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ABSTRACT

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Tropical cyclones pose a great threat to coastal areas and accurate forecasting of their tracks is important for reducing and preventing coastal disasters. Multi-mode super-ensemble method was proposed to make full use of the forecasted tracks from different forecasting institutes. This paper proposed a modified multi-mode super-ensemble method, namely Error-Estimation Ensemble method, to overcome the shortcomings of traditional multi-mode super-ensemble method. The hypothesis, methodology and implementation of Error-Estimation Ensemble method are described. The EEE hindcast results of two typical tropical cyclones and all tropical cyclones that affects China coast are compared to those of four forecasting institutes. The comparison show that the EEE method reduces both the mean error and root-mean-square error of tropical cyclone track forecast, indicating that EEE method has better prediction accuracy and reliability. Discussions on present performance of EEE method and future works are present at last.

ADDITIONAL INDEX WORDS: *Typhoon track, Hurricane track, Control track, Accuracy improvement.*

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INTRODUCTION

Tropical cyclones may cause significant storm surges and pose a great threat to coastal areas. Accurate forecasting of tropical cyclone tracks is important in terms of reducing and preventing coastal disasters. Usually, after a tropical cyclone is detected, different forecasting institute would announce their track forecasting individually, and forecasted tracks from different forecasting institutes perform differently in different tropical cyclone cases, which raises a question: how to make full use of all the forecasted tracks and get a better one?

Multi-mode super-ensemble method has been employs to make full use of the forecasted tracks to improving the precision of track forecasting (e.g., Cane et al., 2013; Chen *et al.*, 2014; Ding *et al.*, 2016; Krishnamurti *et al.*, 1999; Kumar *et al.*, 2003). Multi-mode super-ensemble method is proposed based on ensemble method which use initial disturbance or mode perturbation to generate multiple groups of forecast results (e.g., Epstein, 1969; Rao and Srinivas, 2014;Wang and Liang, 2007). In multi-mode super-ensemble method, different simulation models are used instead of the initial disturbance or mode perturbation in ensemble method, in which way the calculation is more effective and practical (Krishnamurti *et al.*, 1999).

The basic idea of multi-mode super-ensemble method is to evaluate the performance of each forecasting institute on historical tropical cyclones, and based on the performance

evaluation a weighted averaging of the bias-removed forecast results is calculated as the forecasted control track. Based on the control track and the historical forecasting error, several possible tracks can be forecasted (Chen *et al.*, 2014). With the control track and possible tracks, parametric models can be employed to generate wind fields and drive storm surge models (e.g., Chen *et al.*, 2017; Pan *et al.*, 2016).

The key of multi-mode super-ensemble method is the calculation of forecasted control track, which can be calculated with a two-step approach (Ding *et al.*, 2016). The first step, namely training step, determines the weight of each forecasting institute according to its historical performance.

$$\alpha_i = \frac{E_i}{\sum_{i=1}^{N} E_i} \quad (1)$$

where α_i is the weight of the ith forecasting institute; $E_i = 1/f_i$ with f_i is the averaged forecast error of the ith forecasting institute during forecasting historical cyclones; N is the number of considered forecasting institute.

The second step, namely forecasting step, uses bias-removed ensemble mean method to calculate the forecasted control track as:

$$F_C = \sum_{i=1}^{N} \alpha_i \left(F_i \text{-} f_i \right) \quad (2)$$

where F_C is the forecasted control track and F_i is the forecast track of the ith forecasting institute.

The traditional multi-mode super-ensemble method can reduce the mean forecast error compared to each forecasting institute (Chen *et al.*, 2014; Ding *et al.*, 2016). However, it has two shortcomings. The first is that it need plenty of historical forecast

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and measured track data to calculated e_i, and the considered number of historical cyclones has an influence on the value of e_i. The second is that although the mean error is reduced, the forecast error of a specific cyclone might be large, for the weights are calculated based on historical forecasts.

In this paper, a new Error-Estimation Ensemble (EEE) method is proposed to overcome the shortcomings of Super-ensemble method. The core concept of the EEE method is to estimate the possible error of the forecasting of each institute based on the relative positions of forecasted positions and actual positions of the cyclone center, and then use the "estimated error" to fix and weight the forecast of the corresponding institute. The weighted average value of the fixed forecasts of each institute is the final EEE value. With the EEE method, all the tropical cyclones that move into East China Sea during 2013 to 2016 are hindcasted with the EEE method based on the forecasts of China Meteorological Administration (CMA), Joint Typhoon Warning Centre (JTWC) of USA, Japan Meteorological Agency (JMA) and Taiwan Meteorological Centre (TMC). The EEE values are compared to the estimated values of the traditional super-ensemble method. It is found that, compared to traditional super-ensemble method, the EEE method needs less data and has better performances in both the average error and standard deviation of the cyclone track forecasting.
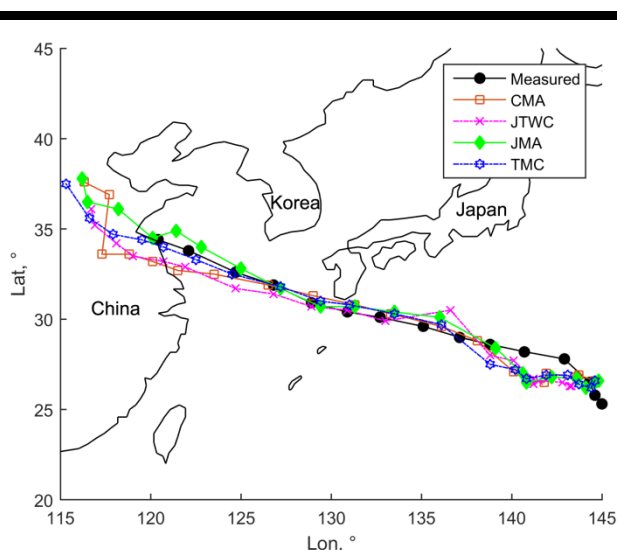

Figure 1. Measured and 24-hour forecasted tracks of tropical cyclone Damrey (1210). The time interval is 6 hours.

METHODS

In this section, the hypothesis, methodology and implementation of EEE method are given.

Hypothesis

In order to explain the hypothesis of EEE method, the 24 hour forecasts of CMA, JTMA, JMA and TMC of tropical cyclone Damrey (1210) are plotted in Figure 1 together with the measured track. As seen, the deviation of the forecasts from the measured track to be locally coherent, that is to say the deviations of the

forecasted tracks in the next time point can be estimated by the forecasted and measured tropical cyclone tracks in present and previous time point. Based on this feature, it is assumed that the forecasted track extends in a locally coherent trend, and hence the error of the forecasted track can be estimated roughly by the extend trend of the forecasted and measured tracks.

Error-Estimation Ensemble Method

Based on the hypothesis, the possible error of the forecasted cyclone track of the next time point can be estimated according to the extension lines of forecasted and measured typhoon track, as illustrated in Figure 2. The e_i is so called "Error-Estimation" and the forecast of the next time point can be "fixed" with e_i. Considering that the forecasting institutes usually tune their models according to real-time errors, a reduction coefficient k is used when fixing the forecasted track. The "fixed" forecast of a forecasting institute can be estimated with its forecast position and reduced "Error-Estimation" as in Figure 2.
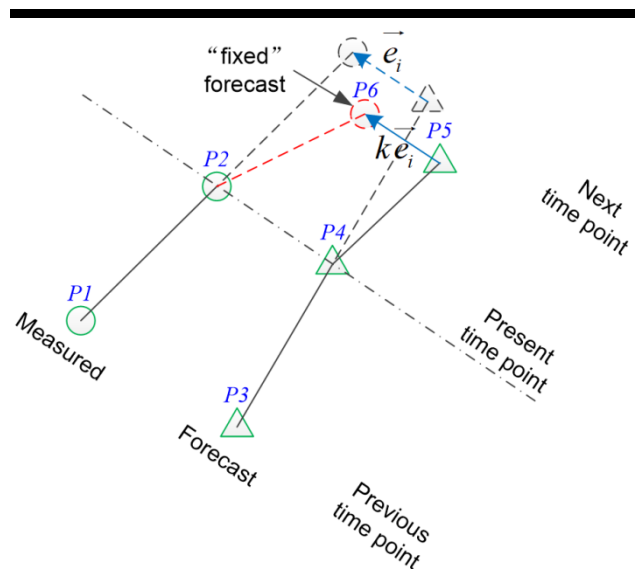

Figure 2. Diagrammatic sketch of "estimated error" and "fixed" forecast.

After the "fixed" forecast of each forecasting institute is obtained, the weighted average value of the "fixed" forecasts can be calculated with

$$F_C = \sum_{i=1}^{N} \alpha_i X_i \qquad (3)$$

where F_C is the EEE-forecasted control track; X_i is the "fixed" forecast of ith forecasting institute; α_i can be calculated by Eq. (1) with

$$E_i = 1/\left|\vec{e_i}\right| \qquad (4)$$

Implementation

Figure 3 gives the calculation procedure of "fixed" forecasts of a given forecasting institute. Using the calculation principle given in Figure 2, the "fixed" forecast can be calculated with 5 known positions, which is referred to as "five-point method" hereinafter.

All the need data in the calculation of "fixed" forecasts of a given forecasting institute is implied by the solid line symbols (No.1 to 8) in Figure 3, with circles indicating measured positions and triangles indicating forecasted positions.

The dashed line boxes in Figure 3 indicate the five-point method, and the dashed line circles of No. 9 to 12 indicate the "fixed" forecasts of 6, 12, 18 and 24 hours. As shown in Figure 3, "fixed" forecasts of 6 hours can be calculated with 2 measured point and 3 forecasted point using five-point method. Use the "fixed" forecasts of 6 hours as a measured point and with five-point method the "fixed" forecasts of 12 hours can be calculated. On the analogy of this, the "fixed" forecasts of 18 and 24 hours can be calculated. The reduction coefficient k is set to 0.5, 0.4, 0.3 and 0.3 for calculating "fixed" forecasts of 6, 12, 18 and 24 hours respectively according to sensitivity study.
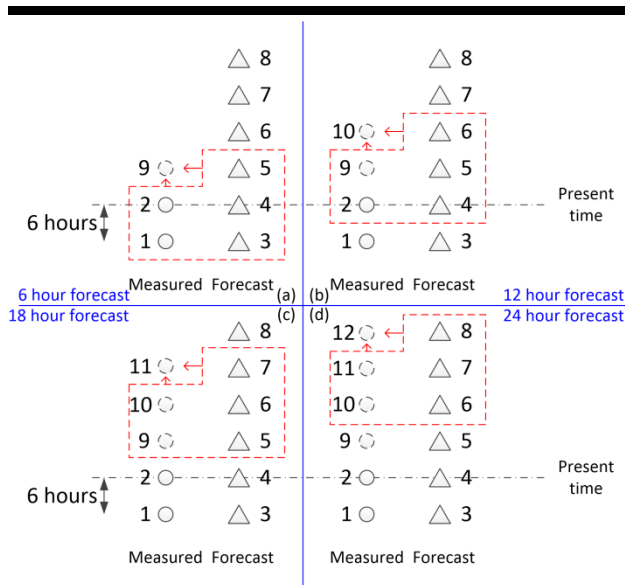

Figure 3. Calculation of "fixed" forecasts of a given forecasting institute.

After the "fixed" forecast of each forecasting institute is calculated, the EEE forecast is the weighted average value of "fixed" forecasts of all considered forecasting institutions.

RESULTS

This section gives comparison of forecasted results of EEE method and the four considered forecasting institutes including CMA, JTWC, JMA and TMC. Comparisons are given based on the forecasting results of two typical tropical cyclones (Damrey [1210] and Fitow [1322]) and all tropical cyclones that affects China coast during 2013 to 2016 respectively.

Typical Tropical Cyclones

The first chosen typical tropical cyclone is Damrey (1210), which is formed in the night of July 28th, 2012 and makes landfall in the night of August 2nd, 2012 on the coast of Jiangsu Province, China. Tropical cyclone Damrey is the strongest typhoon landed in the north of the Yangtze River since 1949. The second chosen

typical tropical cyclone is Fitow (1323), which is formed in the September 27th, 2013 and makes landfall in October 7th, 2013 on the coast of Fujian Province, China. Tropical cyclone Fitow causes the most economy loss to China since 1996. The tracks of tropical cyclone Damrey and Fitow are given in Figure 3.
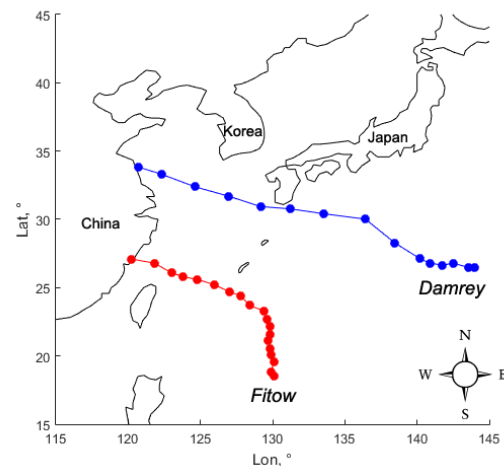

Figure 4. Tracks of tropical cyclone Damrey (1210) and Fitow (1323).
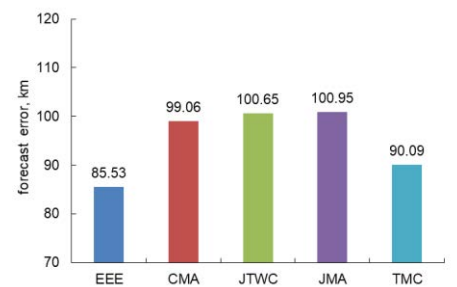

Figure 5a. Forecast errors of EEE method and 4 forecasting institutes during tropical cyclone Damrey (1210).
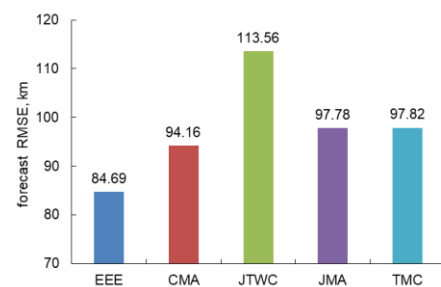

Figure 5b. Forecast root-mean-square errors of EEE method and 4 forecasting institutes during tropical cyclone Damrey (1210).

The forecasted mean errors and root-mean-square errors (RMSE) of tropical cyclone Damrey calculated by EEE method and the four considered forecasting institutes are plotted in Figure 5a Figure 5b, respectively. The mean error reflects the average

forecast accuracy, while the RMSE reflects the reliability of the forecast results, since a large deviation of one forecast would increase the RMSE significantly. As seen, both the mean error and RMSE of EEE forecast are smaller than those of the considered forecasting institutes. Compared to the results of CMA, JTWC, JMA and TMC, the error of EEE forecast reduces 13.7 %, 15.0 %, 15.3 % and 5.1 %, and the RMSE of EEE forecast reduces 10.1 %, 25.4 %, 13.4 % and 13.4 %, respectively.

The forecasted mean errors and root-mean-square errors of tropical cyclone Fitow calculated by EEE method and the four considered forecasting institutes are plotted in Figure 6a Figure 6b, respectively. As seen, both the mean error and RMSE of EEE forecast are smaller than those of the considered forecasting institutes. Compared to the results of CMA, JTWC, JMA and TMC, the error of EEE forecast reduces 7.4 %, 33.1 %, 28.0 % and 17.0 %, and the RMSE of EEE forecast reduces 6.7 %, 32.0 %, 27.1 % and 16.8 %, respectively.
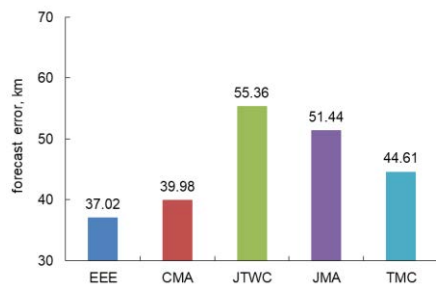

Figure 6a. Forecast errors of EEE method and 4 forecasting institutes during tropical cyclone Fitow (1312).
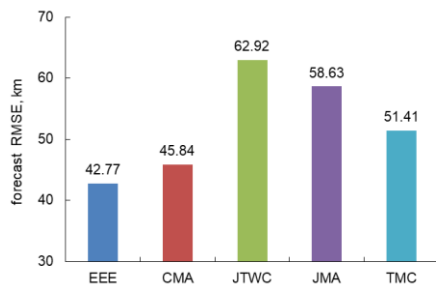

Figure 6b. Forecast root-mean-square errors of EEE method and 4 forecasting institutes during tropical cyclone Fitow (1312).

Tropical Cyclones in 2013~2016

All the tropical cyclones that moved across the 24-hour warning line of China during 2013 to 2016 are hindcasted by EEE method. The forecast mean errors and root-mean-square errors of EEE method and the four considered forecasting institutes are plotted in Figure 7a Figure 7b, respectively. As seen, both the mean error and RMSE of EEE forecast are smaller than those of the considered forecasting institutes. Compared to the results of CMA, JTWC, JMA and TMC, the error of EEE forecast reduces 9.4 %, 9.9 %, 6.5 % and 11.1 %, and the RMSE of EEE forecast reduces 11.9 %, 12.5 %, 8.4 % and 12.9 %, respectively.
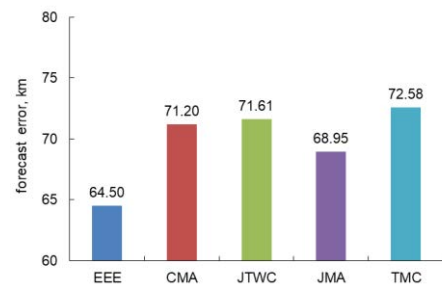

Figure 7a. Forecast errors of EEE method and 4 forecasting institutes of all tropical cyclones that affect China coast in 2013-2016.
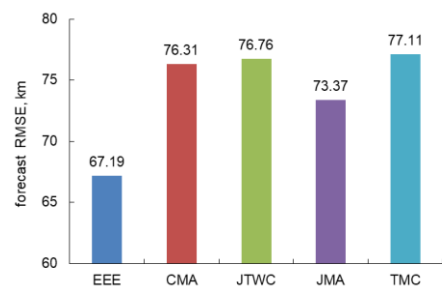

Figure 7b. Forecast root-mean-square errors of EEE method and 4 forecasting institutes of all tropical cyclones that affect China coast in 2013-2016.

DISCUSSION

Comparisons between the EEE hindcast results and the forecasts of considered forecasting institutes show that the EEE method reduces both the mean error and root-mean-square error of tropical cyclone track forecast, indicating that EEE method has better prediction accuracy and reliability.

The mean error of EEE hindcast result is approximately 10 % smaller than those of the four considered forecasting institutes. The degree of improvement is similar to traditional multi-mode super-ensemble method (Ding *et al.*, 2016). However, as can be seen in Figure 1, the locally coherent feature of the forecast tracks of the forecasting institutes is more significant in the stable moving phase rather than the beginning phase of a tropical cyclone, that is to say the hypothesis of EEE method is closer to reality in the stable moving phase. And hence the EEE forecast results performs better in the stable moving phase, which is the disaster-inducing phase of a tropical cyclone.

Unlike traditional multi-mode super-ensemble method using historical data, EEE method uses the measured and forecasted tracks of the present cyclone to estimate an ensemble track of the same cyclone. In this way, the requirement of large amount of data is avoid; and due to the same reason, the uncertain influence of the considered number of historical cyclones to the forecast result can be avoid.

The locally coherent hypothesis and five-point method are the core of EEE method. However, when conducting five-point method, the involvement of some exceptions makes the forecast result better. For example, a tricky skill is to use the vector distance from forecast position to measure position (e.g., point 4

to point 2 in Figure 2) as the "Error-Estimation" when the measured and forecasted tracks intersects (e.g., the line P1P2 and P3P4 intersects). In this way, the mean forecast error can be reduced. Actually, we also tried to use the vector distance from forecast position to measure position as the "Error-Estimation" for all cases and found that the forecast error is large. So it is a better way to work with the five-point method but just define some exceptions.

This paper only gives comparisons on the 24 hour forecasts. Actually, with the same philosophy, 48 hour and 72 hour forecasts can also be calculated with EEE method. The results also show some improvement compared to the forecasts of the four considered forecasting institutes, but the improvement is limited (e.g., for all tropical cyclones that moved across the 24-hour warning line of China in 2016, the mean error of 48-hour EEE forecast is slightly bigger than that of JMA, and the RMSE of 72-hour EEE forecast is slightly bigger than that of CMA). Future works are still needed to improve the performance of EEE method on 48 and 72 hour forecast.

CONCLUSIONS

A modified multi-mode super-ensemble method, namely Error-Estimation Ensemble (EEE) method, is proposed to make full use of forecasted tropical cyclone tracks of different forecasting institute to get a better forecast.

The EEE method is based on the hypothesis that the forecasted track extends in a locally coherent trend, and the error of the forecasted track can be estimated roughly by the extend trend of the forecasted and measured tracks. With this "Error-Estimation", the forecast tracks of different forecasting institute can be fixed and weighted. The weighted average value of the fixed forecasts is the EEE forecast value. The EEE method is used to hindcast two typical tropical cyclones and all tropical cyclones that affects China coast during 2013 to 2016. Comparisons between the EEE hindcast data and the forecasts of considered forecasting institutes show that the EEE method reduces both the mean error and root-mean-square error of tropical cyclone track forecast, which indicates that EEE method has better prediction accuracy and reliability. Compared to traditional super-ensemble method, the EEE method needs less data and has better performances in both the average error and standard deviation of the cyclone track forecasting.

The EEE method provide a new idea to make ensemble forecast of tropical cyclone tracks. However, the five-point method is just a basic method and more works (e.g., the involvement of exceptions) are still needed to improve the performance of EEE method, especially on 48 and 72 hour forecast.

This paper addresses the forecast control track aspect of EEE method. Based on the control track, possible tracks with different probabilities can be calculated according to the distribution feature of EEE control track around the measured track. This part of study is in progress and not discussed in this paper.

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