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Authors: Ding, Xuelin, Chen, Yongping, Pan, Yi, and Reeve, Dominic

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Fast Ensemble Forecast of Storm Surge along the Coast of China

Xuelin Ding†, Yongping Chen‡, Yi Pan‡ and Dominic Reeve††

†State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China
‡College of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing, China
††College of Engineering, Swansea University, Swansea, The United Kingdom

ABSTRACT

The uncertainties in typhoon wind field forecasts may introduce significant errors in storm surge forecasts. The common method to tackle this problem is based on ensemble forecasting of a typhoon wind field by using different initial and/or boundary conditions in the adopted weather forecast model. However, this method demands very high computational costs and therefore may not always be acceptable for operational use. In order to improve time efficiency, this paper introduces a new method which mainly relies on the forecast results from different weather forecast centres. With the bias modification, the control typhoon forecast is first generated by the weighted averaging of forecast results from individual forecast centres. The weighted factor for each centre is calculated under a dynamic training scheme. The ensemble typhoon forecasts are then generated by combination of five different typhoon tracks and three different wind speeds around the control forecast. The ensemble storm surge forecasts are conducted by running a well-validated storm surge model driven by the wind fields obtained from the above ensemble typhoon forecasts. Since each storm surge forecast can be calculated independently, the ensemble storm surge forecast can be fast conducted without significant increase in computational time. The above method is applied to the forecasting of storm surge in 2013 along the coast of China. By comparison with the traditional forecast, the control forecast exhibits a higher accuracy, and the ensemble forecasts provide more types of forecast results, such as the occurrence probability of storm surge over a certain surge level, which are useful for the probabilistic decision of protection measures against storm surge.

ADDITIONAL INDEX WORDS: Multi-model super-ensemble, probability circle, storm surge, probabilistic forecast.

INTRODUCTION

Typhoon-induced storm surge can cause severe damage to coastal areas. An accurate storm surge forecast needs to be provided in a fast way for early decision-making. However, the accuracy of storm surge forecast is likely to be affected by the uncertainties arising from the typhoon forecast. These uncertainties can stem from the settings of initial and boundary conditions in the weather forecast models adopted, and the errors of those models in the description of typhoon physical processes such as typhoon generation, development and dissipation. To reduce the effect of these uncertainties, the ensemble method was developed where small perturbances on initial conditions could be accounted for and the forecasting errors could be successfully reduced (Epstein, 1969). Subsequently the ensemble method, through perturbing initial conditions (e.g., Buizza et al., 1998) and/or physical parameters (e.g., Buizza et al., 2000), were widely applied to solve the uncertainty problems.

Although the ensemble methods mentioned above were able to improve the accuracy of typhoon forecasts, two problems remained unsolved: (1) the uncertainty arising from the model selection was not considered; (2) the number of ensemble members should be large enough to obtain an acceptable forecast result, thus the computational costs were too expensive for operational use. To solve these problems, a multi-model super-ensemble method was proposed by Krishnamurti et al. (1999), which is based on the weighted averaging of the bias-removed forecast results from several selected weather forecast centres. The weighted factors for each forecast centre could be uniform or non-uniform. Previous studies show that this method performed well in the forecast of typhoon wind fields (e.g., Kumar et al., 2003).

Chen et al. (2014) used a similar method to forecast the ensemble typhoon wind fields, in which a fixed training scheme was proposed to calculate the weighted factors for each weather forecast centre. According to their results, the ensemble forecast method can effectively increase the reliability and accuracy of the storm surge forecast. This study aims to further improve this method by introducing a new training scheme, which dynamically determines the weighted factors for each forecast centre. The ensemble forecast wind fields will be used to drive a
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storm surge to conduct the ensemble storm surge forecast. Several types of new probabilistic forecast products obtained from the ensemble storm surge forecast will be introduced in this study.

Meteorological Data

The meteorological data used in this study was obtained from Fujian Province Water Conservancy Information Network (http://www.fjwater.gov.cn). The data includes the 24h, 48h and 72h forecast results of typhoon tracks and intensities (maximum wind speed) over the Western Pacific (0°N~50°N, 90°E~160°E) from four operational weather forecast centres: the China Meteorological Administration (CMA), Japan Meteorological Agency (JMA), Joint Typhoon Warning Centre (JTWC) of USA and Taiwan Meteorological Centre (TMC). The forecasts of typhoons were conducted four times a day at 02:00, 08:00, 14:00 and 20:00 (Beijing time ~ GMT+08).

METHODS

The fast ensemble forecast of storm surge consists of three steps: (1) using a modified multi-model super-ensemble method to generate a control typhoon forecast; (2) making perturbations on the control typhoon forecast to generate an ensemble of several typhoon forecasts, including one control forecast and fourteen perturbed forecasts; (3) using each typhoon forecast to drive the storm surge model and obtaining fifteen ensemble storm surge forecasts.

Control Typhoon Forecast

The control typhoon forecast is generated by using a modified multi-model super-ensemble approach. In this approach, the forecast procedure is divided into two periods, i.e., training period and forecasting period. The weighted factors for each centre are determined by its performance of typhoon forecast in the training period, i.e., a higher weighted factor will be assigned to the centre that performed more accurately in the training period. It can be numerically described as,

\[
\alpha_i = \frac{E_i}{\sum_{i=1}^{N} E_i}
\]

(1)

in which \(\alpha_i\) is the weighted factor for the \(i\)-th forecast centre; \(E_i\) is the multiplicative inverse of the mean forecast errors of \(i\)-th forecast centre in the training period.

Once the weighted factor is determined, the control forecast can be calculated by using the bias-removed ensemble mean (WEM) method, which is described as:

\[
FWEM = \frac{E_i}{\sum_{i=1}^{N} \alpha_i}
\]

(2)

in which \(FWEM\) is the control forecast value; \(E_i\) is the forecast value of the \(i\)-th forecast centre; \(N\) is the number of the forecast centres, with \(N=4\) in this study; \(\overline{\varepsilon_i}\) is the mean forecast bias of the \(i\)-th centre in the training period.

From the above equations, we can see that the forecast value is affected by the mean bias \(\overline{\varepsilon_i}\) and the weighted factor \(\alpha_i\) of each centre, while the bias and the factor are both determined by the forecasting errors of each centre during the training period. Therefore, how to determine the training period becomes very important. The traditional way to determine the training period is based on the fixed training method, in which all the forecasting typhoons have the same training period (Figure 1). However, as the accuracy of forecast value relies on the consistency of forecasts between the training period and the forecasting period for each centre, the fixed training method may perform worse for the forecast typhoons which occurs far from the training period. To overcome this problem, this study proposes a new training method to dynamically determine the weighted factor for each centre. In this method, each forecasting typhoon has its own training period. The training period moves with the new occurrence of typhoon, but the number of typhoons in the training period is fixed. The weighted factors are calculated based on this ‘moving’ training scheme (Figure 2). In this way, the forecast performance of each centre can be updated on a regular basis.

Perturbed Typhoon Forecasts

As the typhoon track and intensity (maximum wind speed) are two of the main factors used in the parametric typhoon wind model, the uncertainties during the forecast of these two parameters may introduce significant errors in the typhoon forecasts and subsequently in the storm surge forecasts. In order to generate the ensemble forecast, small perturbances are made on these two parameters, which values have been determined in the control typhoon forecast.

As for the perturbation on the typhoon tracks, the concept of “probability circle” (Wang et al., 2010) is introduced. With these circles, four perturbed typhoon tracks are built according to the control typhoon track and the mean error of the corresponding centre in the training period. These four tracks are the left track, right track, quick track and slow track (Figure 3). As for the perturbation on the maximum wind speed, the mean absolute error of the maximum wind speed of all centres in the training period is used as a perturbed value. By adding and subtracting the error to and from the value of the control track, two perturbed maximum wind speeds can be generated.

By combining the five typhoon tracks (1 control track plus 4 perturbed tracks) with the three maximum wind speeds (1 control speed plus 2 perturbed speeds), an ensemble of fifteen groups of typhoon parameters can be obtained. Subsequently,
fifteen ensemble typhoon wind fields can be generated by substituting these parameters in the modified Jelesnianski parameteric typhoon model (Jelesnianski, 1965).

Ensemble Storm Surge Forecast

The ensemble storm surge forecast is obtained by driving a well-validated storm surge model (Tan et al., 2009) with the above ensemble typhoon wind fields. This surge model is robust with a high-precision, and has been used for the real-time forecasts along China coasts since 2007. Since each typhoon ensemble member is independent, the ensemble storm surge forecasts can be processed in parallel. If fifteen computers/CPUs were used for computation at the same time, the computational time for a 15-member ensemble of storm surge forecasts would remain almost the same as for only one forecast. In this study, the computed period of a storm surge event includes a 2-day warm-up and 3-day forecast for 24h, 48h and 72h forecasts. It takes less than 10min for a 5-day ensemble storm surge forecast using this storm surge model on a 64-bit system, including the time of pre-processing, 15-member ensemble forecasting and post-processing.

RESULTS

Control Storm Surge Forecast Results

As the perturbed forecasts are built on the control forecast, the accuracy of the control one needs to be examined first. Due to the page limit, this paper only presents the results for the control storm surge forecast, which is obtained by adopting the control typhoon wind field forecast to drive the storm surge model. To show the relative accuracy of the control storm surge forecast (i.e., WEM forecast), it is compared with the traditional storm surge forecast driven by the typhoon forecasting data from the CMA forecast centre.

The average improvement of storm surge forecast errors \( \Delta E_{\text{MAI}} \) in 2013 along China coasts is shown in Table 1. The improvement is calculated as,

\[
\Delta E_{\text{MAI}} = \left( E_{\text{MAI, ERF}} - E_{\text{MAI, CMA}} \right)
\]

in which \( E_{\text{MAI, ERF}} \) is the average forecast error of control storm surge forecast, \( E_{\text{MAI, CMA}} \) is the average forecast error of traditional storm surge forecast, which is based on the typhoon forecast from the China Meteorological Administration (CMA).

It can be seen that the control forecast is generally better than the traditional forecast, with the improvement of forecast errors in the range of 1–9 cm in the timely water level forecast and 1–14 cm in the maximum water level forecast at most of the tidal observation stations.

Table 1. Average improvement of storm surge forecast errors of typhoons along China coasts in 2013 (unit: m)

<table>
<thead>
<tr>
<th>Station</th>
<th>( \Delta E_{\text{MAI}} ) (Timely water level)</th>
<th>( \Delta E_{\text{MAI}} ) (Maximum water level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luchaogang</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Zhapu</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>Zhenhai</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Dinghai</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Jiantao</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Haimen</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td>Wenzhou</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Ruian</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Chongwu</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Ensemble Storm Surge Forecast Results

As the ensemble storm surge forecast can provide 15 different forecast results at the same time, several types of probabilistic products for the storm surge forecast can be obtained. As an example, Figure 4 shows the time series of ensemble forecast results of water level at Denglongshan Station. By taking the extreme values (maximum/minimum) and the average values of the 15 forecast results at each forecast time, the time series of the maximum envelope, minimum envelope and ensemble average forecast can be obtained. They can present the possible extreme large/small values and average value of storm surge forecast, respectively.

![Figure 4. Time series of ensemble forecast of water level for Typhoon Fitow in 2013 at Denglongshan Station, with maximum and minimum envelopes shown in dotted black lines, and the ensemble average value shown in red line.](image-url)
whole East China Sea are presented. They are plotted according to the results of ensemble average (on the left) and the ensemble values with 50\% guarantee rate (on the right) in that region. It can be seen that there is a slight difference between these two contour maps, particularly in the south part of East China Sea.

Figure 5. Filled contour maps of ensemble average (left) and ensemble value with guarantee rate of 50\% (right) of storm surge forecast for Typhoon Fitow in 2013.

As the maps shown in Figure 5 can only present average status of the ensemble forecast results, some important details may be missing, particularly for some extreme cases. To avoid this problem, similar to those presented in the study of Flowerdew et al. (2009), the stamp maps are proposed to present all members’ forecasts at the same time in Figure 6. The maps can present the results under different perturbances in a more straight way. As shown in Figure 6, the storm surge forecasts in a line have larger difference than those in a row, which indicates a bigger effect from perturbances on the typhoon track than on the maximum wind speed.

Figure 6. Stamp maps of ensemble storm surge members for Typhoon Fitow in 2013, with perturbances made on typhoon track between the members in a line and perturbances made on typhoon maximum wind speed between members in a row.

In addition, the occurrence possibility map (Figure 7) can be used to show the distribution of occurrence possibility of storm surge over a certain surge level at the interested sites. The occurrence possibility is calculated by the equation below:

\[ P(L > L_0) = \frac{n(f > L_0)}{N} \]

in which \( P(L > L_0) \) is the possibility of forecast values exceeding a given value, \( L_0 \); \( n(f > L_0) \) is the number of ensemble members that have forecasts exceeding the value of \( L_0 \); and \( N \) is the total number of ensemble members, with \( N = 15 \) in this study.

Figure 7. Occurrence possibility map of storm surge exceeding 0.6m for Typhoon Fitow in 2013.

DISCUSSION

The multi-model super-ensemble approach is one of the effective ways to reduce the effect of uncertainties in typhoon forecast (e.g., Chen et al., 2014), and therefore the ensemble storm surge forecast shows improvement over the traditional storm surge forecast. As the maximum water level forecast is more sensitive to the uncertainties in typhoon forecast, it is understood that the multi-model super-ensemble approach contributes a more significant improvement in the maximum water level forecast than that in the timely water level forecast, as shown in Table 1. This improvement can help to make a better prevention decision against the storm surge, because the maximum water level is more concerned for the coastal disaster protection. Although this study has shown a promising result, more studies on the ensemble storm surge forecasts in other regions and time periods are necessary in the future to make a more general conclusion on the performance of ensemble storm surge forecasts.

As the ensemble storm surge forecasts can provide 15 forecast results at the same time, various types of probabilistic products can be generated. Those products can provide much more information than that from the traditional forecast. For example, the time series of ensemble forecasts, as shown in Figure 4, can show how the uncertainty varies by time at a specific site; the ensemble average and ensemble value with guarantee rate of 50\%, as shown in Figure 5, can show the forecast uncertainty lying in selection of different statistical values of ensemble forecasts; and the stamp maps, as show in Figure 6, can clearly show the influence of perturbances on each parameter. In fact, some of these probabilistic products have already been proposed.
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in previous studies, such as in the storm surge prediction for Atlantic Canada (e.g., Bernier et al., 2015) and the North Atlantic and European domain (e.g., Flowerdew et al., 2009). This implies that those products can be generally used in the storm surge forecast in different regions.

The high time-efficiency of ensemble storm surge forecasts in this study is mainly due to three reasons: (1) the utilizing of the WEM method has small time requirement on the pre-processing; (2) the perturbances on forecast of typhoon parameters are based on the statistical forecast errors in the past, and thus no extra time is needed to generate the ensemble wind fields. (3) The computation of 15 ensemble storm surge members can be conducted in parallel. In fact, the overall time cost of a 5-day ensemble storm surge forecast takes less than 10 min on a single computer in this study. It is relatively small compared to many other ensemble storm surge forecast models, such as the model in the study of Suh et al. (2015), with the average time of 69 min for the storm surge forecast.


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LITERATURE CITED


CONCLUSIONS

Based on the forecasts of typhoon tracks and intensities (maximum wind speed) from China Meteorological Administration, Japan Meteorological Agency, Joint Typhoon Warning Centre of USA and Taiwan Meteorological Centre, the control typhoon forecast is fast generated by using the weighted average of bias-removed forecasts from the four forecast centres. Based on the concept of “probability circle” and the parametric typhoon wind model, a 15-member ensemble of typhoon wind fields are then generated. The ensemble storm surge forecasts are conducted by running a storm surge model driven by the ensemble wind field forecasts. Since each ensemble member is independent and can be calculated in parallel, the ensemble forecast of storm surge can also be fast conducted.

The accuracy of the control storm surge forecast along China coasts in 2013 has been examined. The results show that the control forecast has a slightly better performance than the traditional forecast. Apart from the control forecast, several types of probabilistic storm surge forecasting products are generated based on the 15 ensemble forecast results. Those results are useful for the probabilistic decision of protection measures against the storm surge.

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