Advanced Visualizations of Scale Interactions of Tropical Cyclone Formation and Tropical Waves

A current challenge in tropical cyclone research is to improve our understanding of TC formation and intensification by studying TC interactions with environmental flows. A coupled, advanced global multiscale modeling and concurrent visualization system (CAMVis) shows potential for such studies, especially with the integration of StreamPack—a quasi-3D streamline package.

During the past 10 years, statistics have shown that hurricanes (also known as tropical cyclones, typhoons, tropical storms, cyclonic storms, and tropical depressions) are the deadliest weather event in the US (see Figure 1). Consequently, there's an urgent need to improve both short- and long-term hurricane forecasts. At the same time, studies in tropical cyclone (TC) interannual variability and the impact of climate change (such as global warming) on TCs have received increasing attention[1]—in large part because 2004 and 2005 were the most active hurricane seasons in the Atlantic, yet 2006 wasn't as active as predicted. However, while TC track forecasts have been steadily improving over the past several decades, intensity and genesis forecasts have lagged behind (see Figure 2).

To help with hurricane forecasting, we developed the Coupled NASA Advanced Global Multiscale Modeling and Concurrent Visualization System (CAMVis), which improves our understanding of TC formation and intensification by revealing TC interactions with environmental flows. Here, we discuss some of the challenges that exist in this line of research, what we've been able to accomplish thus far with CAMVis, and the improvements made by integrating 3D StreamPack (a quasi-3D streamline package that we developed to generate streamlines at different heights).

Primary Challenges and Background Information

One of the major challenges in TC-genesis prediction is the accurate simulation of complex interactions across a wide range of scales, from the large-scale environment (deterministic) to mesoscale flows to convective-scale motions (stochastic). Therefore, improving intensity prediction relies on the accurate representation of a TC's structure and its interactions with both large-scale environmental processes and small-scale moist processes (such as convection and

1521-9615/13/$31.00 © 2013 IEEE
Copublished by the IEEE CS and the AIP

Bo-Wen Shen
University of Maryland, College Park, and NASA Goddard Space Flight Center
Bron Nelson
NASA Ames Research Center
Wei-Kuo Tao
NASA Goddard Space Flight Center
Yuh-Lang Lin
North Carolina A&T State University

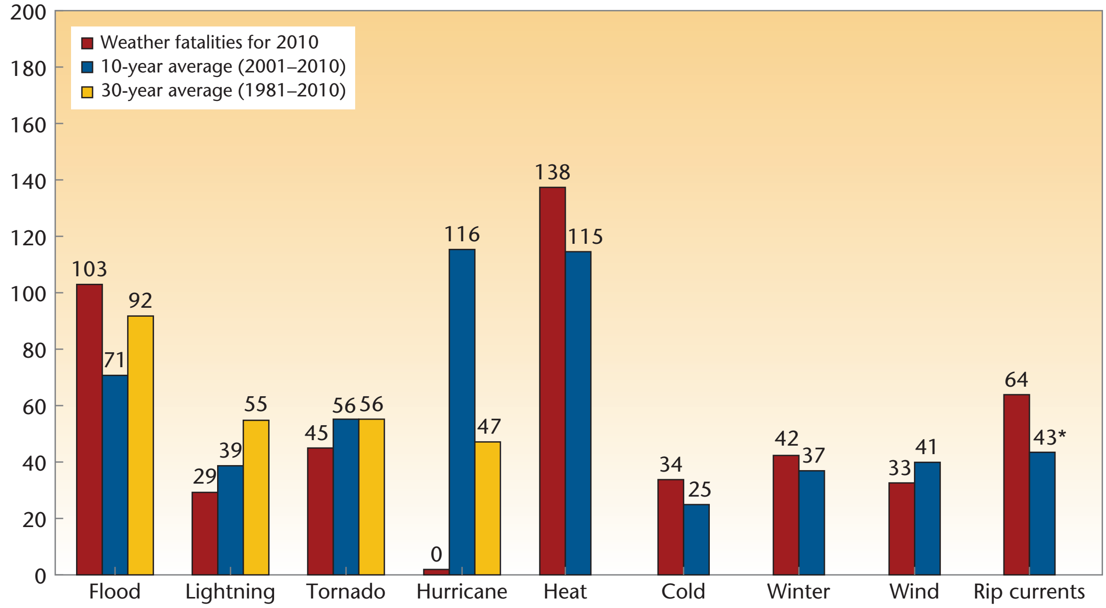

Figure 1. Statistics of fatalities caused by extreme weather events during the past 10 years (blue) and 30 years (yellow). The 10-year statistics show that the hurricane is the deadliest extreme weather event. (Data source: www.nws.noaa.gov/os/hazstats.shtml.)

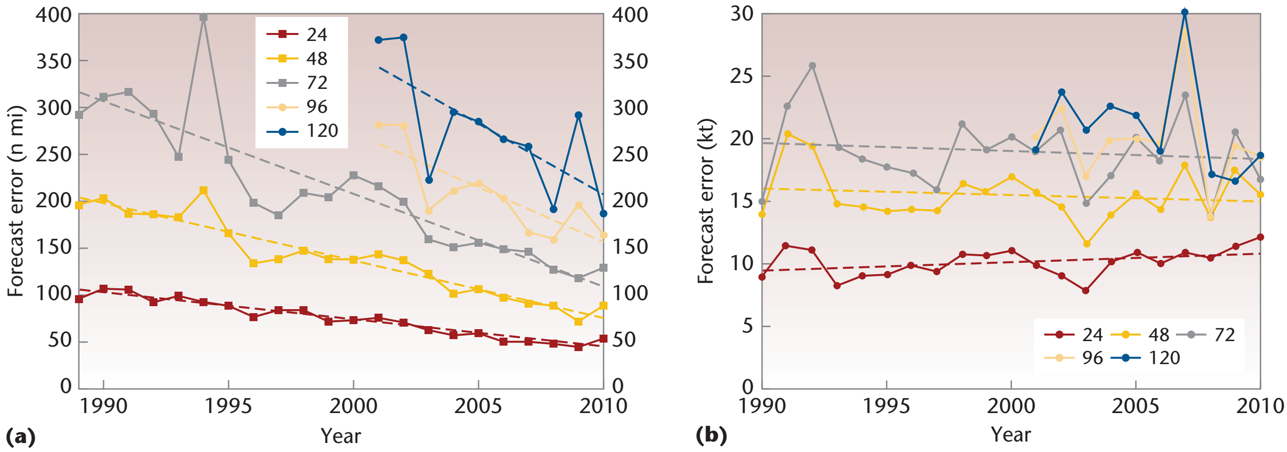

Figure 2. The progress of hurricane forecasts by the National Hurricane Center. The horizontal axis indicates the years from 1989 to 2010; the vertical axis represents forecast errors. Lines with different colors show different forecast intervals, from 24 hours (red) to 120 hours (blue). During the past 20 years, track forecasts have been steadily improving (left panel), but intensity forecasts have lagged behind (right panel). (Data source: www.nhc.noaa.gov/verification/verify5.shtml.)

surface fluxes exchanges). Figure 3 shows the major features of a TC, which include

- an eye,
- an eyewall,
- an elevated warm-core,
- low-level inflow with counterclockwise circulation, and
- upper-level outflow with clockwise circulation.

The TC *eye* refers to a region in the TC's center where winds are light and skies are clear to partly cloudy; the *eyewall* refers to a wall of dense thunderstorms that surrounds the hurricane's eye. An elevated warm-core usually appears at upper levels (about 200–300 hectopascals, or hPa) where the cyclone's temperature is warmer at its center than at its periphery.

General circulation models (GCMs) have been used to study TC genesis statistics and interannual variability, but their insufficient grid spacing and unsophisticated physics parameterizations are known limiting factors in simulating a TC's structure and its interaction with environmental flows.

Recent advances in high-resolution global modeling and supercomputing have made it possible to mitigate some of these issues.

When NASA's Columbia supercomputer became operational in late 2004, its computing power enabled the deployment of the global mesoscale model (GMM) at high resolution (for example, 0.25, 0.125, and 0.08 degrees), which resulted in remarkable hurricane forecasts during the very active 2004 and 2005 Atlantic hurricane seasons.[2,3] The GMM's ability to forecast hurricane intensity was first demonstrated with Hurricane Katrina (2005), which was the sixth most intense hurricane in the Atlantic, and which devastated New Orleans and the surrounding Gulf Coast region. Although both 0.25- and 0.125-degree runs showed remarkable track forecasts, the higher-resolution (that is, 0.125-degree) runs produced more realistic intensity forecasts. This suggested that the better intensity forecasts are due to finer resolution, which became sufficient to resolve the near-eye wind distribution. Further analysis of the 96-hour, 0.125-degree simulations for Katrina showed realistic vertical structures of the storm, including maximum winds near the top of the boundary layer, a narrow eyewall, and an elevated warm core. Similarly, while discussing the impact of petascale computing on NASA's missions, Rupak Biswas and his colleagues documented the performance of the 0.08-degree model for Hurricane Rita (2005) and showed improved track and intensity forecasts with increasing resolution (for example, from 0.25 to 0.125 to 0.08 degrees).[4]

Since 2007, in addition to the simulations of intense hurricane structures, we've investigated the interaction of TC formation and tropical waves to understand the model's performance in predicting the evolution of TC intensity. Tropical wave theory was first developed by Taroh Matsuno[5] using *the linearized equations of motion* valid for the tropical regions. He obtained five different wave modes that included eastward- and westward-propagating inertiogravity waves, eastward-propagating Kelvin waves, westward-propagating Rossby waves, and mixed Rossby gravity (MRG) waves. MRG is a special wave mode that behaves like a Rossby wave for large zonal wave numbers (for example, at synoptic scales) and an inertio-gravity wave for small zonal wave numbers.

Since Matsuno's 1966 findings, many researchers have studied the role of these idealized waves in daily weather and their impact on TC activities. For example, William Frank and Paul Roundy[6] conducted a comprehensive observationally based

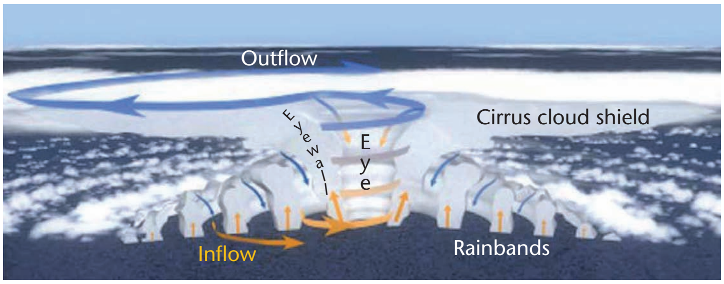

Figure 3. Major characteristics of a hurricane. These characteristics include: the eye—a region in the center of a tropical cyclone (TC) where winds are light and skies are clear to partly cloudy; the eyewall—a wall of dense thunderstorms that surrounds the TC's eye; an elevated warm-core (not shown), in which the cyclone's temperature is warmer at its center than at its periphery; low-level counterclockwise circulation; and upper-level clockwise circulation. (Courtesy of the COMET program at the National Center for Atmospheric Research.)

study to search for the predictive relationship between tropical waves and TC formation. They found a strong relationship between TC formation and enhanced activities in equatorial Rossby waves, tropical depression (TD)-type disturbances (or easterly waves), MRG waves, or Madden-Julian Oscillation (MJO), suggesting it might be possible to extend the lead time of TC genesis prediction with numerical models. (Neither easterly waves nor MJOs belong to normal mode solutions of Matsuno's equations. Easterly waves can be viewed as off-equatorial westward-propagating Rossby gyres.[7] Later, we'll discuss the distinction between an equatorial Rossby wave and an MRG wave and their impact on TC formation.)

Although many have suggested that tropical waves are a precursor to TC genesis, it has only recently become feasible to simulate the complicated multiscale interactions of TC formation and tropical waves using advanced global modeling and supercomputing technologies. Here, the term *multiscale interaction* is loosely defined as the nonlinear processes that involve flows with different scales, including wavelength reduction of large-scale waves, TC genesis associated with the appearance of a mesoscale vortex, and/or interactions of waves and a TC with resolved or parameterized convective-scale processes.

Since 2007, we've examined the association of TC formation with three types of tropical waves (see Figure 4) in three case studies.[8–11] In our first case study,[8] we showed that accurate representation of multiscale flows can contribute to the predictability of TC Nargis formation, including northward movement of a westerly wind belt, enhanced monsoonal circulation, formation of a pre-TC mesoscale vortex, and convective-scale precipitation associated with the Nargis during

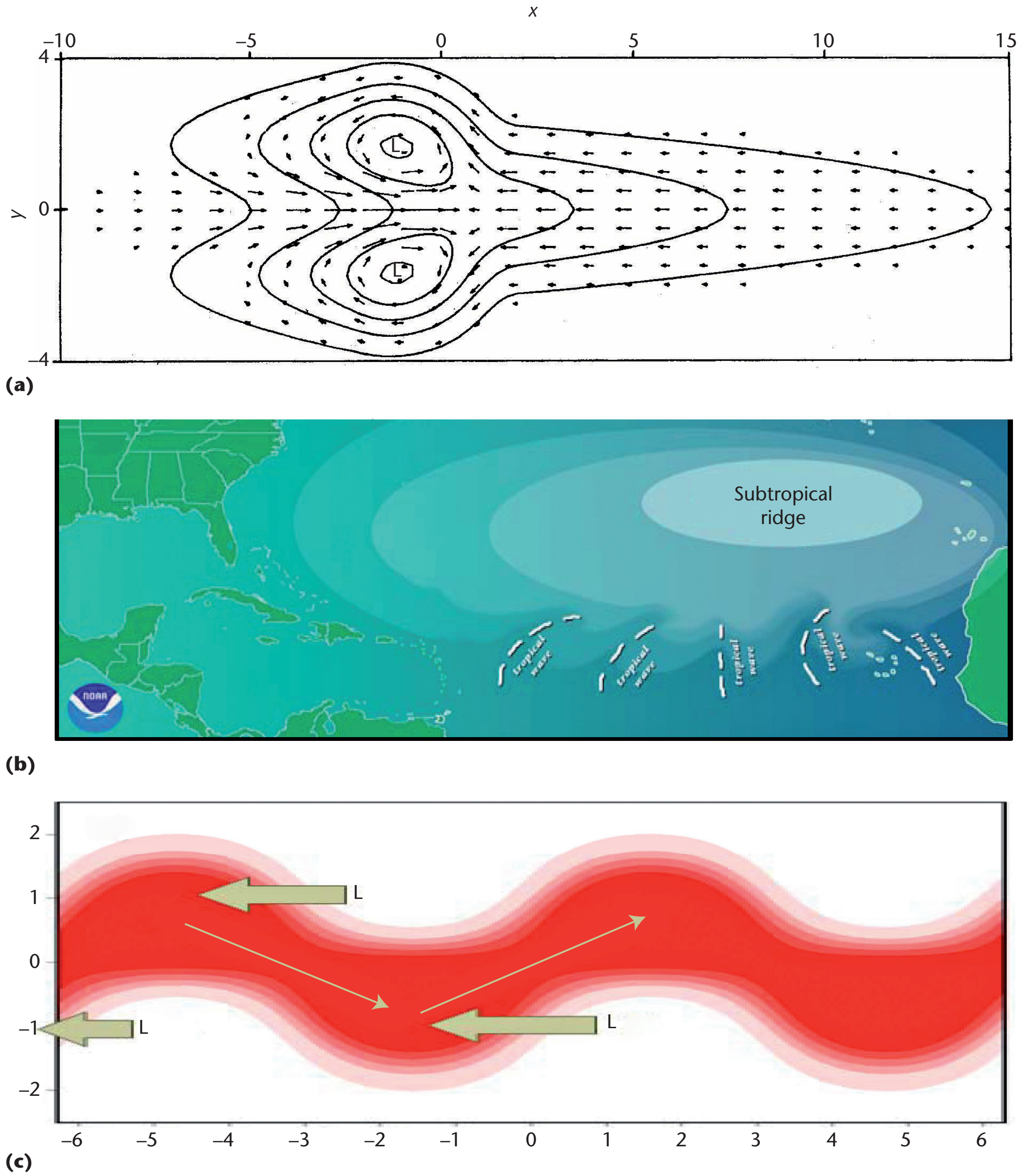

Figure 4. A schematic view of three different types of tropical waves. (a) An equatorial Rossby wave appears as a pair of vortex circulations and low-pressure centers (L)—in the northern hemisphere (NH) and southern hemisphere (SH), respectively—that are symmetric with respect to the equator. (b) African easterly waves (AEWs) are identified by the inverted trough in white dashed lines and have their origins over north Africa (courtesy of Chris Landsea; see www.aoml.noaa.gov/hrd/tcfaq/A4.html). (c) A mixed Rossby gravity (MRG) wave appears asymmetric with respect to the equator, as shown by the zonal winds (red) and low pressures (L). As in other work,[11] the thin arrow lines indicate the direction of total winds.

its intensification stage. We also showed that the pre-TC vortex was indeed associated with the northern vortex of an equatorial Rossby wave. However, because of the complexities in scale interactions, insightful visualizations have become crucial for both improving the understanding of these transient processes and illustrating them in a simple way, which could in turn provide an efficient tool to systematically verify (or monitor) a model's performance. To achieve this goal, we successfully deployed a coupled, advanced global multiscale-modeling and concurrent visualization system (CAMVis) on NASA supercomputers.[9] Recently, to further CAMVis' capabilities, we developed StreamPack and integrated it into the CAMVis system.

The NASA CAMVis and Recent Developments

To improve high-impact tropical weather prediction, the CAMVis system[9] has been successfully deployed on NASA's Columbia and Pleiades supercomputers, showing promise in pursuing related TC studies. CAMVis consists of a state-of-the-art GMM[3,8,10] and global multiscale modeling framework (MMF)[12] running on Pleiades (as of November 2012, ranked 14th on the TOP500 list), and employing a concurrent visualization (CV) framework on the 128-screen hyperwall-2.[13] The hyperwall-2 has modern graphics cards, InfiniBand interconnects, 1,024 cores, and 475 terabytes of fast disk, and thus is capable of rendering one-quarter-billion pixel graphics. Recent developments and improvements to CAMVis include

- a revised parallel implementation to improve the MMF's performance and parallel scalability;
- deployment of the 1/8-degree GMM on the Pleiades supercomputer;
- an improved parallel "*M*-on-*N*" data transfer model in the CV system version 2.0, which enables parallel data transfer between *M* computing nodes on Pleiades and *N* visualization nodes on the hyperwall-2;
- development of data modules to fuse NASA satellite data—such as QuikSCAT sea winds and Tropical Rainfall Measuring Mission (TRMM) precipitation—for intercomparisons with model simulations at comparable resolutions;
- development of the CV to Web (CV2Web) interface, which enables real-time access to CV products via Web browsers; and
- development of StreamPack to provide insightful understanding of the hurricane's multiscale interactions and transient dynamics.

We've discussed the first four items elsewhere,[9,14] and address the last two items in the following sections.

A Web Interface: Concurrent Visualization to Web (CV2Web)

To maximize the results from a single simulation run, multiple products are usually generated, representing various fields and regions of interest as well as numerous feature-extraction and visualization techniques. When time-stamped outputs arrive from the computing nodes, each visualization node sequentially computes all of the requested visualizations, producing one image per visualization request. As part of the CV pipeline, the resulting animations are streamed, as they're being generated, to remote displays at the investigators' facilities. Although these features provide unprecedented opportunities for researchers to conduct research activities, the dependence on supercomputer-scale visualization facilities seems to be an issue for many end users.

To support more end users (such as managers), CV2Web was recently implemented to provide a simple means for accessing real-time CAMVis visualization results. This new capability is built on a hyperwall CV pipeline, enabling real-time Web access to CV products. The CV2Web interface leverages the InfiniBand fabric between Pleiades and hyperwall-2 to let users with instrumented codes see multiple visualizations of their simulation in progress using a Web browser from any location. The current version supports real-time image updates for each visualization.

Quasi-3D Streamline Package (StreamPack)

To seamlessly visualize all different fields and their predictive relationship among different scale flows using CAMVis simulations, we developed and integrated different visualization packages. As we mentioned earlier, it's important to improve the representation of a TC's structure and its interaction with environmental flows. Because a TC's structure displays altitude dependence, such as low-level cyclonic circulation (for example, counterclockwise circulation in the NH) and upper-level anti-cyclonic circulation, visualizations of the TC's circulations at different heights can be helpful for illustrating both its evolution and interactions with environmental flows. To achieve this, we developed the StreamPack, which is used to generate the streamlines at different heights in different colors. However, the current version doesn't really use the information on vertical wind velocity in the Z dimension (altitude), partly because the atmosphere is basically hydrostatic, with a horizontal scale on the order of tens or hundreds of kilometers, but a vertical extent up to 10 to 40 km. Consequently, the streamlines produced in the visualizations aren't true 3D lines. Rather, each pressure level is treated independently: 2D streamlines are produced within a pressure level, and then the levels are stacked to produce a quasi-3D image. To facilitate the discussions, we conceptually divide the levels into three layers—lower, middle, and upper layers. Each of these layers, which are shown mainly in blue, green, and pink, respectively, contain several (three to five) contiguous levels.

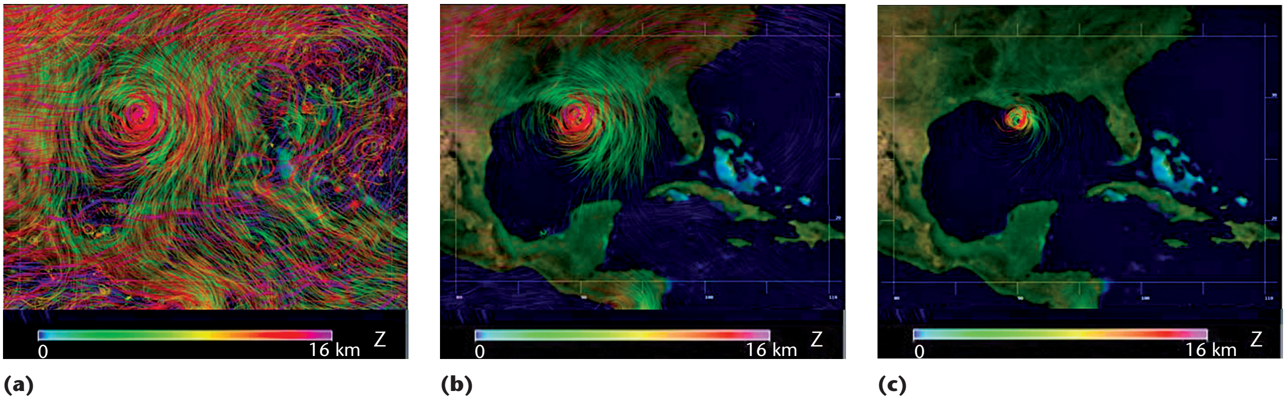

Figure 5. Impact of opacity on the 3D streamline representation of a TC and its surrounding flows: (a) high opacity, (b) medium opacity, and (c) low opacity. Lower-level winds are in blue, mid-level winds are in green and yellow, and upper-level winds are in red and pink.

We use opacity to control streamline transparency 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 all three layers and/or a specific layer. In the StreamPack, the degree of opacity is determined by the *alpha* parameter, which is a function of wind speeds. The larger the alpha value, the more opaque the streamlines. In other words, if the streamlines exist at multiple, different levels (layers), they will look less transparent.

Figure 5 shows the impact of opacity on quasi-3D streamlines generated from exactly the same model data. Each panel uses a different alpha (opacity) value. The symbol Z in the color bar indicates altitudes (heights). As mentioned, red lines show high-altitude (upper-level) winds, green lines show middle-altitude (middle-level) winds, and blue lines show low-altitude (lower-level) winds. If the alpha is set too high (Figure 5a), we see too much unimportant wind information and thus streamlines at different layers appear to overlap. If the alpha is set too low (Figure 5c), we see the main feature, but not enough detail about surrounding (environmental) winds. In the visualizations discussed in the next section, we chose the alpha value in Figure 5b.

StreamPack displays streamlines at a specific level only when their speeds are faster (than a wind speed threshold), so they're assigned larger alpha values. Alternatively, we could say that when wind speeds (w) exceed the critical wind speed (w_c), larger alpha values are assigned to the corresponding streamlines, so they become more visible. Therefore, given the same dataset (for one specific frame), a larger alpha means a smaller w_c. Thus, given the same alpha (such as w_c) in a time series of data, the appearance (or disappearance) of streamlines in a moving frame (for example, following the TC) represents a change of wind speeds from $w < w_c$ ($w > w_c$) to $w > w_c$ ($w < w_c$), suggesting an increase (or decrease) of wind speeds. In other words, the evolution of streamline density might qualitatively indicate the evolution of average wind speeds—for example, the denser the streamlines, the stronger the average wind speeds.

Visualizations of Tropical Waves and Tropical Cyclone Formation

Improving the understanding of hurricane formation is one of the most challenging hurricane research activities. During the past several years, the performance of GMM in simulating TC formation has been verified against global analyses and NASA satellite data such as QuikSCAT ocean surface winds and TRMM precipitations. Some of the selected TC cases include the severe cyclonic storm Nargis (2008),[8] Hurricane Helene (2006),[10] and twin TCs in May 2002.[11] The formation mechanisms of these TCs are closely related with an equatorial Rossby wave, an African Easterly Wave (AEW), and a mixed Rossby gravity wave, respectively. Here, we demonstrate the capabilities of StreamPack and CAMVis in examining the scale interactions of TC formation and tropical waves (except for the Nargis, which was previously discussed elsewhere[8]).

Visualizations of Scale Interactions for Katrina

We begin with the visualizations of scale interactions between Katrina and an approaching upper-level jet.

Enabled by NASA supercomputing technologies, we first deployed the global mesoscale model (GMM) at a resolution of 1/8 degree on a

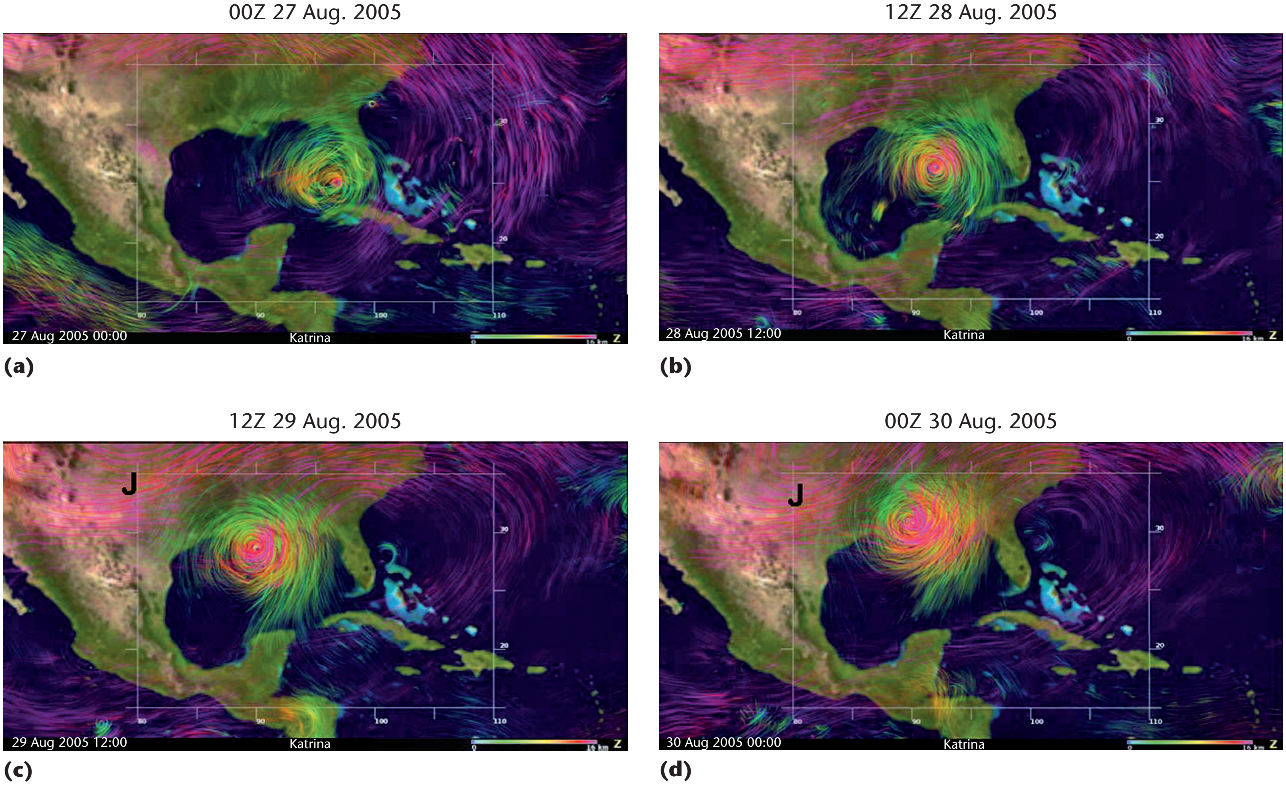

Figure 6. Streamline visualization of multiscale interaction between the outflows of Hurricane Katrina and an approaching upper-level jet stream from a five-day, 1/8-degree run, which is associated with the intensification of Katrina before landfall. Lower-level streamlines are in blue, upper-level streamlines are in pink and red. Katrina's intensification is indicated in (c) and (d) by the appearance of dense, red streamlines at the upper levels, which are associated with strong vertical motion. "J" indicates the jet stream. This figure is generated by the Streampack, and the corresponding animations are available at http://goo.gl/FtMHz.

Columbia supercomputer and obtained a realistic simulation of Katrina's movement, intensity, and near-eye wind distribution from a five-day run.[3] In previous work,[3] we showed that the 1/8-degree model captured intensity evolution during the second phase of intensification—for example, between 00:00 Coordinated Universal Time (UTC) 28 August 2005 and 12:00 UTC 29 August 2005. Recently, the model has been ported and tested successfully on the Pleiades supercomputer, where it produced similar results to the version on Columbia.

With the newly developed streamline package, it becomes feasible to examine the role of the interaction between Katrina's outflow and its environmental flows in the storm's intensification. Figure 6 shows the evolution of a simulated Katrina from a five-day run. All frames are derived from a high-resolution visualization (http://goo.gl/FtMHz). As time progresses, stronger upper-level anti-cyclonic flows (in red) developed in association with the initial intensification of Katrina (see Figure 6b). Later, Katrina experienced rapid intensification. The animation helps lead to a hypothesis that the (horizontal) phasing of an approaching jet stream and Katrina's southwesterly outflow (to the southeast of the jet) further strengthened the upper-level anticyclonic flow over Katrina, as indicated by the appearance of denser upper-level streamlines in expanding areas in pink; it thus enhanced Katrina's development along with strong, deep convections (see also Figures 6c and 6d).

A systematic study for potentially verifying this hypothesis is planned for future work, but here we provide a preliminary reanalysis of 200 hPa winds from the National Centers for Environmental Prediction (NCEP) analysis (as "observations") and the model run. As NCEP analysis data are available only at a time interval of six hours, it's challenging to apply these data in a way that can take advantage of StreamPack's high temporal-resolution capabilities. We therefore used a different graphics package, which is the Grid Analysis and Display System (GrADS; www.iges.org/grads) to generate vector and wind speeds' (shaded) plots to examine the evolution of velocities at 200 hPa (see Figure 7), which we used to

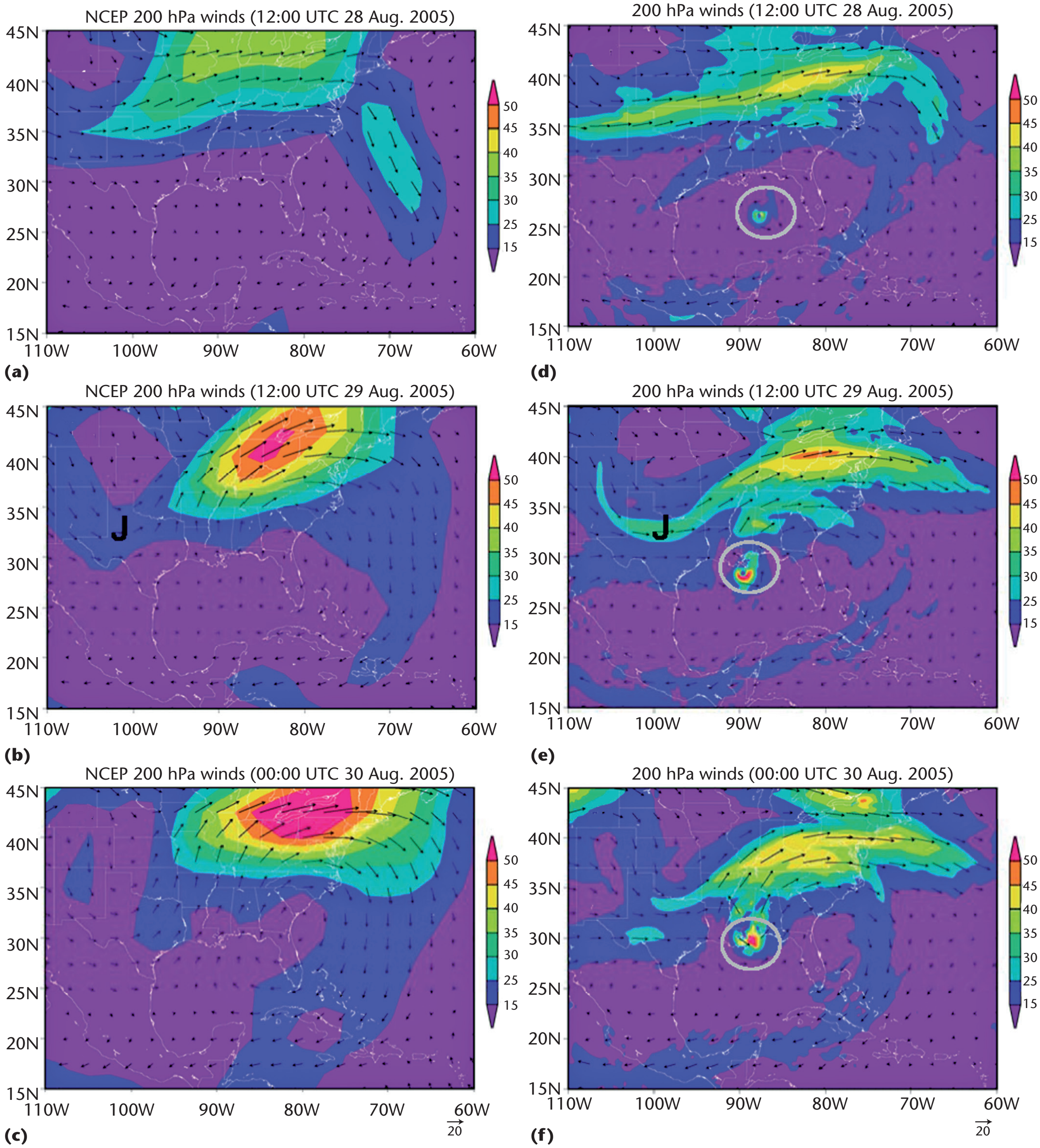

Figure 7. Evolution of the upper-level jet steam and the upper-level circulation of Katrina at 200 hectopascals (hPa) from the National Centers for Environmental Prediction (NCEP) reanalysis (a–c) and the model run (d–f). The jet stream's general location and the simulated Katrina's location are denoted by "J" and a grey cycle, respectively.

verify our methodology in generating the visualization in Figure 6.

As we can see, the jet stream and Katrina moved closer from 12:00 UTC 28 August to 12:00 UTC 29 August, and there was a possible horizontal phasing, since both of the jet streaks and upper-level flow of Katrina were enhanced. Shaded blue areas in Figure 7 indicate the existence of jet streaks that are localized regions of very fast winds embedded within the jet stream. This kind of "mutual" and "cooperative" interaction that could potentially lead to the intensification of Katrina before its landfall is being investigated in a separate study. During the period of 12:00 UTC

29 August to 00:00 UTC 30 August, the simulated Katrina continued to intensify, which is different from the observed Katrina. The false intensification might have occurred because

- the simulated Katrina in the 5-day run moved slower and stayed over the ocean for a longer time period, and thus it could extract more energy from the ocean; or
- the simulated jet streaks were about 5 degrees south of what was observed (see Figures 7c and 7f), and might have falsified the interaction with simulated Katrina outflow, leading to intensification.

Although the NCEP analysis data revealed jet streaks with stronger intensity (about 5–10 m/s larger) than the simulated ones, its representation of Katrina is weaker than that of both the best track and the model simulation. Note that Figure 7 displays vector wind fields at a specific level, while Figure 6 shows streamlines in different layers that contain multiple levels. The quasi-3D streamlines generated by the StreamPack seem to be highly effective in representing the scale interaction and linking it to Katrina's intensification. However, more rigorous verification is still needed and is a subject for future study.

Visualizations of Helene's (2006) Formation and an Intensifying AEW

The second visualization examines the predictive relationship between an intensifying AEW and the formation of Hurricane Helene (2006).[10] Previous studies have shown that nearly 85 percent of intense hurricanes over the eastern north Atlantic[15] have their origins as AEWs, and the initiation of an AEW was found to be related to the release of instability associated with an African easterly jet (AEJ), among other mechanisms proposed in the past.

Therefore, to extend the lead time for predicting hurricanes that originate near the Cape Verde Islands, it was important to accurately simulate the multiscale interactions between hurricanes, AEWs, and the AEJ, as well as the impact of surface processes. During the NASA African Monsoon Multidisciplinary Analyses (NAMMA) period between late August and late September 2006, six AEWs appeared over Africa, propagated westward, and then passed by the Cape Verde Islands. In early September, an observed AEW developed into a Cape Verde storm—Hurricane Helene. With the CAMVis GMM,[10] we conducted extended-range (30-day), high-resolution global numerical experiments to simulate the initiation and propagation of these six consecutive AEWs and their association with hurricane formation. Our work showed that the statistical characteristics of individual AEWs are realistically simulated, with larger errors in the fifth and sixth AEWs. We also obtained remarkable simulations of a mean AEJ. It therefore might be possible to extend the lead time for predicting hurricane formation as the fourth AEW is realistically simulated (see Figure 4 in our previous work[10]); we briefly illustrate this in Figure 8 with a 3D streamline visualization. This experiment, along with other parallel experiments,[10] suggested the potential to extend the lead time (up to 20 days in this case) for predicting hurricane formation.

Visualizations of Twin TCs and an MRG Wave

Previous studies suggest that a pair of twin TCs, symmetric with respect to the equator, can occur when associated with a large-scale MJO. On 1 May 2002, MJO-organized convection appeared over the Indian Ocean and moved eastward. Five days later, two TCs—Kesiny and 01A—formed successively and then turned into a twin TC. In a recent study,[11] we hypothesized that these twin TCs formed as a result of the scale interactions of three gyres associated with an MRG wave during an active MJO phase. Because of its asymmetric features, an MRG wave can be a precursor to the successive formation of TCs at different longitudes with time lags in different hemispheres—one in the northern hemisphere (NH) and the other in the southern hemisphere (SH). A pair of TCs might move at different phase speeds and eventually turn into twins symmetric with respect to the equator, appearing as a transition from an MRG wave to an equatorial Rossby wave. However, from a modeling perspective, predicting these TCs is extremely challenging, because a formation time lag of three to five days would require high-level performance in extended-range simulations (beyond five days).

High-resolution simulations suggested that our model can reproduce the MRG wave's evolution and thus predict the formation of TCs Kesiny and 01A about two to five days in advance, as well as their subsequent intensity evolution and movement over an eight- to 10-day period.

Figure 9 shows the formation of these twin TCs from a 10-day simulation initialized at 00:00 UTC 1 May 2002. In each panel, the NH and SH are on the left and right sides of the panel, respectively; E and W indicate easterly and westerly winds, respectively. Figure 9a shows the

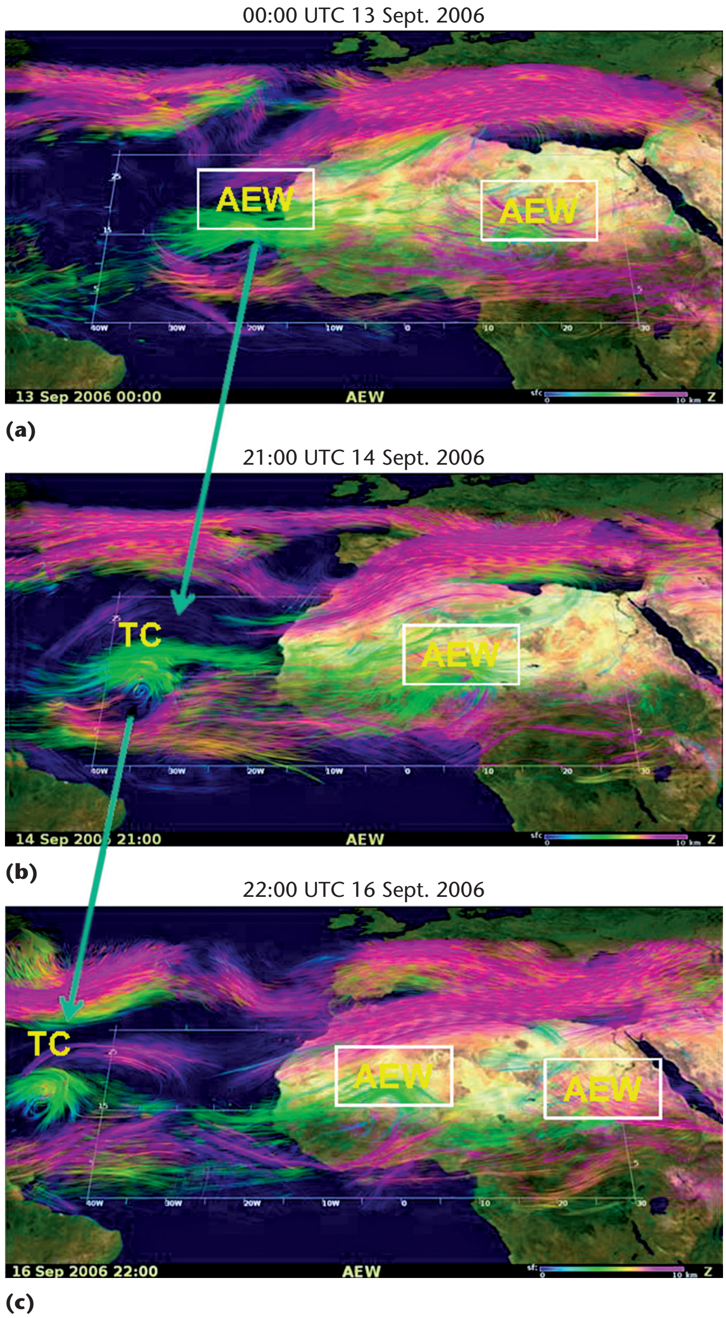

Figure 8. Formation of Hurricane Helene (2006) and its association with the intensification of an AEW in a 30-day run initialized at 00:00 UTC 22 August 2006. Upper-level winds are in pink, middle-level winds in green, and lower-level winds in blue. (a) Initial formation of a closed circulation associated with the fourth AEW that moves over the ocean, validated at 00:00 UTC 13 September (day 22); (b) initial formation of Helene associated with enhanced low-level inflow with counterclockwise circulation (indicated by the appearance of lower-level streamlines in blue), validated at 21:00 UTC 14 September; (c) further intensification of Helene with an enhanced outflow with clockwise circulation (indicated in pink), validated at 22:00 UTC 16 September. An animation is available at http://goo.gl/arWSZ.

formation of TC Kesiny, the southern part of the twin TCs. As time proceeds, the interaction between the westerly and easterly winds (Figure 9b) and the intensified MRG wave (Figure 9c) might have led to the formation of TC 01A, the northern part of the twin TCs (Figure 9d). The animation (http://goo.gl/qXH2p) clearly shows that the successive formation of TCs Kesiny and 01A is associated with the intensification (appearance) of an MRG wave along the equator (for example, during the period of 5–7 May), which can be identified in Figure 9c by rotating this panel 90 degrees clockwise and comparing the embedded white box with Figure 4c.

As we can see, because of its intensification after the twin TC formed and started moving off the equator, the MRG wave becomes more visible in the 3D visualization (Figure 9c). The white arrow in each of the zoomed-in panels (the middle panels of Figure 9) is referred to as the *spinning axis*, and roughly indicates the location of vortex centers at different heights. Through the high temporal-resolution visualization, we can see that the spinning axis of a mature TC points vertically (in the Z direction), while the direction of the spinning axis changes with time during the formation stage. The latter suggests that vortex centers at different heights aren't coherent, which in turn suggests that it's challenging to improve the initialization of a weak vortex because of the absence of vertical coherence.

A View of TC Genesis

In this study, we showed the potential of StreamPack with high temporal-resolution visualizations capabilities for illustrating the transient dynamics of TC formation. Based on this study and earlier studies,[8–11] we propose the following views regarding TC genesis on a triple-scale system (that is, large, medium, and small scales).

First, we propose that both large-scale (tropical wave) systems and small-scale (precipitation) systems are important for the intensification and formation of a TC (or vortex) at the mesoscale. Because of the asymmetry in spatial and temporal scales and the strengths among these systems, it's important to understand the relative importance of large-scale and small-scale forcing at different stages of a TC's lifecycle. In this way, we can view the large and small scales as the external and internal processes, respectively, following Raymond Zehr's conceptual model of TC genesis.[16]

Second, large-scale tropical waves such as an AEW or MRG wave could help determine the timing and location of TC genesis. Namely, an

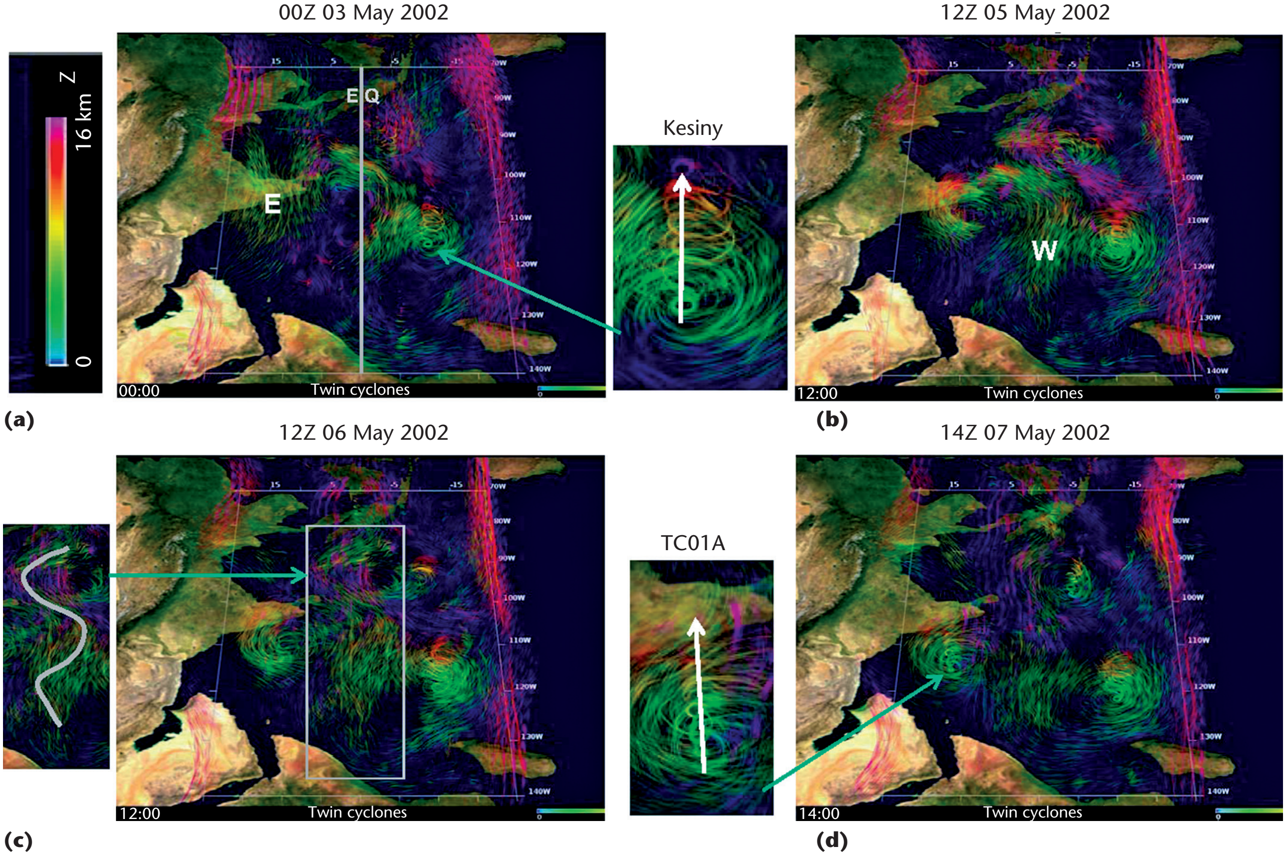

Figure 9. Visualization of the formation of the twin TCs in May 2002. In each panel, the northern hemisphere (NH) and northern hemisphere (SH) are on the left and right sides of the panel, respectively; E and W indicate easterly and westerly winds. (a) The formation of TC Kesiny in the SH. (b–d) The formation of TC 01A, the part of the twin TCs in the NH. The white arrow (the spinning axis) in each of the zoomed-in panels (middle) indicates the location of the vortex centers at different heights. The equator is labeled EQ and indicated by a white line in panel (a). The appearance of the intensified mixed Rossby gravity wave is shown in the white box in (c), which includes a side panel with a sketched wave pattern (bottom left). An animation is available at http://goo.gl/qXH2p.

accurate representation of the evolution of the large-scale tropical waves might help narrow down uncertainties in the area and period for TC formation.

Third, accurate simulations of small-scale processes remain challenging, but we can simulate their aggregate feedback to the TC genesis with some satisfaction, especially under strong forcing—as with an MRG or equatorial Rossby wave.[8,10,11] However, to display a truly accurate simulation, we'll need to further improve the visualization package to illustrate feedback processes (such as by including strong vertical motion associated with heavy precipitation). In reality, there's no clear separation between the external and internal processes. In deference to this view on TC genesis and intensification, large-scale forcing might continue to impact a TC's strength after its genesis, and thus should be considered properly to predict the TC's intensity.

To save lives and reduce the costs associated with storm damage, it's crucial to improve the short-term forecasts of hurricane intensity and formation, and to improve our understanding of TC interannual variability and how climate change (for example, doubling carbon dioxide emissions and/or global warming) affects TC activities. Because TC dynamics involve multiscale interactions among large-scale flows, mesoscale vortices, and small-scale cloud motions, an ideal numerical modeling system suitable for TC studies should be capable of simulating and displaying (that is, visualizing) these multiscale processes and their cross-scale interactions. CAMVis has shown potential for simulating the predictive relationship between TC formation and tropical waves. Using StreamPack to generate streamlines at different heights enables us to emphasize the relative role of large-scale and small-scale processes, which aren't completely separable, in a TC's evolution at different stages.

The quasi-3D StreamPack is a powerful tool for displaying TC cross-scale interactions. However, the current version doesn't use information about vertical wind velocity in the Z dimension. Ultimately, we'd like to do true 3D real-time simulations and visualizations, which will involve considerable work to accomplish greater realism; this is a subject for future study. We'll use a future version of StreamPack, coupled with the enhanced scalability of CAMVis—which is being prepared for publication[14]—with experimental, real-time simulations to systematically monitor the realism of TC formation and its association with different tropical waves.

Acknowledgments

We thank the reviewers for their valuable suggestions, which have substantially improved the manuscript. We're grateful to the following organizations for their support: the NASA Earth Science Technology Office, the NASA Advanced Information Systems Technology Program, the US National Science Foundation's Science and Technology Center, and the NASA Modeling, Analysis, and Prediction Program. We also appreciate the support of computing time and facilities at the NASA High-End Computing Program and the NASA Advanced Supercomputing facility at Ames Research Center (ARC). We thank Jill Dunbar of NASA ARC for proofreading this manuscript.

References

1. L.K. Bengtsson, I. Hodges, and M. Esch, "Tropical Cyclones in a T159 Resolution Global Climate Model: Comparison with Observations and Re-Analyses," *Tellus A*, vol. 59, no. 4, 2007, pp. 396–416; doi:10.1111/j.1600-0870.2007.00236.x.
2. R. Atlas et al., "Hurricane Forecasting with the High-Resolution NASA Finite Volume General Circulation Model," *Geophysical Research Letters*, 2005, vol. 32, no. 3, article L03801; doi:10.1029/2004GL021513.
3. B.-W. Shen et al., "Hurricane Forecasts with a Global Mesoscale-Resolving Model: Preliminary Results with Hurricane Katrina (2005)," *Geophysical Research Letters*, 2006, vol. 33, no. 13, 2006, article L13813; doi:10.1029/2006GL026143.
4. R. Biswas et al., "Petascale Computing: Impact on Future NASA Missions," *Petascale Computing: Architectures and Algorithms*," D. Bader, ed., Chapman and Hall/CRC Press, 2007, pp. 29–46.
5. T. Matsuno, "Quasi-Geostrophic Motions in the Equatorial Area," *J. Meteorological Soc. Japan*, vol. 14, 1966, pp. 25–42.
6. W.M. Frank and P.E. Roundy, "The Role of Tropical Waves in Tropical Cyclogenesis," *Monthly Weather Rev.*, vol. 134, no. 9, 2006, pp. 2397–2417.
7. G.N. Kiladis et al., "Convectively Coupled Equatorial Waves," *Rev. Geophysics*, vol. 47, no. 2, 2009, article RG2003; doi:10.1029/2008RG000266.
8. B.-W. Shen et al., "Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008)," *J. Geophysical Research*, vol. 115, no. D14, 2010, article D14102; doi:10.1029/2009JD013140.
9. B.-W. Shen, W.-K. Tao, and B. Green, "Coupling Advanced Modeling and Visualization to Improve High-Impact Tropical Weather Prediction," *Computing in Science & Eng.*, vol. 13, no. 5, 2011, pp. 56–67; doi:10.1109/MCSE.2010.141.
10. B.-W. Shen, W.-K. Tao, and M.-L. C. Wu, "African Easterly Waves in 30-Day High-Resolution Global Simulations: A Case Study During the 2006 NAMMA Period," *Geophysical Research Letters*, vol. 37, no. 18, 2010, article L18803; doi:10.1029/2010GL044355.
11. B.-W. Shen, W.-K. Tao, and Y.-L. Lin, "Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: The Role of Mixed Rossby Gravity Wave," *J. Geophysical Research*, vol. 17, no. D13, 2012; doi:10.1029/2012JD017450.
12. W.-K. Tao et al., "The Goddard Multi-Scale Modeling System with Unified Physics," *Annals Geophysicae*, vol. 27, no. 8, 2009, pp. 3055–3064.
13. D. Ellsworth et al., "Concurrent Visualization in a Production Supercomputing Environment," *IEEE Trans. Visualization and Computer Graphics*, vol. 12, no. 5, 2006, pp. 997–1004.
14. B.-W. Shen et al., "Scalability Improvement of the NASA Multiscale Modeling Framework for Tropical Cyclone Climate Study," *Computing in Science & Eng.*, preprint, 10 Aug. 2012; http://doi.ieeecomputersociety.org/10.1109/MCSE.2012.90.
15. C.W. Landsea, "A Climatology of Intense (or Major) Atlantic Hurricanes," *Monthly Weather Rev.*, vol. 121, no. 6, 1993, pp. 1703–1713.
16. R.M. Zehr, *Tropical Cyclogenesis in the Western North Pacific*, NOAA tech. report NESDIS 61, US Dept. of Commerce, 1992, 181 pp.

***Bo-Wen Shen** is a research scientist at the University of Maryland, College Park, and NASA Goddard Space Flight Center. His research interests include high-resolution global and regional modeling, high-end computing, and numerical hurricane and weather prediction. Shen has a PhD in atmospheric sciences from North Carolina State University. He's a member of the American Geophysical Union. Contact him at bowen.shen@gmail.com or bo-wen.shen-1@nasa.gov.*

Bron Nelson *is a senior software engineer for the Computer Sciences Corporation (CSC), and a member of the Visualization Group at the NASA Ames Research Center's Advanced Supercomputing facility. Bron has an MS in Computer Science from the University of California, Los Angeles. Contact him at bron.c.nelson@nasa.gov.*

Wei-Kuo Tao *is a senior research meteorologist at the NASA Goddard Space Flight Center and is the leader of the Goddard Mesoscale Modeling and Dynamic Group. His research interests include cloud physics and modeling mesoscale convective systems. Tao has a PhD in atmospheric sciences from the University of Illinois. He's a fellow of the America Meteorological Society and Royal Meteorological Society. Contact him at wei-kuo.tao-1@nasa.gov.*

Yuh-Lang Lin *is a professor and a distinguished scientist of the Interdisciplinary Scientific Environmental Technology Center at North Carolina A&T State University. His research interests include tropical cyclone dynamics, mesoscale dynamics, and modeling (including mountain meteorology, cloud microphysics and storm dynamics, and gravity wave dynamics). Lin has a PhD in meteorology and geophysical fluid dynamics from Yale University. He's a member of the American Geophysical Union and the American Meteorological Society. Contact him at ylin@ncat.edu.*

cn *Selected articles and columns from IEEE Computer Society publications are also available for free at http://ComputingNow.computer.org.*