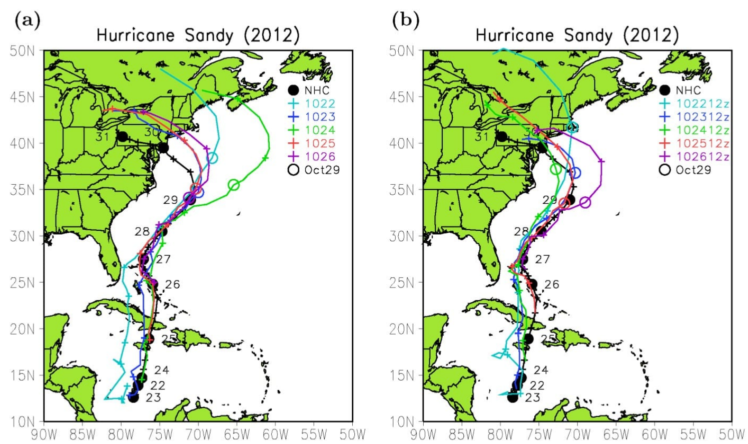

Simulations and Visualizations of Hurricane Sandy (2012) as Revealed by the NASA CAMVis

Earthzine / December 2, 2013 / ESTO Showcase 2013, Original

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Storm Sandy first appeared as a tropical storm in the southern Caribbean Sea on Oct. 22, 2012, moved northeastward, turned northwestward, and made landfall near Brigantine, New Jersey in late October. Sandy devastated surrounding areas, caused an estimated damage of $50 billion, and became the second costliest tropical cyclone (TC) in U.S. history, surpassed only by Hurricane Katrina (2005). To save lives and mitigate economic damage, åÊa central question to be addressed is to what extent the lead time of severe storm prediction such as Sandy can be extended (e.g., Emanuel 2012; Kerr 2012). In this study, we present 10 numerical experiments initialized at 00 and 1200 UTC Oct. 22-26, 2012, with the NASA coupled advanced global modeling and visualization systems (CAMVis). All of the predictions realistically capture Sandy's movement with the northwestward turn prior to its landfall. However, three experiments (initialized at 0000 UTC Oct. 22 and 24 and 1200 UTC Oct. 22) produce larger errors. Among the 10 experiments, the control run initialized at 0000 UTC Oct. 23 produces a remarkable 7-day forecast. To illustrate the impact of environmental flows on the predictability of Sandy, we produce and discuss four-dimensional (4-D) visualizations with the control run. 4-D visualizations clearly demonstrate the following multiscale processes that led to the sinuous track of Sandy: the initial steering impact of an upper-level trough (appearing over the northwestern Caribbean Sea and Gulf of Mexico), the blocking impact of systems to the northeast of Sandy, and the binary interaction with a mid-latitude, upper-level trough that appeared at 130degrees west longitude on Oct. 23, moved to the East Coast and intensified during the period of Oct. 29-30 prior to Sandy's landfall.

Introduction

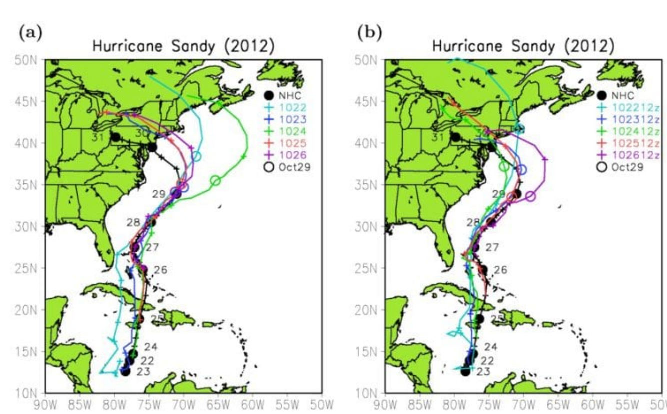
NASA's major hurricane research activities focus on improving our understanding of how tropical storms form, develop, and intensify. Recent studies using high-resolution model simulations and satellite data have shown a potential for improving our understanding of TC formation and thus extending the lead time of TC genesis prediction. Knowledge gained from these studies could ultimately save lives and reduce property damage. In a series of papers with a high-resolution global model, Shen et al. (2010a,b; 2012a) have conducted case studies to examine the impact of large-scale tropical waves on TC activities such as formation, including åÊ(i) TC Nargis (2008) and its association with an equatorial Rossby (ER) wave; (ii) Hurricane Helene (2006) and its association with an intensifying African easterly wave; and (iii) Twin TCs (2002) and its association with a mixed Rossby-gravity wave embedded in organized large-scale convective systems. Multiscale processes and their interactions that could impact the aforementioned TCs' formation and initial evolution are illustrated with advanced scientific 4-D (X-Y-Z-time) visualizations by Shen et al. (2013a). Based on these studies, it has been hypothesized that improved predictability of TC activities (e.g., formation) can be achieved by improving hierarchical scale interactions of a TC and its environmental flows, such as different type of tropical waves. In this study, the impact of large-scale flows on the movement of Hurricane Sandy is illustrated with advanced simulations and visualizations. We first discuss our modeling and visualizations approaches and then present track predictions and visualizations.

Modeling and Visualization Approaches

Simulations are performed with the global mesoscale model (GMM) (Shen et al., 2006a,b) and verified with global reanalysis and NASA satellites. The GMM at the highest resolution of 1/12 degree (~9 kilometers in the equator) was deployed based on the finite-volume general circulation model (e.g., Lin, 2004) and has been used to demonstrate the potential for improving the multiscale interactions of a TC with environmental flows and thus TC activities such as movements (e.g., Atlas et al., 2005; Shen et al., 2006a,b), as well as intensities and genesis (e.g., Shen et al., 2006b; 2010a,b; 2012; 2013a,b). During the past several years, we have coupled the GMM with modern concurrent visualization technology (Ellsworth et al., 2006; Green et al., 2012) into the coupled advanced global mesoscale (multiscale) modeling and visualization (CAMVis) system, which has been used to exploit the enabling role of the high-resolution, 4-D visualizations in illustrating TC's transient dynamics and their interaction with tropical waves (Shen et al., 2011; 2013a).

When a TC's vertical structure varies with height, such as low-level cyclonic circulation and upper-level anticyclonic circulation, visualizations of the TC's circulations at different altitudes can be helpful for illustrating both its evolution and interactions with environmental flows. In order to achieve this, we developed the 3-D streamline package (StreamPack), which is used to generate the streamlines at different heights with different colors. The current version does not really use the information on vertical wind velocity in the vertical dimension. Each pressure level is treated independently: 2-D streamlines are produced within a pressure level, and then the levels are stacked to produce a quasi-3-D image. Opacity is used to control the ‰ÛÏtransparency‰Û of the streamlines at different heights to illustrate both the TC's structure and its relationship with surrounding flows. The goal is to clearly display major features that appear in three major ‰ÛÏlayers,‰Û including low, middle and upper layers. Each of these layers, which are shown mainly in blue, green, and pink, respectively, contains several (e.g., 3-5) contiguous levels. In the StreamPack, the degree of opacity is determined by a parameter called ‰ÛÏalpha,‰Û which is a function of wind speeds. The larger the alpha value, the more opaque streamlines are. In other words, if there exist more streamlines at different levels (layers), they would look less transparent. On the other hand, the evolution of streamline density at a specific level may qualitatively indicate the evolution of average wind speeds, i.e., denser streamlines represent stronger average wind speeds. It has been shown that the 3-D StreamPack is useful for illustrating the multiscale interactions between TC formation and tropical waves (Shen et al., 2013a).

In this study, we present 10 track predictions of Sandy that were initialized at 0000 and 1200 UTC Oct. 22-26. These runs are referred to as ‰ÛÏMM/DD/HH‰Û here. MM, DD and HH represent the month, day, and hour, respectively. For example, 10/23/00z is used to refer the run initialized 00Z Oct. 23. We then discuss visualizations with the control run (10/23/00z) created by the StreamPack.



Simulations and Visualizations of Hurricane Sandy

FIGURE 1: TEN CONSECUTIVE 5-8 DAY TRACK PREDICTIONS OF HURRICANE SANDY. PANELS (A) AND (B) SHOW THE RESULTS INITIALIZED AT 00Z AND 12Z ON DIFFERENT DAYS. COLORED LINES REPRESENT MODEL FORECASTS, WHILE THE BLACK LINE INDICATES THE LOCATIONS OF THE BEST TRACK. THE LIGHT BLUE, BLUE, GREEN, RED AND PURPLE LINES REPRESENT THE FORECASTS STARTING FROM OCT. 22, 23, 24, 25 AND 26, RESPECTIVELY. AN OPEN CIRCLE WITH THE SAME COLOR SCHEME INDICATES THE PREDICTED LOCATION OF SANDY AT 00Z OCT. 29 FROM THE CORRESPONDING RUN. IMAGE CREDIT: B. SHEN

Figure 1 displays the 10 track forecasts of Hurricane Sandy. All of runs capture the northwestward turn prior to Sandy's landfall, and most of runs produce accurate and consistent track forecasts. However, three runs (10/22/00z, 10/22/12z, and 10/24/00z) simulate tracks with larger errors. For example, the 10/22/00z run produces larger errors that include an initial error of 151.6 kilometers and an initial clockwise movement, instead of a counter-clockwise movement, between Oct. 22 and 24. The 10/24/00z run simulates the track with a smooth northwestward turn prior to Sandy's landfall. Among the 10 experiments, the 10/23/00z run produces an accurate track with errors of 127.9, 210.5 and 335.0 kilometers and slightly overestimates intensities with errors of -10.1, -15.5, and -13.3 hPa on days 6-8, respectively. To illustrate the remarkable predictability on the northwestward turn on day 6 and landfall on day 7, a 4-D visualization is created and discussed below.

Figure 2 displays 4-D visualizations of Hurricane Sandy consisting of temporal evolution of 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 the period, Sandy initially moved northward under the influence of the sub-tropical middle- and upper-level trough (to Sandy's northwest) (Figure 2a), interacted with the trough that experienced deepening (Figure 2b), increased its spatial extent (Figure 2c), and encountered a pair of high-and-low blocking pattern over the North Atlantic which prevented Sandy from moving eastward (Figure 2d, Blake et al., 2013). The blocking pattern consists of the middle-latitude cyclonic system (to Sandy's northeast) and anti-cyclonic system (to the north of the cyclonic system). In the next 24-36 hours, Sandy interacted with the intensifying upper-level trough, which moved eastward from 130 degrees west longitude on Oct. 23, turned northwestward, and made landfall in New Jersey, which is discussed below.

Figure 3 shows 4-D visualizations of the second Sandy-trough interactions prior to its landfall 0000 UTC Oct. 28 (a), 0600 UTC Oct. 29 (b), 1200 UTC Oct. 29 (c), and 1800 UTC Oct. 29 (d). The middle-latitude trough appeared near longitude 130 degrees west longitude on Oct. 23 (Figure 2a) and moved eastward and arrived on the East Coast by of Oct. 29-30. During this period, two cyclonic vortices (with positive vortices) associated with Sandy and the trough rotated cyclonically about each other and then merged together. This may be viewed

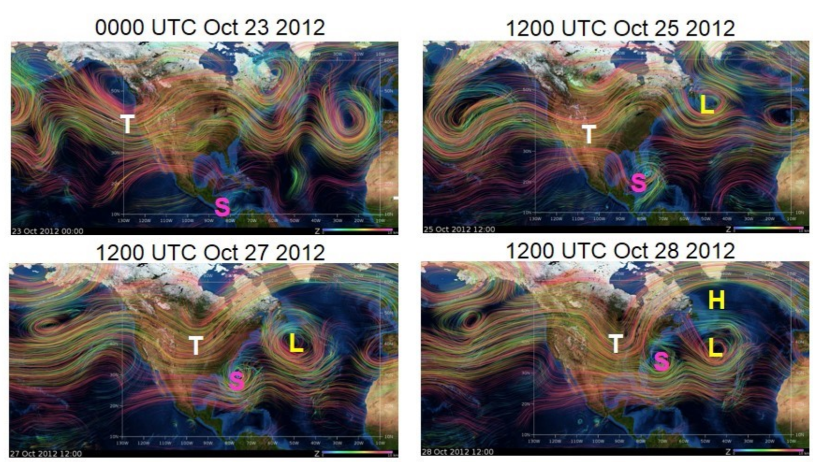


FIGURE 2: 4-D VISUALIZATIONS OF HURRICANE SANDY CONSISTING OF TEMPORAL EVOLUTION OF 3-D VISUALIZATION AT 0000 UTC OCT. 23 (A), 1200 UTC OCT. 25 (B), 1200 UTC OCT. 27 (C), AND 1200 UTC OCT. 28 (D). DURING THE PERIOD, SANDY (LABELED IN A PINK ‰ÛÏS‰Û)MOVED NORTHWARD UNDER THE INFLUENCE OF THE SUB-TROPICAL MIDDLE- AND UPPER-LEVEL TROUGH (TO SANDY'S NORTHWEST) (A), INTERACTED WITH THE TROUGH THAT WAS DEEPENING (B), INCREASED ITS SPATIAL EXTENT (C), AND ENCOUNTERED A PAIR OF HIGH-AND-LOW BLOCKING PATTERN OVER THE NORTH ATLANTIC, WHICH PREVENTED SANDY MOVING EASTWARD FURTHER (D). AT THIS TIME, THE MIDDLE-LATITUDE, UPPER-LEVEL TROUGH (LABELED IN A WHITE ‰ÛÏT‰Û) INTENSIFIED. THE BLOCK PATTERN CONSISTS OF THE MIDDLE-LATITUDE CYCLONIC SYSTEM (TO SANDY'S NORTHEAST) AND ANTI-CYCLONIC

as a Fujiwhara effect (e.g., Sobel 2012), Fujiwhara interaction, or binary interaction.

SYSTEM (TO THE NORTH OF THE CYCLONIC SYSTEM). IN THE NEXT 24-36 HOURS, SANDY INTERACTED WITH THE INTENSIFYING UPPER-LEVEL TROUGH, WHICH MOVED EASTWARD FROM 130 DEGREES WEST LONGITUDE ON OCT. 23, TURNED NORTHWESTWARD, AND THEN MADE LANDFALL IN NEW JERSEY (FIGURE 3). THE CORRESPONDING ANIMATION IS AVAILABLE AS A GOOGLE DOCUMENT AT HTTP://GOO.GL/HMKND. IMAGE CREDIT: DAVID ELLSWORTH.

In summary, simulations and visualizations of Hurricane Sandy show that the lead time of TC predictions can be extended by improving multiscale interactions of Sandy with the large-scale flows that include a sub-tropical, upper-level trough (appearing over the northwestern Caribbean Sea and Gulf of Mexico), blocking systems to the northeast of Sandy, and a mid-latitude, upper-level trough that moved eastward from 130 degrees west longitude. However, due to the complexity of scale interactions, it is desirable to have a tool that can effectively analyze environmental flows at different scales. âÊTo achieve, this, currently, we are developing a multiscale analysis package (MAP) with the core technology of the empirical mode decomposition (Huang et al. 1998), and will integrate the MAP into the CAMVis for hurricane climate study.

Acknowledgment:

We would like to thanks Drs. M. DeMaria, J.-L. F. Li, and S. Cheung for their help that led to the publication of Shen et al. (2013a), Dr. David Ellsworth for his scientific visualizations, and Dr. Y.-L. Lin's for valuable discussions on hurricane dynamics. We are grateful to the following organizations for their support: the NASA Earth Science Technology Office, and the Advanced Information Systems Technology, and Computational Modeling Algorithms and Cyberinfrastructure programs. *Resources supporting this work were provided by the NASA High-End Computing Program through the NASA Advanced Supercomputing Division at Ames Research Center and the NASA Center for Climate Simulation at Goddard Space Flight Center.*

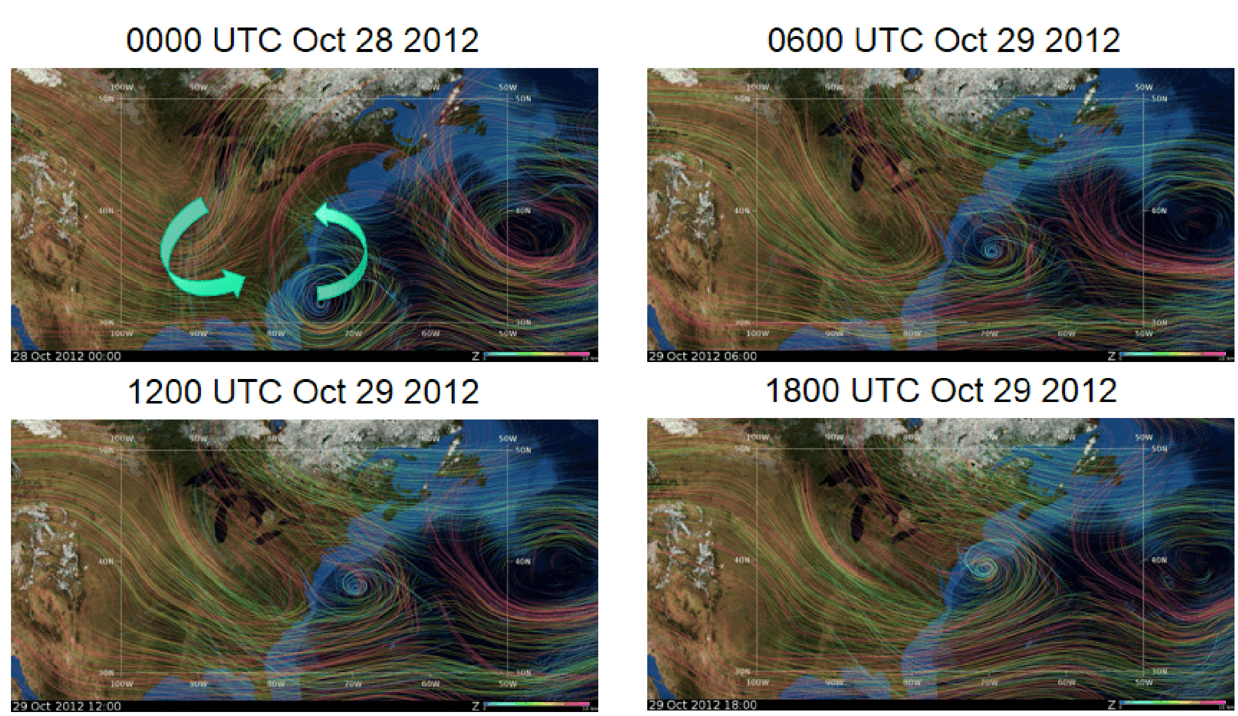


FIGURE 3: 4-D VISUALIZATIONS OF THE SECOND SANDY-TROUGH INTERACTIONS PRIOR TO ITS LANDFALL AT 0000 UTC OCT. 28 (A), 0600 UTC OCT. 29 (B), 1200 UTC OCT. 29 (C), AND 1800 UTC OCT. 29 (D). THE MIDDLE-LATITUDE TROUGH APPEARED NEAR LONGITUDE 130 DEGREES WEST LONGITUDE ON OCT. 23, 2012 (FIGURE 2A) AND MOVED EASTWARD AND ARRIVED ON THE EAST COAST BY OCT. 29-30. DURING THIS TIME PERIOD, TWO CYCLONIC VORTICES (WITH POSITIVE VORTICES), WHICH ARE ASSOCIATED WITH SANDY AND THE TROUGH, ROTATED CYCLONICALLY ABOUT EACH OTHER AND EVENTUALLY MERGED TOGETHER. THE CORRESPONDING ANIMATION IS AVAILABLE AS A GOOGLE DOCUMENT AT HTTP://GOO.GL/KC7JDM. THIS MAY BE VIEWED AS A FUJIWHARA EFFECT (E.G., SOBEL 2012), FUJIWHARA INTERACTION, OR BINARY INTERACTION. IMAGE CREDIT: DAVID ELLSWORTH.

References

Atlas, R., et al., 2005: Hurricane forecasting with the high-resolution NASA finite volume general circulation model. *Geophys. Res. Lett.*, 32, L03801, doi:10.1029/2004GL021513.

Blake, E. S., et al., 2013: Tropical Cyclone Report: Hurricane Sandy, Rep. AL182012. Natl. Hurricane Cent., Miami, Fla.

Kerr R, 2012: One Sandy Forecast a Bigger Winner Than Others. Science 9 Nov. 2012:åÊ **338** pp. 736-737.

Ellsworth D., B. Green, C. Henze, P. Moran, T. Sandstrom, 2006: Concurrent Visualization in a Production Supercomputing Environment. *IEEE Trans*. on Visualization and Computer Graphics,. 12, 5, Sept./Oct. 2006.

Emanuel, K., 2012: Why America Has Fallen Behind the World in Storm Forecasting. The Wall Street Journal. Oct. 28 2012.

Fujiwhara, S., 1921: The natural tendency towards symmetry of motion and its application as a principle in meteorology". *Quart. J. Roy*. *Meteor*. Soc., 47, 287‰ÛÒ293.

Green, B., C. Henze, B.-W. Shen, 2010: Development of a scalable concurrent visualization approach for high temporal- and spatial-resolution models. Eos Trans. AGU, 91(26), West. Pac. Geophys. Meet. Suppl., Abstract A23B-142. AGU 2010 Western Pacific Geophysics Meeting, Taipei, Taiwan, June 22-25, 2010.

Huang, et al., 1998: "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis." *Proc. R. Soc. Lond.* A (1998) 454, 903‰ÛÒ995.

Lin, S.-J. (2004), A vertically Lagrangian finite-volume dynamical core for global models, Mon. Weather Rev., 132, 2293‰ÛÒ2307, doi:10.1175/1520-0493(2004)132<2293:AVLFDC>2.0.CO;2.

Shen, B.-W. et al., 2006a: Hurricane Forecasts with a Global Mesoscale-Resolving Model: Preliminary Results with Hurricane Katrina (2005). Geophys. Res. Lett., 33, L13813.

Shen, B.-W. et al., 2006b: The 0.125 degree Finite Volume General Mesoscale Circulation Model: Preliminary simulations of mesoscale vortices. Geophys. Res. Lett., 33, L05801, doi:10.1029/2005GL024594.

Shen, B.-W. et al., 2010a: Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008). J. Geophys. Res.,115, D14102.

Shen, B.-W. et al., 2010b: African Easterly Waves in 30-day High-resolution Global Simulations: A Case Study during the 2006 NAMMA Period. Geophys. Res. Lett., L18803.

Shen, B.-W., W.-K. Tao, and B. Green, 2011: Coupling Advanced Modeling and Visualization to Improve High-Impact Tropical Weather Prediction (CAMVis), IEEE Computing in Science and Engineering (CiSE), vol. 13, no. 5, pp. 56-67, Sep./Oct. 2011, doi:10.1109/MCSE.2010.141.

Shen, B.-W. et al., 2012: Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: the Role of Mixed Rossby Gravity Wave. J. Geophys. Res., 117, D13114.

Shen, B.-W. et al., 2013a, “Advanced Visualizations of Scale Interactions of Tropical Cyclone Formation and Tropical Waves,” Computing in Science and Engineering, vol. 15, no. 2, pp. 47-59, March-April 2013, doi:10.1109/MCSE.2012.64

Shen, B.W., M. DeMaria, J.-L. F. Li, and S. Cheung, 2013b: Genesis of Hurricane Sandy (2012) Simulated with a Global Mesoscale Model. Geophys. Res. Lett. 40. DOI: 10.1002/grl.50934.

Sobel, A., 2012: How Fujiwhara effect will toss Hurricane Sandy into U.S.?âÊ Climate Central.