Applied Mathematical Modelling 000 (2016) 1–17

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Application of breeding ensemble to tropical cyclone track forecasts using the Regional Atmospheric Modeling System (RAMS) model

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ARTICLE INFO

Article history:
Received 25 December 2014
Revised 27 February 2016
Accepted 13 April 2016
Available online xxx

Keywords:
Ensemble technique
Tropical cyclones forecasting
Breeding ensemble

ABSTRACT

In this study, a breeding ensemble technique that is designed specifically for tropical cyclone (TC) track forecasting is presented. By introducing two different scaling factors to represent two different growing modes for the storm-scale and the large-scale processes during the breeding cycling, it is shown that ensemble TC track forecasts with the Regional Atmospheric Modeling System (RAMS) model can be improved. Retrospective experiments with 14 TCs during the 2009–2011 seasons in the north Western Pacific basin show that the proposed TC-breeding (TCB) method could reduce the track forecast errors most significantly at 4–5 day lead times. Comparison of the track forecast bias between deterministic forecasts and TCB ensemble forecasts shows however that both the TCB ensemble and the deterministic forecasts possess similar pattern of the cross- and along-track forecast errors. This suggests that a significant component of the track bias in the RAMS model is determined by model inherent uncertainties that cannot be removed with the TCB method. Sensitivity experiments with different ensemble members show further that increasing the number of ensemble members could reduce the track forecast errors, but the rate of the track error reduction saturates when the number of ensemble members is larger than 30 due to the inefficiency of the TCB method in orthogonalizing bred vectors. While the TCB method cannot remove intrinsic model errors related to inadequate representation of model physics in the RAMS model or the model resolution, this method could optimize the use of the breeding ensemble for TC track forecasts in real-time forecasting systems with limited computational resources.

1. Introduction

Atmospheric processes are inherently multi-scale dynamical systems. Unlike large-scale flows that are generally characterized by atmospheric states on a slow more predictable manifold, small-scale to meso-scale systems are often fast-moving processes and so highly sensitive to initial conditions and random forcings [1–6,46]. Hierarchy of numerical models with increasing complexity has been developed over last several decades, but uncertainties in the current numerical weather prediction models still exist despite numerous improvements in model dynamics, physical representations, observational net-

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http://dx.doi.org/10.1016/j.apm.2016.04.010
S0307-904X(16)30211-6/

work, data assimilation methods, and computational infrastructure due to the limited predictability nature of atmospheric flows [5,7–9,45].

Given the complex nature of multi-scale interactions of atmospheric flows, predicting tropical cyclone (TC) tracks and intensity has been challenging due to inherent uncertainties in both forecasting models and the atmosphere [10–13]. Model uncertainties associated with inadequate understanding and representation of physical processes or approximations in a numerical model often result in large track and intensity forecast errors, especially under circumstances with strong topography or complicated vortex–vortex interaction [14,15,43,47]. At present, the official 3-day track error reported by the US Joint Typhoon Warning Center (JTWC) in the North Western Pacific (WPAC) basin is still about 220 km and the track forecast error could reach 450 km at the 5-day lead time. Likewise, intensity forecast errors have shown little improvement at all forecast lead times for the last 30 years [16,17].

A current approach to reduce uncertainties in TC forecasts is based mostly on ensemble techniques. In general, development of an ensemble forecast system can be carried out in three different directions: (i) use a set of different initial conditions for one specific model in which initial conditions are generated based on a posteriori analysis error distribution (the Monte Carlo ensembles. See, e.g., [4,6,18–22]), (ii) use a single initial condition for different forecast models (a multi-model approach. See, e.g., [15,23–25]); and (iii) combine both different initial conditions and different forecast models (a super-ensemble approach. See, e.g., [26,27]). The breeding ensemble approach for which pairs of perturbed initial conditions are generated from previous forecast cycles and added to a control forecast is a typical example of the ensemble techniques developed in the first direction. This breeding scheme was implemented in the operational Global Forecasting System (GFS) at the National Center for Environmental Prediction (NCEP) in 1993, and later became common for various practical applications and development ([21,22] hereinafter TK93 and TK97, respectively). By continuously employing previous cycles to generate the fastest growing vectors and then normalized these error vectors regularly, this breeding approach could allow for projecting the fastest growing modes onto the so-called bred vectors, which are perturbations generated in each breeding cycle. Likewise, the European Center for medium-term weather forecast (ECMWF) implemented an ensemble forecasting system in early 1992 that could capture also the fastest growing perturbations, albeit the ECMWF technique is based on singular vectors instead of bred vectors [6,46].

While the fastest growing modes should be in principle projected onto bred vectors (at the far limit of the backward Lyapunov vectors), our experiments with TK93's breeding method show that this breeding approach tends to produce an ensemble with TC tracks very close to each other, i.e., the system is still much underdispersive (cf. Fig. 9). One possible reason for such small ensemble spread is likely because the bred vectors collapse into the same dominant direction after several cycles as discussed in studies by Corazza et al. [48], Magnusson et al. [9]. Unlike singular vectors that represent the directions of the fastest growing modes in orthogonal directions within a short range interval (via a tangential linear model), the breeding cycle is to some extent equivalent to a nonlinear finite-amplitude method used to obtain the leading Lyapunov vectors [28,29]. As such, bred vectors could eventually become linearly dependent in the presence of the lower dimension attractor [9,49].

By taking into account the spatial and temporal variations of the scaling factor at each cycle, the performance of the breeding method can be in principle improved, as bred vectors in this construction could capture better the local growing directions and thus allow for larger ensemble spread [22,30,31]. However, fast convective instabilities often saturate very quickly after several breeding cycles, especially within the region where the atmospheric instability is dominant [32,33]. For multi-scale systems like TCs, it is expected that the instability within the storm central region should have different characteristics as compared to the far-field environmental region. Previous studies by Guinn and Schubert [34], Chen and Yau [35], or Black and Willoughby [36] showed that perturbations within the TC inner-core region often develop and propagate rapidly in terms of gravity and vortex Rossby waves due to the strong radial vorticity gradient with time scale of 12–24 h. In contrast, the large-scale environmental perturbations propagate on a much slower manifold, often clustering along the most unstable front regions [5]. Representing the coupling between the faster storm-scale instabilities and slower large-scale environment is a challenging problem in designing an ensemble breeding system for TC forecasts.

In this study, the TK93's breeding approach is extended for the TC track forecast applications. The main objective is to develop a breeding method that could capture the unstable directions of the large-scale steering environment while still allowing for faster storm-scale instabilities to grow such that the multi-scale interaction of TCs with the ambient environment can be represented. Unlike the original breeding approach, TC track forecasts require not only good representation of the steering flow but also the structure and strength of TCs so that TCs can interact with environment properly.

The rest of this study is organized as follows. Section 2 presents a TC breeding method that allows both the storm-scale and large-scale instability modes to grow and interact. Model and experiment descriptions are discussed in Section 3. Section 4 provides analyses for the TC breeding ensemble experiments during the 2009–2011 TC seasons in the WPAC basin. Concluding remarks are given in the final section.

2. TC breeding method

Although the original breeding method proposed by TK93 could capture the fastest growing directions after several spinup cycles, it is happened in reality that TCs have finite lifecycle. Due to large computation associated with high-resolution regional models, TC forecasting models are typically activated only when a depression warning is first issued, because it is difficult to maintain a continuous ensemble of high-resolution breeding cycles daily. As such, TK93's breeding

Please cite this article as: C. Thanh et al., Application of breeding ensemble to tropical cyclone track forecasts using the Regional Atmospheric Modeling System (RAMS) model, Applied Mathematical Modelling (2016), http://dx.doi.org/10.1016/j.apm.2016.04.010