.S. NCEP global dynamical model through ftp	2
	GFS_TIGGE	GFS from TIGGE	2
	GRAPES_TCM	CMA STI typhoon model through ftp	4
	JGSM	JMA global dynamical model through GTS	4
	KWRF	KMA WRF model	4
	NOGAPS (NAVGEM)	US Navy global dynamical model through ftp	2
	RDAPS	KMA regional dynamical model based on UKMO model	4
	TWRF	NTC/KMA WRF typhoon model	2
	CMA_EPS	CMA ensemble prediction system through TIGGE	2
Ensemble Prediction Systems	CMSC_EPS	CMC ensemble prediction system through TIGGE	2
	ECMWF_EPS	ECMWF ensemble prediction system through TIGGE	2
	EGRR_EPS	UKMO ensemble prediction system through TIGGE	2
	GFS_EPS	NCEP ensemble prediction system through TIGGE	2
	KEPS	KMA ensemble prediction system	2
	TEPS	JMA's ensemble prediction system from GTS	4

CMC = Canadian Meteorological Centre, CMA = China Meteorological Administration, ECMWF = European Centre for Medium Range Weather Forecasts, EMC = Environmental Modeling Center, GTS = Global Telecommunication System, NCEP = US National Centers for Environmental Prediction, JMA = Japan Meteorological Agency, TIGGE = the THORPEX (The Observing System Research and Predictability Experiment) Interactive Grand Global Ensemble, UKMO = United Kingdom Met Office

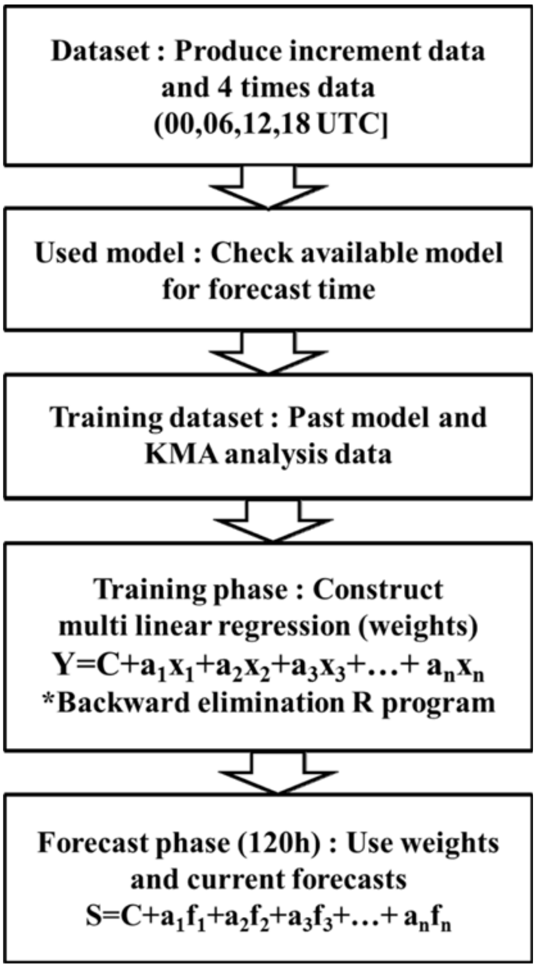

Fig. 2. Flow chart for the superensemble forecast procedure.

considering model performance.

The procedure for producing the superensemble forecast is summarized below. Usable models were identified for each forecasting time (0000, 0600, 1200, and 1800 UTC forecast cycles), and the most recent tropical cyclone forecast data were used to produce the multiple regression equation (Fig. 2). To guarantee the reliability of the equation, models with associated forecast locations corresponding to less than 90% of the analysis data locations were excluded from the training data. In addition, the backward elimination method (Venables and Ripley, 2002) in the R statistical package was applied, which gradually removes variables with low levels of contribution. This process is initiated beginning from all possible regression variables. Multi-linear regression analysis produces weights using the least squared-errors, which is called Ordinary Least Squares (OLS) method, between the analyzed typhoon positions and model-predicted positions. These weight values can be positive or negative.

In the forecast phase, superensemble forecasts were calculated by using the regression coefficients (weights) from the training phase and the model track forecasts (Fig. 2). Different weights and forecast values of the superensemble were produced on the basis of latitude, longitude, and forecast time (Krishnamurti *et al*., 2000; Williford *et al*., 2003). The input data in the training and forecast phases are incremental data converted on the basis of the analyzed locations. For instance, if the latitude of the analyzed position is 25.5°N and the 24 h latitude forecast is 28.6°N, the 24 h latitude forecast increment is 3.1°N. Track forecasts from twice daily models were interpolated and translated to intermediate positions to make these forecasts available four times a day. For example, assuming there are four numerical models such as × 1, × 2, × 3, × 4 for producing the superensemble, their 48 h latitudinal forecast increments (°N) are 5.4, 5.7, 4.9, and 5.2, and the weights are 0.57, 0.34, 0.39, and −0.29, each increment is multiplied by each weight and a constant (−0.12) is added to get an increment forecast of 5.3°N. Lastly, the forecast value (22.6) is produced by adding this increment forecast (5.3) to the initial typhoon position (17.3).

Given that the superensemble relies on the consistency of the forecasting performance of constituting models, a relatively short period of training data (2-3 year) is used (Williford *et al*., 2003). Considering that the number of tropical cyclone models used by the KMA has considerably increased since 2011, the experiment was conducted for the years 2012 and 2013. Tropical cyclone track forecasts in 2012 were generated using the training set, 2011, and forecasts in 2013 were generated using the training set, 2011 and 2012. The training dataset includes data from the previous and the current tropical cyclone season until the forecast time. In the tropical cyclone Leepi (1304) case, training dataset included 46 tropical cyclones from 2011-2012 and 1-3 tropical cyclones in 2013. The NOGAPS model was excluded from the 2013 superensemble forecasts because the consistency of its performance was low since it had been modified into the NAVGEM in February 2013.

To assess the applicability of the superensemble constructed here, its performance was compared with that of a simple mean consensus, ECMWF_TIGG, and GFS. The simple mean consensus and superensemble were formulated from the same model data. ECMWF_TIGG and GFS were selected since they were the best-performers among single numerical models in the Atlantic and the eastern North Pacific during 2012 (Cangialosi and Franklin, 2013). Each simple mean consensus or superensemble was applied when two or more members were available for given forecast values. Track errors were estimated by using the Haversine equation (Sinnott, 1984) with the KMA's tropical cyclone analysis data set as reference values.

3. Results

a. Forecast performance

Annual-average track forecast errors for the superensemble were lower than the simple mean consensus, the ECMWF_TIGG, and GFS throughout the 24- to 120-h forecast times in

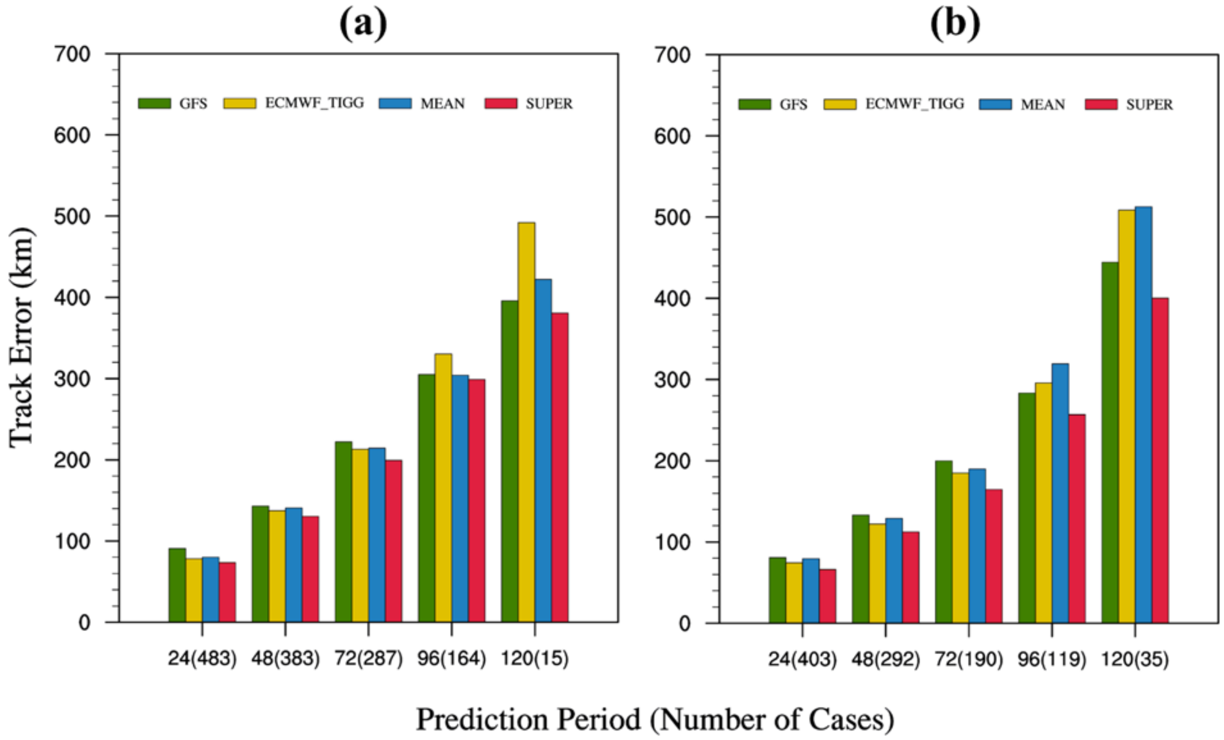

Fig. 3. Comparison of the annual mean track errors of the superensemble (SUPER), simple mean consensus (MEAN), ECMWF_TIGG, and GFS by forecasting period (24-, 48-, 72-, 96- and 120-h) for (a) 2012 and (b) 2013.

Table 2. Two years (2012 and 2013) mean track errors (km) and improvement rate (%) of the superensemble, relative to a simple mean consensus, ECMWF_TIGG, and GFS for forecasting periods (24-, 48-, 72-, 96- and 120-h).

Prediction period (h)/Number of cases	24/886	48/675	72/477	96/283	120/50
Superensemble	69.9	121.3	182.0	277.9	390.4
Simple mean consensus	79.7(12.3)	134.9(10.1)	202.1 (9.9)	311.7(10.8)	467.4(16.5)
ECMWF_TIGG	76.3 (8.4)	129.8 (6.5)	199.0 (8.5)	313.0(11.2)	500.2(22.0)
GFS	85.8(18.5)	138.0(12.1)	210.9(13.7)	294.2 (5.5)	420.0 (7.0)

2012 (Fig. 3a) and in 2013 (Fig. 3b). The results from 2013, in particular, reflect the consistent performance characteristics of the superensemble. The superensemble outperformed the simple mean consensus, the ECMWF_TIGG, and GFS at all forecast times, but particularly in the extended forecasts (96- and 120-h). However, the performance of the superensemble at 120 h was based on a minimal number of cases (15 and 35 cases for 2012 and 2013, respectively) due to limited availability of training data for the forecast period.

For a combination of the 2012 and 2013 datasets, the mean track errors of the superensemble were smaller than for the simple mean consensus by 9.8, 13.6, 20.1, 33.8, and 77.0 km at 24-, 48-, 72-, 96-, and 120-h, respectively which represents a 9.9% performance improvement at 72 h (Table 2). Superensemble mean forecast track errors were 6.4, 8.5, 17.0, 35.1, and 109.8 km smaller than the ECMWF_TIGG, which is a 8.5% improvement, at 72 h. Likewise the superensemble outperformed the GFS by 15.9, 16.7, 28.9, 16.3, and 29.6 km, with a 13.7% improvement at 72 h (Table 2). These results suggest that the superensemble could be a useful tool for operational tropical cyclone forecasting.

Although annual-average track forecast errors are an important model performance characteristic, consistency defined in terms of track forecast error distributions must also be considered. Mean track errors from 24- to 120-h forecasts for 25 and 31 tropical cyclones, respectively, in 2012 and 2013 are shown in Figs. 4a, b. The best-performing models listed on the right side of the charts in Fig. 4 are the individual models or the superensemble and simple mean consensus that had the smallest track error averages for each tropical cyclone at that forecast interval. For this two-year sample, the tropical cyclone track errors of the superensemble were smaller than those of the simple mean consensus method for over 60% of the total cases, and smaller than those of the best-performing model for about 50% of the total cases for 24-72-h forecasts. It is noteworthy that the mean 24-72-h track forecast errors of the

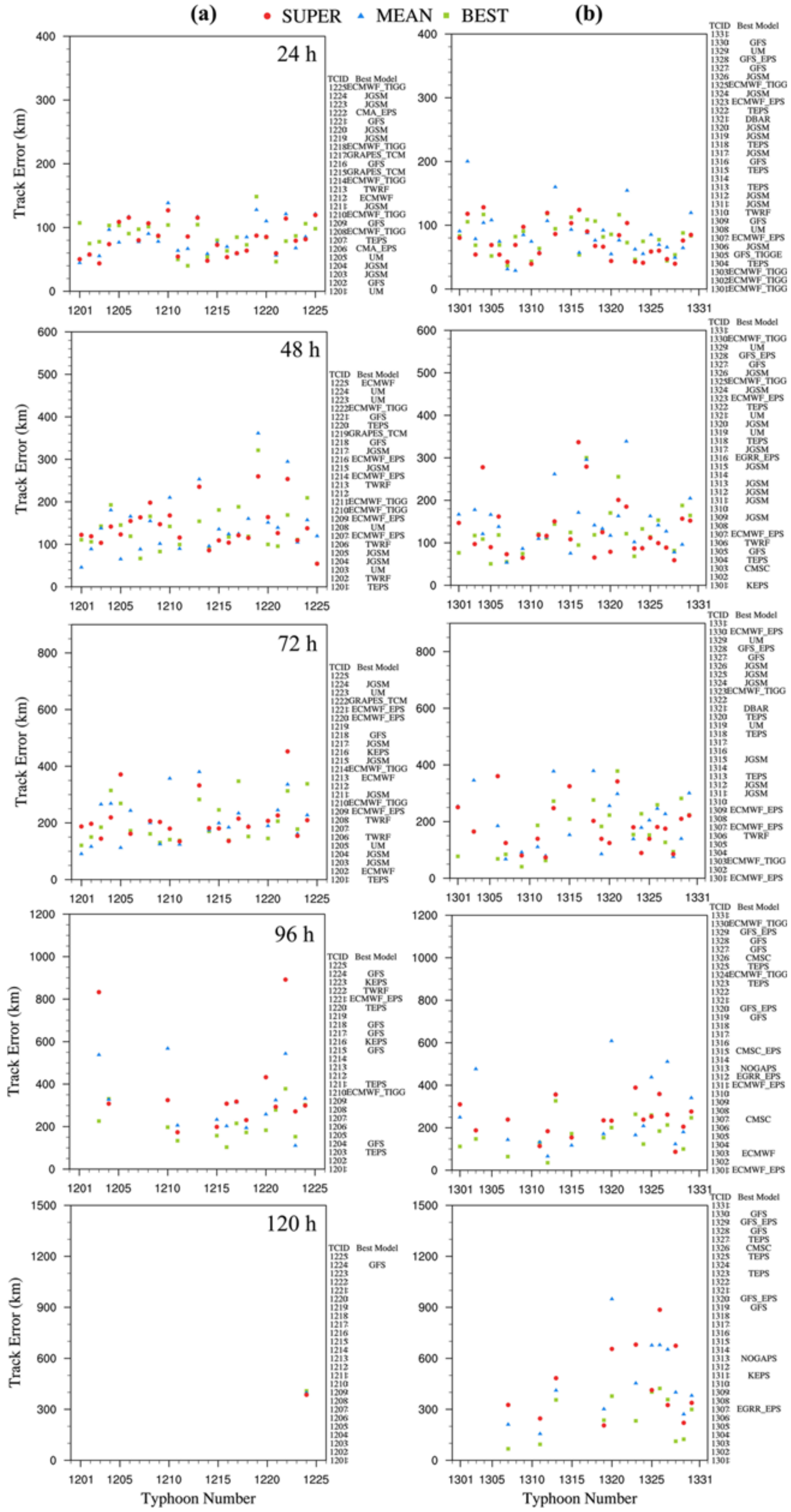

Fig. 4. Mean track errors at 24-, 48-, 72-, 96-, and 120-h for the individual tropical cyclones during (a) 2012 and (b) 2013 for the superensemble (SUPER, red circle), simple mean consensus (MEAN, blue triangle), and best-performing model (BEST, green box). The best-performing model for each tropical cyclone during each year is also listed on the right side for each forecast interval.

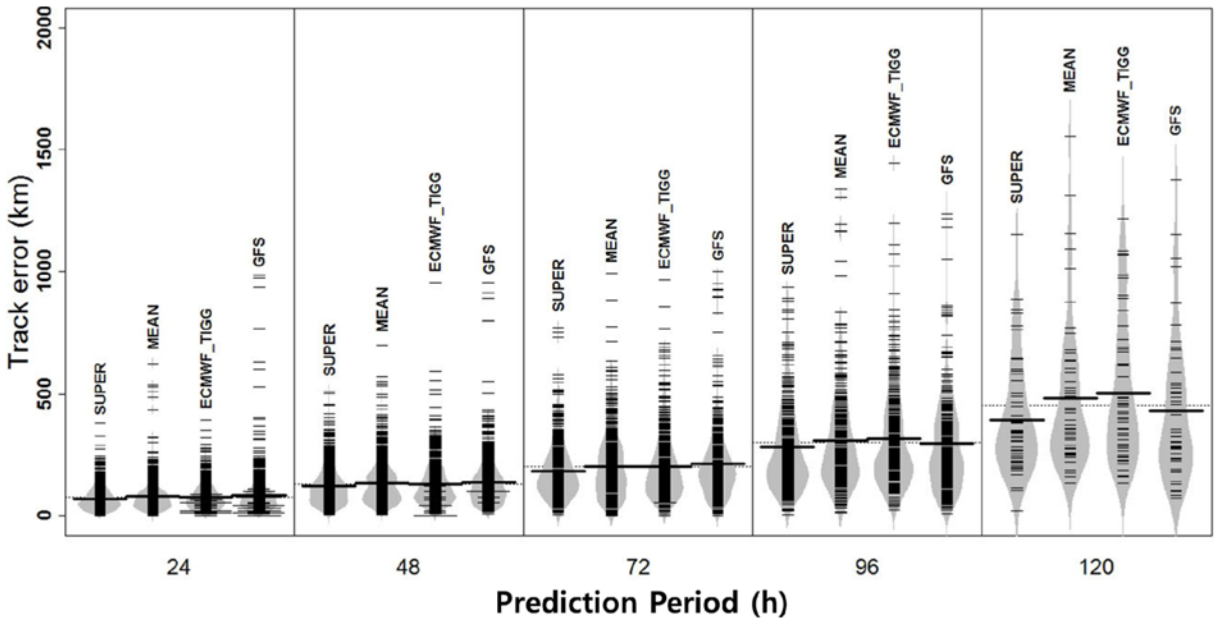

Fig. 5. Beanplots (Kampstra, 2008) of the 24-, 48-, 72-, 96- and 120-h track errors of the superensemble (SUPER), simple mean consensus (MEAN), ECMWF_TIGG, and GFS for the combined 2012-2013 sample. Gray areas indicate the probability distribution of individual forecast errors, black thin lines denote frequencies, and black thick lines represent individual tropical cyclone average track errors.

superensemble were smaller than the best-performing model for over 60% of the tropical cyclones during 2013 (Fig. 4b).

Of course the forecaster does not know which model will be the best-performing model for each forecast or for each individual tropical cyclone. However, the inclusion of the model performance for all prior storms during the season in the training set for the superensemble will begin to incorporate knowledge of best-model performance. It is noted that the ratio of cases in which the superensemble mean track forecast errors were smaller than those of the simple mean consensus or the best-performing models tends to increase toward the end of the season. This improvement in the performance of the superensemble may then be attributed to the employment of the most recent training data.

Track error distributions were analyzed using Beanplots (Kampstra, 2008), which display the distributions of individual track errors along with the probability density distributions (Fig. 5). For the 24-, 48-, and 72-h forecast intervals, the density of smaller errors were similar for the simple mean consensus and superensemble forecasts, but the density of larger errors was lower for the superensemble forecasts. For the 96- and 120-h forecasts, the simple mean consensus had a larger median error distribution than the superensemble because the density of the smaller errors decreased and some extremely large errors were included in the distribution. For the ECMWF_TIGG, the number of extremely large errors was rather moderate except at 96 h, but the density of the smaller-error forecasts tended to be smaller, and especially at 96 h. Similarly, the GFS had a smaller proportion of small-error forecasts than that of the superensemble, and a larger number of large track errors in the 24- and 48-h forecast intervals. In summary, the ECMWF_TIGG and GFS had a smaller density of small track errors, and the simple mean consensus had a larger density of larger track errors than the superensemble. Therefore, This cumulative analysis for mean tropical cyclone track errors and track error distributions indicates that the superensemble has consistently smaller track forecast errors than the other three methods. Indeed, the performance of the superensemble is similar to that of the best-performing model for individual tropical cyclones, which is not known to the forecaster in real-time.

b. Case studies

To illustrate track forecast error trends for the superensemble, two tropical cyclones that affected Korea [Tembin (1214) and Danas (1324)], were selected. Tropical cyclone Tembin (1214) had an abnormal track near Taiwan (Fig. 6) because of its interactions with Bolaven (1215). For Tembin (1214), the average track errors for the superensemble and the simple mean consensus were similar (Fig. 4a). However, the superensemble had a different forecast tendency (Fig. 6). During the early stage of Tembin's lifecycle, the superensemble forecasts more closely matched the verified track than did the simple mean consensus or individual model forecasts. In particular, the superensemble better predicted the track loop. Both consensus methods more accurately forecast the loop tracks than did the individual models. Although the superensemble tended to predict excessively westward forecasts during the later stage of Tembin, its landfall forecast location on Korea was

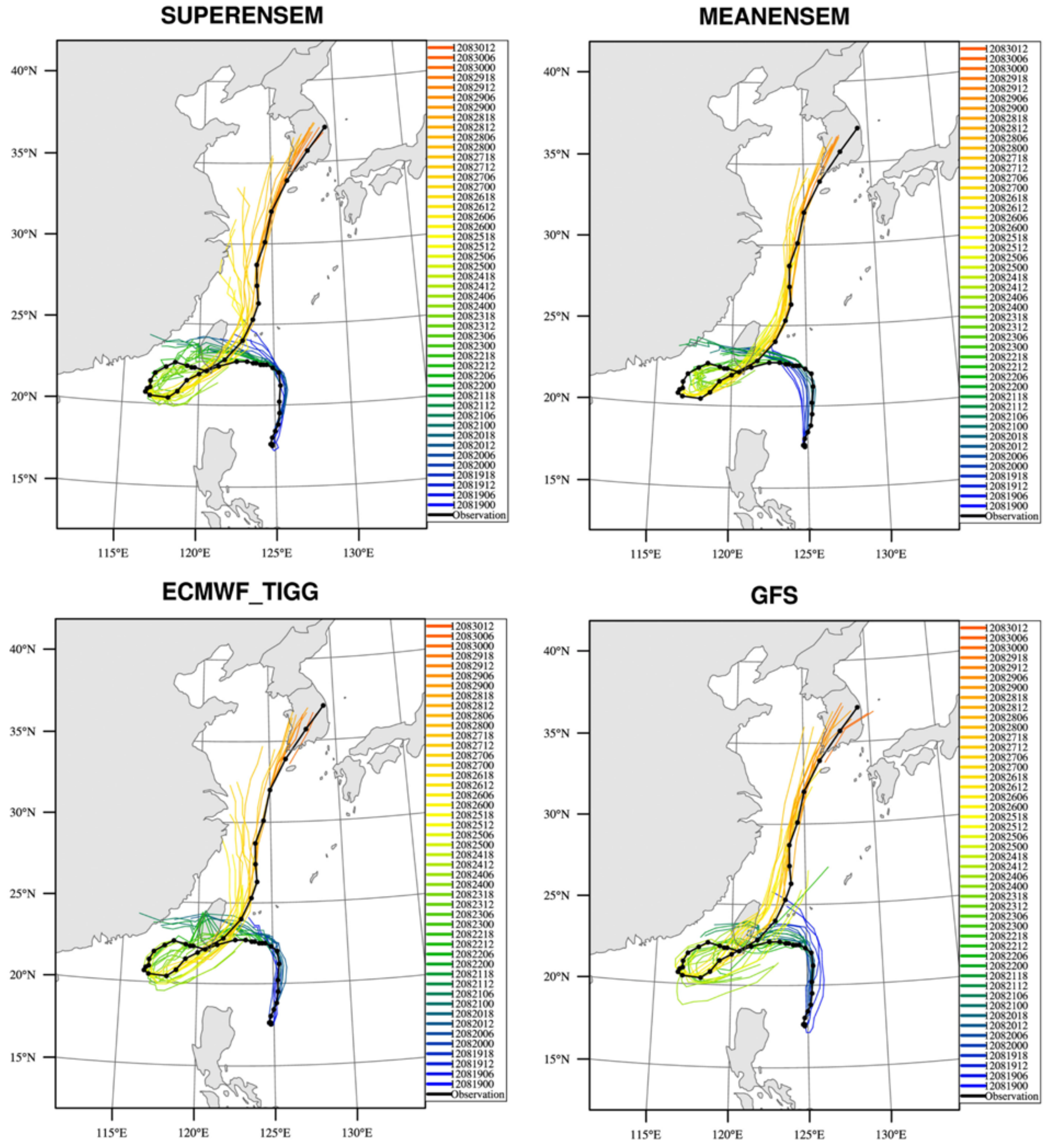

Fig. 6. Tracks of KMA analysis (black line) and model forecasting (superensemble, simple mean consensus, ECMWF_TIGG, and GFS) for Tembin (1214). The track colors in the legends on the right indicate forecast times.

somewhat better than the simple mean consensus or the other model forecasts.

Tropical cyclone Danas (1324) has become another tropical cyclone that directly affected Korea during October since tropical cyclone Zeb (9810) in 1998. Tropical cyclone Danas (1324) had a classical recurvature-type track that was generally well forecasted by the ECMWF_TIGG, and GFS and the two consensus techniques (Fig. 7). However, the superensemble forecast tracks for Danas (1324) more closely matched the verifying track than the forecasts derived from the other three methods (Fig. 7). The superensemble track errors were similar to those of the simple mean consensus at 48 h, but lower at 24- and 72-h (Fig. 4b).

Time series for 24-, 48- and 72-h track forecast errors as a function of times after the tropical cyclone formation are shown in Fig. 8. For Tembin (1214), track forecast error variability for the superensemble was similar to that of the ECMWF_TIGG, which outperformed the GFS and the simple

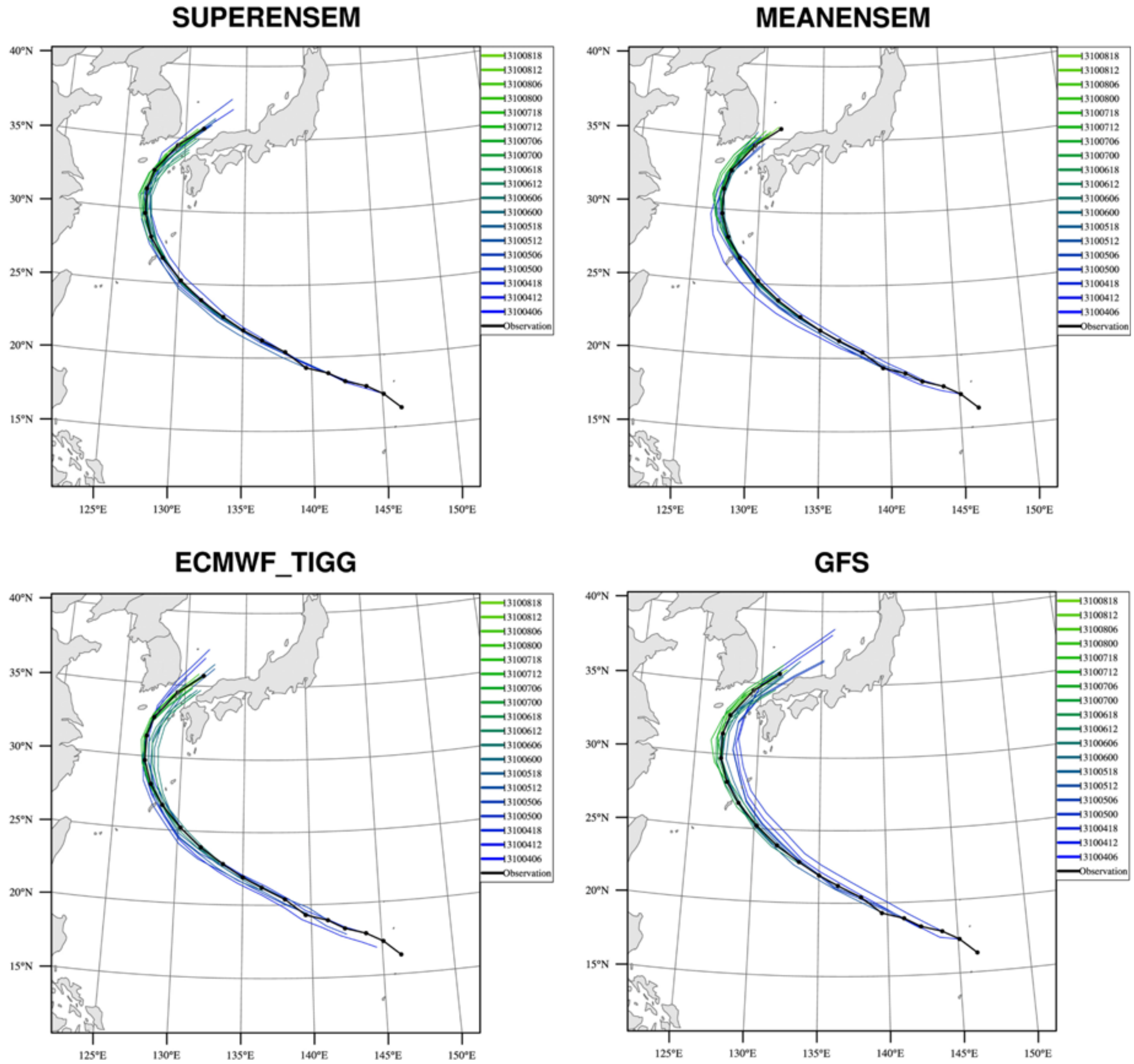

Fig. 7. Tracks of KMA analysis (black line) and model forecasting (superensemble, simple mean consensus, ECMWF_TIGG, and GFS) for Danas (1324). The track colors in the legends on the right indicate forecast times.

mean consensus (Fig. 8a). For the Danas (1324) case, the track errors for the superensemble were similar to those of the GFS, whose errors were smaller than those of the ECMWF_TIGG for the 24- and 48-h forecasts (Fig. 8b). The superensemble generally had smaller track errors than the simple mean consensus and specifically had produced considerably smaller track errors than the other models at 72 h. It is important to note that even though the best-performing model varied from forecast to forecast for Temin (1214) and Danas (1324), the superensemble had a similar performance to the best-performing model for most times.

4. Concluding remarks

The superensemble forecast technique originally developed by Krishnamurti *et al*. (1999) is an objective and weighted consensus method based on the past performance of member models. In this study, a superensemble technique is developed based on the tropical cyclone track forecasts in the western North Pacific available at the KMA. The performance and applicability of this newly constructed superensemble was evaluated by comparisons with a simple mean consensus, and the ECMWF_TIGG and GFS models that were generally the best-performance models.

The superensemble performance assessment for the years 2012 and 2013 are summarized as follows. First, the annual-average track forecast errors for the superensemble forecasts were smaller than those of the simple mean consensus, ECMWF_TIGG, and GFS for the 24- to 120-h forecast intervals during 2012 and 2013. The analysis of the average track errors indicates that the performance of the superensemble was 9.9, 8.5, and 13.7% more accurate at 72 h than the simple mean consensus, ECMWF_TIGG, and GFS, respectively. The superior performance of the superensemble

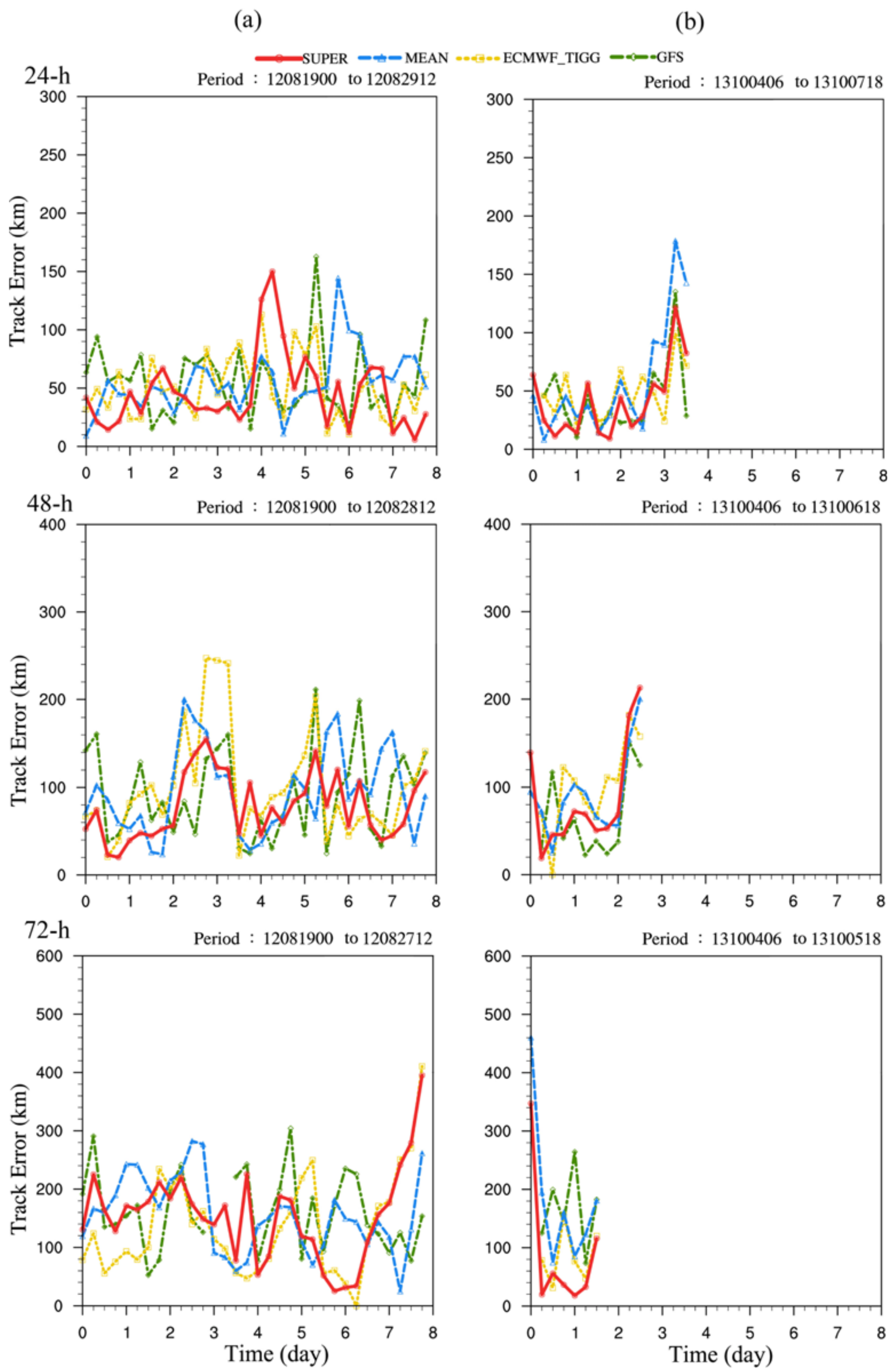

Fig. 8. Time series of 24-, 48-, and 72-h track errors for (a) Tembin (1214) and (b) Danas (1324).

over the simple mean consensus is consistent with previous studies (Vijaya Kumar and Krishnamurti, 2003; Williford *et al*., 2003; Jordan II, 2005; Kramer, 2008).

Second, the track error distributions were examined using mean track errors for individual tropical cyclone cases and with a Beanplot analysis. The best-performing model for individual tropical cyclones was different for each case. The superensemble 24-, 48- and 72-h forecast track errors for the individual tropical cyclone cases were lower than the simple mean consensus methods in over 60% of the cases, and lower than the best-performing model in over 50% of the total cases. In terms of track error distribution, a smaller density of relatively large errors is documented for the superensemble than for the simple mean consensus model, and a larger density of smaller errors than for the ECMWF_TIGG and GFS. Thus, there is a high probability of the superensemble having smaller errors than for the other forecast models.

Third, a case study of tropical cyclone, Tembin (1214) indicated the superensemble more accurately forecasts an early loop in the track and predicted better the landfall position on the Korea Peninsula even though the track forecasts had a westward bias. In the Danas (1324) case, the superensemble forecast track was a little closer to the verified track than the other models. Most importantly, the analysis of the track error time series showed the superensemble was competitive with the models that had the smaller track errors. This result is consistent with Elsberry (2014), who demonstrated that a consensus technique tends to offset random errors generated by individual models.

The consistent outperformance of the superensemble than the simple mean consensus, GFS, and ECMWF_TIGG indicates high potential applicability of the superensemble as an objective reference for tropical cyclone track forecasts. The performance of the superensemble for extended time periods will be analyzed further in a future study when longer training datasets can be obtained.

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