Analysis of Uncertainties in Forecasts of Typhoon Soudelor (2015) from Ensemble Prediction Models

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Abstract

Using data from nine ensemble prediction systems (EPSs), we analyze uncertainties in forecasted tropical cyclone TC track (TCT), TC intensity (TCI) and relevant heavy rainfall (TCHR) for Typhoon Soudelor (2015) as it affected the Taiwan Strait and surrounding regions. The largest uncertainties in track predictions occurred when Soudelor traversed Taiwan and when it recurved northeastward after making landfall in mainland China. These large uncertainties seem to be ascribed to the topography of Taiwan and the spread of the perturbed steering flows, respectively. TCI spread was stronger before rather than after the Soudelor made landfall, with regional EPSs having stronger spread than global EPSs. This TCI spread showed high correlation with the evolution of the spread of vertical wind shear at the location of TC center. Large spread in 24-h TCHR during Soudelor’s landfall correlated with low-level jets and convergences in most EPSs, and TC track variation had played important role in TCHR uncertainty. At last, the spread–skill relationships among different groups are explored.


1. Introduction

Tropical cyclones (TCs) are one of the major natural disasters affecting the Taiwan Strait, bringing great threat to human lives and property (Mu et al. 2009; Kim et al. 2010; Lang et al. 2012; Wu et al. 2013; Chan et al. 2014; Chen and Wu 2015). Although significant improvement has been achieved during the past decade in predicting TC track (TCT), there remain large uncertainties in operational forecasts for TCs over Taiwan and the surrounding region, especially for TC intensity (TCI) and TC-related precipitation (Harnisch and Weissmann 2010; Kim et al. 2010; Wu et al. 2013).

Many studies have focused on the uncertainty in TC ensemble forecasts. Yamaguchi and Majumdar (2010) compared the ensemble spread of TC track (TCT) predictions using data of The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE, Bougeault et al. 2010). The results show that the spread of TCT forecasts, which varied among ensemble models, was strongly correlated with initial perturbations. Yamaguchi et al. (2012), who also focused on global ensemble models, found that uncertainties in TCT forecasts were not only associated with initial conditions but also model uncertainties. Similar conclusions were reached by Bassill (2014), who demonstrated that the choice of cumulus parameterization led to TCT differences between two operational models of the European Center for Medium-Range Weather Forecasting (ECMWF). Through an assessment of TIGGE data for hurricane Sandy (2012), Magnusson et al. (2014) demonstrated that higher-resolution global models performed better than coarse global models in their prediction of tropical cyclone intensity (TCI).

Uncertainty in tropical cyclone prediction can also be attributed to the shortcomings of forecast models, e.g., a lack of sufficient observations over the ocean, differences in the methodology of the tracking algorithm, the ineffective data assimilation techniques, inadequate model representation of air-sea interaction, and improper description of the topography of Taiwan in numerical models (Braun 2002; Buizza et al. 2005; Ding and Li 2008; Zhang and Luo 2010; Ding and Li 2012; Kunii and Miyoshi 2012; Duan et al. 2013; Li et al. 2013; Liu et al. 2015; Mu et al. 2015).

Large uncertainties in the forecasts of TCs that struck the Taiwan region are always associated with the factors mentioned above. Therefore, challenges still exist in the enhanced use of ensemble forecasts over the region. An evaluation of uncertainty in the TC forecasts for the region would improve our understanding of TC uncertainties and provide reference information for the enhanced use of ensembles.

In this study, we analyze the common uncertainties in forecasts of Typhoon Soudelor (2015) in nine ensemble prediction systems (EPSs) from several major operational centers. The possible reasons of these uncertainties are also investigated. As TCT, TCI, and TC-related heavy rainfall (TCHR) are the most important forecast parameters in TC prediction (Fournié et al. 2006), these parameters form the basis of our investigation.

2. Typhoon, datasets, and methodology

Overviews of the typhoon, datasets, and methodology used in this study are given in Text S1. We analyze uncertainties in Soudelor (2015) for the period when it caused greatest damage to the region (1200 UTC 7 to 0600 UTC 11 August 2015), by averaging ensemble forecasts initialized at 1200 UTC 6, 0000 UTC 7, and 1200 UTC 7 August 2015. The position of TC center was identified as the location of minimum sea-level pressure.

3. Results

3.1 Uncertainty in typhoon track forecasts

Most EPSs provided good forecasts of the general movement of Soudelor (2015) in the vicinity of the Taiwan Strait. TCT forecast error varied among the nine models, ranging from 20 to 100 km at 1200 UTC 7 August 2015 with an average of 53 km, and up to 180 km four days later (Table 1).

Figures 1 and S1a show the spatiotemporal characteristics of the spread in TCT predictions. In general, the spread tended to
PSF is known to have an important role in TCT recurvature. PKE can be used as the crucial predictor of TC recurvature, for the high correlation between PKE and PSF. The increasing of PKE would have greatly influenced the prediction of TC motions and resulted in large TCT uncertainty.

Most of the models showed large spread in track prediction after the typhoon passed over Taiwan’s Central Mountain range (CMR) (Figs. 1 and S1a; Table 1). TCs similar to Soudelor have been observed to deflect slightly southwest, (relative to their northwestward movement along the steering flows southwest increase as Soudelor moved from ocean to land, reaching its maximum when the typhoon was deflected northward after making landfall, indicating that large uncertainty in TCT predictions often appears during TC recurvature. This certainty seems to be closely related to perturbed kinetic energy (PKE) in the upper troposphere (Fig. 2). It is clear that PKE in all models tended to increase with lead time, implying the growth of the magnitude of wind perturbations. The evolution of the spread of perturbed steering flows (PSF) in the troposphere (200–850 hPa) also increased markedly with lead time and showed high relationship with PKE (Fig. S2).
of the subtropical high) after they pass over the CMR. This is followed by a northwest path prior to landfall, in China, resulting in a “V-like” track in the Taiwan Strait (Wu et al. 2015). Previous studies have shown that this feature is associated with the topography of the CMR, which can create a mesoscale secondary low that potentially becomes the new TC center on the lee side of the CMR (Wu and Kuo 1999; Lee et al. 2008).

As configurations differ among the nine ensemble models, there may be an occasional feature involved in the assessment for an individual EPS. Therefore, the features in TCT spread, during the period (1800 UTC 7 to 0000 UTC 8) when TC was passing over the CMR, were compared by clustering the nine ensemble models into four groups: global models, regional models, and models sharing a common physics parameterization scheme (single-physics) or whether this varies between members (multi-physics). Table S2 shows the averaged spread during 6−12 h (1800 UTC 7 to 0000 UTC 8) for each group. Regional models were found to have larger spread (41.7 km) than global models (34.8 km), indicating that the regional models had larger uncertainties. Such expansion of ensemble spread may come from the initial perturbations of the high-resolution models, which have a short time-scale for perturbation growth. The spread for multi-physics (41.4 km) was larger than that for single-physics, indicating that use of different physics schemes may have contributed to the larger TCT spread for the period when Soudelor passed over the CMR.

The spread–skill relationship of an ensemble forecast model is often evaluated by comparing the mean ensemble forecast error (MEFE) with the mean ensemble spread (MES). In an idealized situation, the average spread of an ensemble forecast should match the root mean square error (RMSE) of the ensemble mean (Buizza et al. 2005; Fortin et al. 2014; Feng et al. 2016). For TCT grand ensemble forecasts in all EPSs, the mean of grand ensemble forecast error was almost equal to the mean of grand ensemble spread (Table 1). However, for group-averaged forecasts, regional EPSs had larger MEFE and MES than global EPSs before the TC passed through the CMR, while multi-physics models had larger MEFE and MES than single-physics group (Fig. S6a). TCT ensemble spread was suggested to be increased slightly to match the ensemble forecasts in all EPSs, which may be achieved by a multi-physics approach.

3.2 Uncertainty in typhoon intensity forecasts

While TCT forecasts have improved significantly over recent years, there remains large uncertainty in forecasts of TCI (Fitzpatrick 1997; Kim et al. 2010; Wu et al. 2013). This is the case for Soudelor (Table 1), as evidenced by large average TCI forecast errors that ranged from −30 to 40 hPa at 1200 UTC 7 August 2015. These errors decreased gradually over time and fluctuated around 0 hPa after the second landfall, however, this was not the case for TCT forecasts. Averaged TCI forecast error for regional EPSs (21.7 hPa) during 0−48 h was larger than that for global EPSs (10.4 hPa), with regional EPSs predicting stronger intensities and global EPSs weaker intensities compared with the observed values. This could be a consequence of regional models not being coupled to an ocean model, which in a high-resolution model can result in overestimation of TCI (Ito et al. 2015).

Figures 3 and S1b show the spatiotemporal distribution of the spread in TCI forecasts from the EPSs. Results for spread from all EPSs indicate that spread was larger before rather than after Soudelor’s landfall and that it declined as the TC moved inland, particularly after the second landfall. This phenomenon may be
highly associated with the impact of vertical wind shear (VWS) on TCI (Hendricks et al. 2010; Reasor and Eastin 2012; DeMaria 1996; Merrill 1988). Figure S3 shows that the magnitude of the spread of 850–200-hPa VWS at the location of TC center fell significantly with time, which was highly similar to the changes of TCI. In the first few days, the instability of VWS was very large, leading to large TCI spread, while, in the last few days, it was very small, corresponding to small TCI spread.

Similar characteristics can be seen in the forecasts of SLP. The maximum spread for SLP forecasts was located mainly around Taiwan (Fig. 4), where the typhoon showed a marked change in intensity and structure (Chan et al. 2014). The effect of Taiwan’s topography in TCI should also be considered (Wu and Kuo 1999). Subsequent displacement of the TC center would inevitably increase the uncertainty in TC circulation structure and lead to TCI forecasts with lower skill.

Moreover, MGEFE and MGES for TCI forecasts were calculated by removing the results for the regional EPSs. MGEFE was roughly five times MGES on average before Soudelor made landfall in mainland China (Table 1), indicating that the spread–skill relationship of global EPSs on average was not satisfactory and needs to be improved by increasing the TCI spread or reducing the large TCI forecast error. Physical parameters may have less influence in TCI uncertainty than model resolution, as MEFE and MES of multi-physics models were slightly larger than that for single-physics group, and regional models, however, were obviously larger than global models (Fig. S6b).

3.3 Uncertainty in forecasts of TC-related heavy rainfall

We calculated the equitable threat score (ETS; Fig. 5a) and the BIAS (Fig. 5b) for 24-h accumulated total precipitation (> 50 mm) for the period when Soudelor made landfall in mainland China. China’s Global and Regional Assimilation and Prediction System of National Meteorological Center (NMC-GRAPES) obtained the highest ETS, while the Environment and Climate Change Canada (ECCC) had the lowest score. Among the global EPSs, Japan Meteorological Agency (JMA), National Centres for Environmental Prediction (NCEP) and Korea Meteorological Administration (KMA) scored the highest ETS values (~0.35). For the BIAS, all EPSs except NMC-GRAPES overpredicted heavy rainfall, implying that overprediction (rather than underprediction) is an issue for heavy rainfall prediction in EPSs.

Figure 6 shows the spatial distribution of the spread in TCHR predictions for the period of the second landfall. The maximum spread appears to the upper-right of landfall location and the windward side of the CMR, respectively. It is known that low-level jet and divergence can play important role in TCHR predictions (Lin et al. 2001, 2002), so they were analyzed in order to understand the reason for the spatial distribution of TCHR uncertainty. Figure S4 shows the low-level wind field at 850 hPa for the nine EPSs, validated at 1200 UTC 9 August 2015 before the second landfall in mainland China. The overall characteristic for the nine EPSs shows that low-level jet axis was found on both sides of the TC center, one of which propagated westward while another eastward. To the left of those jet axes, there were two low-level coastal convergence centers (Fig. S5), whose locations were reasonably coincided with that of the maximum spread of TCHR.
Since the location of low-level jet is highly associated with that of TC center, uncertainty in TCT predictions would have had a great impact on the prediction of low-level divergence and influenced the distribution of TCHR (Text S2). Therefore, TC track variation should be a crucial factor for uncertainty in TCHR forecast. In addition, the magnitude of low-level coastal convergence may account for the overprediction of heavy rainfall. Models who had large BIAS (e.g., GZ-GRAPES, ECMWF, and UKMO) performed stronger low-level coastal convergence than other models like NMC-GRAPES and ECCC. Reducing the magnitude of low-level convergence thus may be an efficient way to eliminate the overprediction of TCHR in most EPSs.

Model cloud microphysics and cumulus schemes may also be important factors for accurate simulations of rainfall (Wu and Kuo 1999; Nasrollahi et al. 2012). Comparing results for the two regional models, although NMC-GRAPES performed worse than China’s Global and Regional Assimilation and Prediction System of Guangzhou (GZ-GRAPES) model in forecasting TCT, it significantly outperformed GZ-GRAPES in heavy rainfall prediction. The cloud microphysics and cumulus schemes in GZ-GRAPES and NMC-GRAPES are different (Text S3), therefore, GZ-GRAPES could adopt the combination of microphysics and cumulus schemes used in NMC-GRAPES to improve its simulation of rainfall.

4. Summary and discussion

We have analyzed the characteristics of forecast uncertainties for Typhoon Soudelor (2015) during its passage over the Taiwan Strait. TC track (TCT), TC intensity (TCI), and TC-related heavy rainfall (TCHR) forecasts from regional and global ensemble prediction systems were investigated.

Large TCT spread appeared when Soudelor passed over Taiwan’s Central Mountain range (CMR) and later when Soudelor turned north–northeastwards after making landfall in mainland China. The later might be related to the evolution of perturbed kinetic energy (PKE) in the upper troposphere, which increased markedly as TC moved northward. This process had high correlation with the spread of perturbed steering flows (PSF). Therefore, reducing uncertainties in estimates of PKE in the upper troposphere may improve TCT forecasts during TC recurvature.

Regional models, which have a short time-scale for perturbation growth, were found to have larger spread than global models during the passage of Soudelor over the CMR. The larger spread in regional models may be caused by the rapid growth of small-scale initial perturbations that can reach saturation in a short time. The spread in multi-physics models was larger than that for single-physics models, indicating that the multi-physics approach also contributed to the large TCT spread as Soudelor passed over...
Larger uncertainties in TCI predictions appeared before rather than after landfall, which was highly coincided with the changes of the spread of 850–200-hPa vertical wind shear at the location of TC center. Similar characteristics were seen in the forecast of SLP. Its maximum spread appeared mainly around Taiwan, where the typhoon showed a marked change in intensity and structure, indicating the effect of Taiwan’s topography in TCI uncertainty.

Uncertainty in TC-related 24-h heavy rainfall during landfall was strongly associated with the variation in track prediction. Regional models showed better performance than global models in predicting 24-hr precipitation owing to their smaller TCT forecast error. Multi-physics models with larger TCT forecast error showed lower forecasting skill than the single-physics models. In all EPSs, overprediction of rainfall was more of a problem than underprediction, which may be improved by decreasing the magnitude of low-level convergence.

Differences in the mean ensemble forecast error (MEFE) and the mean ensemble spread (MES) for the TCT forecasts between the regional and global models were not obvious, and this was also the case when comparing results for the multi-physics and single-physics models. However, TCT spread can be increased slightly to better match the forecast error by changing the configuration of multiple physics. For TCI predictions, all EPSs, especially regional models, performed worse than global modes and should be improved by reducing the large forecast error.

Considering that the configuration of initial conditions and physical parameterizations vary among the nine models, it is difficult to clearly distinguish the contributions of these two factors to TC uncertainties. A series of sensitive and control experiments focusing on the effect of the two factors need to be conducted by using a single ensemble model in the future. Resolutions, varying among the nine models, may lead to oscillations of TC center and cause differences to the uncertainties. Therefore, more future studies should investigate the influence of methodology that used to identify TC center. This study focused on just a single typical typhoon event, given the computationally expensive task of analyzing the large dataset. Multiple typhoons and additional parameters (e.g. maximum sustained wind speed), should be taken into account in future work.
Acknowledgments

We thank Dr. Shu-Chih Yang and three reviewers for providing useful comments. This study was jointly supported by the Natural Science Foundation of Fujian Province, China (No. 2016J0007), the Social Development Science and Technology Project of Fujian Province, China (No. 2016Y0007), the Open Project of Laboratory of Straits Meteorology, Xiamen, China (No. HXk04), and the Science and Technology Project of Guangzhou City (No. 201604020012).

Edited by: S.-C. Yang

Supplement

Supplement 1 contains three text sections, two tables, and six figures.

References


Manuscript received 4 April 2018, accepted 16 November 2018.