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In 2012, hurricane Sandy, which devastated surrounding areas and caused tremendous economic loss, made an unusual northwestward turn at 00Z October 29 prior to its landfall at 2330Z October 29 near Brigantine, New Jersey (Blake et al., 2013). Since hurricane Sandy, heated debates have arisen within the scientific community regarding whether or not further lead times can be obtained for predicting severe storms. To add to on-going developments regarding hurricane prediction, in this study, I discuss the use of the Coupled Advanced global Modeling and Visualization system (CAMVis; e.g., Shen et al. 2006, 2011) and the parallel ensemble empiric mode decomposition (PEEMD; Shen et al. 2012b) for revealing the role of multiscale processes associated with large-scale tropical waves and an Madden-Julian Oscillation (MJO; Madden and Julian, 1971) in predicting Sandy. In addition, I also outline the use of high-order Lorenz models for illustrating the impact of increased resolution on solution stability.

Since Prof. Lorenz of MIT discovered the sensitive dependence of numerical results on initial conditions 50 years ago (Lorenz, 1963), it has been accepted that a tiny error in initial conditions may quickly contaminate simulations of large-scale flows and that the outlook for extending lead times beyond 5-7 days is not yet optimistic (Anthes, 2011). The term “butterfly effect” was first introduced to describe this type of sensitive dependence. Later, this terminology became a metaphor for indicating that small-scale perturbations can result in enormous impacts on large-scale flows (Pielke, 2008). The former and latter definitions are referred to as a butterfly effect of the first and second kind, respectively (e.g., Shen 2014a); and it has been suggested that the appearance of a butterfly effect of the first kind does not directly lead to a butterfly effect of the second kind (i.e., that small perturbations alter large-scale structure). Such a suggestion is due to the fact that although a butterfly effect of the first kind may appear within a numerical model with a finite degree of nonlinearity (e.g., the original Lorenz model), an improved degree of nonlinearity in high-order Lorenz models (e.g., Shen 2014a; 2015b) can mitigate or suppress the sensitive dependence of simulations on initial conditions.

In spite of the finite predictability of weather prediction models, recent studies have suggested that a large-scale system can provide determinism regarding the prediction of tropical cyclone (TC) genesis, making it possible to extend the lead time of genesis predictions. In past studies, my colleagues and I (Shen et al., 2010a,b; 2012) have examine the relationship between: (i) TC Nargis (2008) and an Equatorial Rossby (ER) wave; (ii) Hurricane Helene (2006) and an intensifying African Easterly Wave (AEW); and (iii) Twin TCs (2002) and a mixed Rossby-gravity wave (MRG) during an active phase of the MJO. We have also investigated the impact of convection on TC genesis. As a result of these investigations, we then proposed a conceptual model for improving our understanding of multiscale processes that are associated with TC genesis. Based on our conceptual model, that includes a triple-scale system with large-scale, mesoscale, and small-scale flows, we suggested that the formation of a TC at the mesoscale depends on the collective and/or competing impacts of downscaling processes by large-scale flows and upscaling processes by small-scale flows (e.g., Shen et al., 2012a, 2013a).
Encouraged by some of our published and unpublished results, we have recently applied the aforementioned tools and the conceptual model in order to understand the role of simulated multiscale processes in determining Sandy’s genesis, movement, and intensification. Our results indicate that:

(1) the CAMVis produced a remarkably detailed 7-day track and intensity forecast for Hurricane Sandy, and multiscale visualizations indicated that extending the lead time of prediction may be possible with the use of improved simulations of Sandy’s interaction with environmental flows (e.g., Figure 1);

(2) Sandy’s genesis was realistically simulated with a lead time of up to six days, and multiscale analysis using the PEEMD revealed the role of tropical waves, a westerly wind belt (WWB), and a Madden-Julian Oscillation (MJO) during Sandy’s initial formation.

To understand whether or not our model simulations are consistent with chaos theory and to examine the fundamental role of nonlinearity (e.g., multiscale interactions) in solution stability, we derived the high-order Lorenz models (5-, 6- and 7-dimensional Lorenz models (5D-, 6D- and 7D-LMs, Shen 2014a,b; 2015a,b; Shen and Yoo 2015)), compared them with the original 3D LM, and obtained the following results:

(3) two additional modes of the 5DLM can provide negative nonlinear feedback for stabilizing solutions (e.g., Figure 2);

(4) the third new mode within the 6DLM introduces an additional heating term that can destabilize solutions;

(5) the findings in (3) and (4) support the view of Lorenz (1972) on the role of small scale processes: If the flap of a butterfly’s wings can be instrumental in generating a tornado, it can equally well be instrumental in preventing a tornado;

(6) the nonlinear feedback loop within the original 3DLM determines the “baseline predictability” and the extension of the nonlinear feedback loop within the 5DLM (or 6DLM), that provides nonlinear negative feedback, leads to better predictability than the “baseline predictability” provided by the 3DLM;

(7) the coupling of a new parameterization with nonlinear terms may change the equilibrium state, and the coupling of a smoothing term (i.e., averaging term) with nonlinear terms may have a similar effect;

(8) further extension of the nonlinear feedback loop within the 7DLM leads to a much larger critical value for the Rayleigh parameter ($rc\sim116.9$) for the onset of chaos, as compared to the $rc$ of 24.74 for the 3DLM and the $rc$ of 42.9 for the 5DLM.

The above findings suggest that an improved degree of nonlinearity within a real-world, high-resolution model may stabilize solutions, leading to improved predictability; and that heating effects associated with excessive precipitation may destabilize solutions, thereby increasing the sensitivity of simulations to small perturbations. Currently, a trajectory separation method for calculation of the Lyapunov exponent is being implemented (Shen, 2014a and references therein) into the global model so we can examine the model’s stability using various model configurations.
Figure 1: 4-D visualizations of Hurricane Sandy consisting of the temporal evolution of a 3-D visualization at 0000 UTC Oct. 23 (a), 1200 UTC Oct. 25 (b), 1200 UTC Oct. 27 (c), and 1200 UTC Oct. 28 (d). During our simulation, Sandy (labeled with a pink “S”) moved northward under the influence of the sub-tropical, middle-, and upper-level trough (located northwest of Sandy) (a), interacted with the trough that was deepening (b), increased its spatial extent (c), and encountered a pair of high-and-low blocking patterns over the North Atlantic which prevented Sandy from further moving east (d). At this time, the middle-latitude, upper-level trough (labeled with a white “T”) intensified. The blocking pattern consisted of a middle-latitude cyclonic system (located northeast of Sandy) and an anti-cyclonic system (located to the north of the cyclonic system). Over the next 24-36 hours (not shown), Sandy interacted with the intensifying upper-level trough that moved eastward from 130 degrees west longitude on Oct. 23, then turned northwestward, and then made landfall in New Jersey. The corresponding animation is available as a google document at http://goo.gl/hMkNd.

Figure 2: Phase space plots for (Y, Z) within the 3DLM and 5DLM with r=25. Here, (Y, Z) represents the time dependent amplitudes of the Fourier models within the models and r is the normalized Rayleigh number, or the so-called heating parameter. The 3DLM produced Lorenz strange attractors (a), while the 5DLM produced stable solutions (b). A mathematical analysis suggested that chaos can be suppressed by the negative nonlinear feedback enabled by high wavenumber modes within the 5DLM. For more details see Shen (2014a).
References
Anthes, R., cited 2011: Turning the tables on chaos: Is the atmosphere more predictable than we assume? NCAR/UCAR AtmosNews. [Available online at https://www2.ucar.edu/atmosnews/opinion/turning-tables-chaos-atmosphere-more-predictable-we-assume-0 ]