An Operational Multiscale Hurricane Forecasting System

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ABSTRACT

The Operational Multiscale Environment model with Grid Adaptivity (OMEGA) is an atmospheric simulation system that links the latest methods in computational fluid dynamics and high-resolution gridding technologies with numerical weather prediction. In the fall of 1999, OMEGA was used for the first time to examine the structure and evolution of a hurricane (Floyd, 1999). The first simulation of Floyd was conducted in an operational forecast mode; additional simulations exploiting both the static as well as the dynamic grid adaptation options in OMEGA were performed later as part of a sensitivity–capability study. While a horizontal grid resolution ranging from about 120 km down to about 40 km was employed in the operational run, resolutions down to about 15 km were used in the sensitivity study to explicitly model the structure of the inner core. All the simulations produced very similar storm tracks and reproduced the salient features of the observed storm such as the recurvature off the Florida coast with an average 48-h position error of 65 km. In addition, OMEGA predicted the landfall near Cape Fear, North Carolina, with an accuracy of less than 100 km up to 96 h in advance. It was found that a higher resolution in the eyewall region of the hurricane, provided by dynamic adaptation, was capable of generating better-organized cloud and flow fields and a well-defined eye with a central pressure lower than the environment by roughly 50 mb. Since that time, forecasts were performed for a number of other storms including Georges (1998) and six 2000 storms (Tropical Storms Beryl and Chris, Hurricanes Debby and Florence, Tropical Storm Helene, and Typhoon Xangsane). The OMEGA mean track error for all of these forecasts of 101, 140, and 298 km at 24, 48, and 72 h, respectively, represents a significant improvement over the National Hurricane Center (NHC) 1998 average of 156, 268, and 374 km, respectively. In a direct comparison with the GFDL model, OMEGA started with a considerably larger position error yet came within 5% of the GFDL 72-h track error. This paper details the simulations produced and documents the results, including a comparison of the OMEGA forecasts against satellite data, observed tracks, reported pressure lows and maximum wind speed, and the rainfall distribution over land.

1. Introduction

The Operational Multiscale Environmental model with Grid Adaptivity (OMEGA) is an atmospheric modeling system developed at Science Application International Corporation (SAIC) with support from the Defense Threat Reduction Agency (DTRA). OMEGA was developed for real-time weather and airborne hazard prediction. Conceived to link the latest computational fluid dynamics and high-resolution gridding technologies with numerical weather prediction, OMEGA permits unstructured horizontal grids of continuously varying spatial resolutions ranging from about 100 km down to about 1 km to better resolve local terrain or important physical features of atmospheric circulation and cloud dynamics. This unique capability provides not only a higher resolution in the region of evolving weather systems but also allows a natural interaction with and influence upon the larger-scale flow, avoiding the wave-reflecting problem at internal boundaries found in traditional multiple nested grid systems or systems with specified grid motion. Therefore, OMEGA is especially applicable to those problems involving an interaction of spatial and temporal scales.

A multiscale model such as OMEGA, however, requires some unique considerations. One of them is that there is no clear spatial scale to the numerical grid that can be used to determine which of several physical assumptions should be used in the parameterizations; in OMEGA, there is a continuous range of scales, hence it is important to develop methodologies for dealing with this issue.

A hurricane is an intense atmospheric vortex with a horizontal scale of over several 100 km and a vertical scale of up to 20 km. Hurricanes are formed over warm oceans and are characterized by strong convective cells with horizontal scales of a few kilometers. The structure

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and evolution of the system are characterized by strong multiscale interactions. Past numerical studies, starting from those by Kasahara (1961); Kuo (1965, 1974); Yamasaki (1977); Anthes (1972, 1977, 1982); Kurihara (1973); Emanuel (1988); Bender et al. (1993); Kurihara et al. (1993, 1995); Krishnamurti et al. (1995); Liu et al. (1997, 1999) have all led to a better understanding of the structure and evolution of hurricanes (see, for instance, Liu et al. 1997 for a brief review on hurricane research).

Yet, to date there is no operational model that can forecast both hurricane track and intensity reasonably well (Emanuel 1999; Willoughby 1998). Given an accurate sea surface temperatures (SST) field and a realistic initial vortex, predictions of hurricanes from tropical synoptic conditions can only be improved by correctly simulating the interactions between the fine-scale structure of the eye and the large-scale environment. However, to adequately resolve the fine structure of a hurricane, model resolution on the order of 10 to 20 km or less is required. Operational limitations make it impractical to treat the entire model domain with fine resolution. The dynamically adaptive, unstructured grid system of the OMEGA model plus its advanced physical parameterizations offers a viable solution for operational forecasting of hurricanes. The research described in this paper has three major objectives:

1) To evaluate the OMEGA model, especially its cumulus parameterization and explicit microphysics, by comparing observations and the simulated large-scale environmental features of Hurricane Floyd (1999)—including its associated rainfall over the East Coast 15–16 September 1999;
2) to explore scale interactions between convective-scale and regional-scale features evolving from synoptic-scale initial conditions by dynamically resolving the eye of the hurricane; and
3) to evaluate the operational capability of the OMEGA model for hurricane track forecasting.

To the best of our knowledge, this is the first time that an unstructured grid adaptive modeling system has been used to forecast hurricanes. Because this is the first application of OMEGA to hurricane forecasting, the scope of this work is of necessity limited; however, we believe that the 20 forecasts encompassing 8 storms represents a significant enough sample to draw some conclusions as to the model capabilities. Since we will focus on hurricane track forecasting, the next section discusses the current state of the art. Section 3 then provides a brief overview of the OMEGA modeling system emphasizing those aspects of the system that make it especially applicable for hurricane forecasting. Section 4 provides a brief overview of the structure and evolution of Hurricane Floyd (1999) and verifies the model simulations against all available observations. A set of forecasts for Hurricane Georges (1998) is presented in section 5 with emphasis on the effectiveness of dynamic adaptation. Section 6 then discusses the results of operational forecasts for six storms performed during the 2000 season. Section 7 summarizes the results of the entire suite of forecasts. Finally, section 8 discusses future directions and presents some conclusions.

2. Hurricane track forecasting

Hurricanes are one of the most devastating meteorological events in terms of societal costs. Jarrell and DeMaria (1999) estimated that the cost of *warning* a mile of coastline was $600,000, hence the average annual warning cost for hurricanes was about $400 million. Pielke and Landsea (1998) computed an average annual cost to the United States of $4.8 billion (referenced to 1995 dollars). Obviously, improving the accuracy of hurricane track forecasting is an important part of the protection of life and property.

An excellent history of hurricane forecasting can be found in DeMaria (1996). The earliest predictive tools were based on climatological or statistical methods and most used guidance from the global model forecasts. Later, limited area dynamical models were developed including the Moveable Fine Mesh (Hovermale and Livezey 1977), the Quasi-Lagrangian Model (QLM) (Mathur 1991), and the Geophysical Fluid Dynamics Laboratory (GFDL) model (Bender et al. 1993). This succession of tools, along with improvements in the global forecast models—the National Weather Service Global Spectral Model [GSM, run in either the Medium Range Forecast (MRF) or Aviation (AVN) configurations] and the U.S. Navy Operational Global Analysis and Prediction System (NOGAPS)—has been a major contributing factor to the improvement in track forecasting over the past two decades. From 1975 to 1998, the 72-h track forecast accuracy improved by 50% (Fig. 1, derived from the data in McAdie and Lawrence 2000).

No forecast system is perfect, however. Many discussions of numerical model guidance errors, especially forecasts with large errors, focus on particular meteorological scenarios (e.g., Carr and Elsberry 2000) such as direct cyclone interaction (interaction of two closely spaced tropical cyclones) or tropical cyclone initial size. The observation that these scenarios are responsible for the blown model guidance illuminates the need for higher spatial resolution and better physical parameterizations, both of which require additional computational resources. The U.S. Weather Research Program has a five-year goal of improving hurricane track forecasting by 20% by improving the observation network, enhancing the utilization of the observations, increasing the model physics and resolution, and providing the computer resources necessary to produce the enhanced forecasts within the operational timeline.

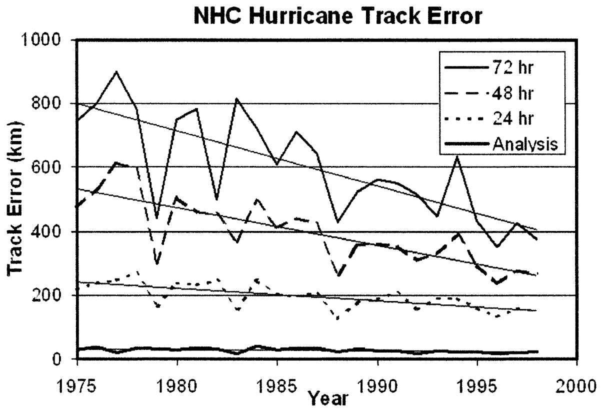

FIG. 1. The National Hurricane Center has made a tremendous improvement in track forecast error over the past 25 yr. Shown are the analysis and 24-, 48-, and 72-h forecast track errors from 1975 to 1998 (based on the data in McAdie and Lawrence 2000). The linear regression trend lines show that in this 23-yr period the 48- and 72-h forecast track error improved by 50%; the 24-h forecast track error improved by 37%.

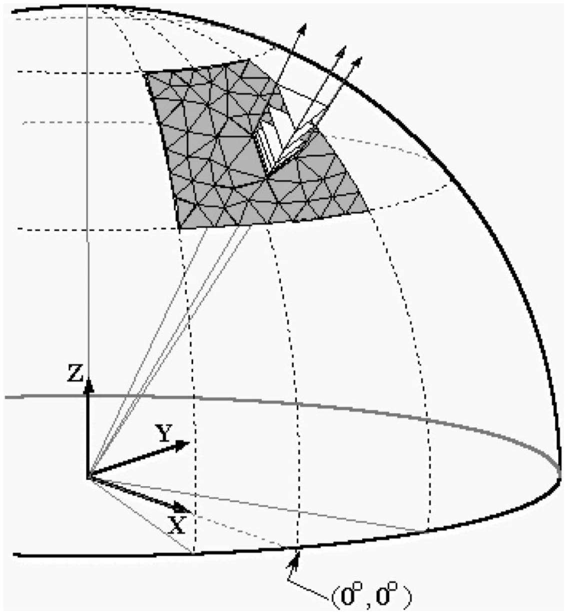

FIG. 2. The OMEGA coordinate system and vertical alignment of OMEGA grid.

3. The OMEGA modeling system

OMEGA represents a different approach to hurricane forecasting using an adaptive unstructured grid forecast system. This system has three primary advantages for hurricane forecasting. The first is that the unstructured triangular grid can simulate coastlines and orographic features without the ''stair step'' geometry required of nested rectilinear grid models and its resultant impact on landfall dynamics (Zhang et al. 1999). Second, the unstructured grid permits a range of scales to be modeled with full scale-interaction over the domain and without the wave-reflecting internal boundaries of traditional nested grid models. Third, adding dynamic adaptation allows the system to maintain high resolution over the storm *automatically* providing computational efficiency and leading to potentially better intensity forecasts. In the next section we will discuss OMEGA and its application to hurricane forecasting in more detail.

A complete description of OMEGA can be found in Bacon et al. (2000). Briefly, OMEGA is a fully nonhydrostatic, three-dimensional prognostic model. It is based on an adaptive, unstructured triangular prism grid that is referenced to a rotating Cartesian coordinate system. The model uses a finite-volume flux-based numerical advection algorithm derived from Smolarkiewicz (1984). OMEGA has a detailed physical model for the planetary boundary layer (PBL) with a 2.5-level Mellor and Yamada (1974) closure scheme. OMEGA uses a modified Kuo scheme to parameterize cumulus effects (Kuo 1965; Anthes 1977), and an extensive bulk water microphysics package derived from Lin et al. (1983). OMEGA computes the shortwave absorption by water vapor and longwave emissivities of water vapor and carbon dioxide (Sasamori 1972). The surface energetics are based upon a force–restore model (Deardorff 1974) modified to include cloud shadowing effects. OMEGA uses an optimum interpolation analysis scheme (Daley 1991) to create initial and boundary conditions and supports piecewise four-dimensional data assimilation using a previous forecast as the first guess for a new analysis. Finally, OMEGA contains both Eulerian (grid based) and Lagrangian (grid free) dispersion models embedded into the model.

A unique feature of the OMEGA model is its unstructured grid. The flexibility of unstructured grids facilitates the gridding of arbitrary surfaces and volumes in three dimensions. In particular, unstructured grid cells in the horizontal dimension can increase local resolution to better capture the underlying topography and the important physical features of atmospheric circulation flows and cloud dynamics. The underlying mathematics and numerical implementation of unstructured adaptive grid techniques have been evolving rapidly, and in many fields of application there is recognition that these methods are more efficient and accurate than the traditional structured grid approach (Baum and Löhner 1994; Sarma et al. 1999; Schnack et al. 1998). OMEGA represents the first attempt to use this CFD technique for atmospheric simulation.

OMEGA is based on a triangular prism computational mesh that is unstructured in the horizontal dimension and structured in the vertical (Fig. 2). The rationale for this mesh is the physical reality that the atmosphere is highly variable horizontally, but generally stratified vertically. While completely unstructured three-dimensional meshes have been used for other purposes (Baum et al. 1993; Luo et al. 1994), the benefit of having a structured vertical dimension in an atmospheric grid is a significant reduction in the computational requirements of the model. Spe-

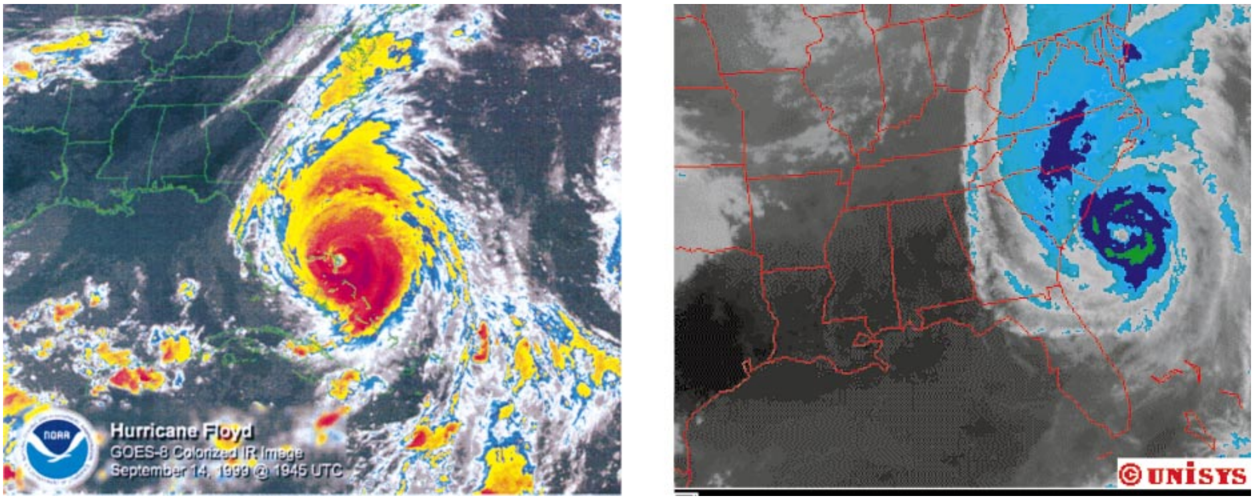

FIG. 3. Enhanced NOAA AVHRR infrared image of Hurricane Floyd at 1945 UTC 14 Sep (left) and the infrared image at 2245 UTC 15 Sep 1999 (right).

cifically, the structured vertical grid enables the use of a tridiagonal solver to perform implicit solution of both vertical advection and vertical diffusion. Since in many grids the vertical grid spacing is 1 or more orders of magnitude smaller than the horizontal grid spacing, the ability to perform vertical operations implicitly relaxes the limitation on the time step.

Two types of grid adaptation options are available in OMEGA. *Static* adaptation creates a numerical grid resolving static features such as land–water boundaries, terrain gradients, and/or any other feature that the user includes in the adaptation scheme with a resolution that smoothly varies from the maximum to the minimum specified. (In addition, the OMEGA grids can also be further refined in one or more specific geographical areas, by the creation of up to 99 subdomains in which higher resolutions can be specified.) *Dynamic* adaptation adds the periodic readaptation of the grid to regions that require high resolution during the course of a simulation (e.g., frontal zones, hurricane circulation, pollutant plumes).

The computational grid does not change during the course of a static adaptation simulation; however, dynamic adaptation consists of three major steps taken at preset time intervals: 1) specific variables or their gradients are evaluated to see if they meet the adaptivity criteria, (2) the mesh is refined or coarsened depending on the prespecified criteria, and (3) the physical variables are interpolated to the new cell centers.

While the goal of OMEGA is to try to explicitly resolve large areas of convection, there will always be regions that are not sufficiently resolved. To circumvent

a)

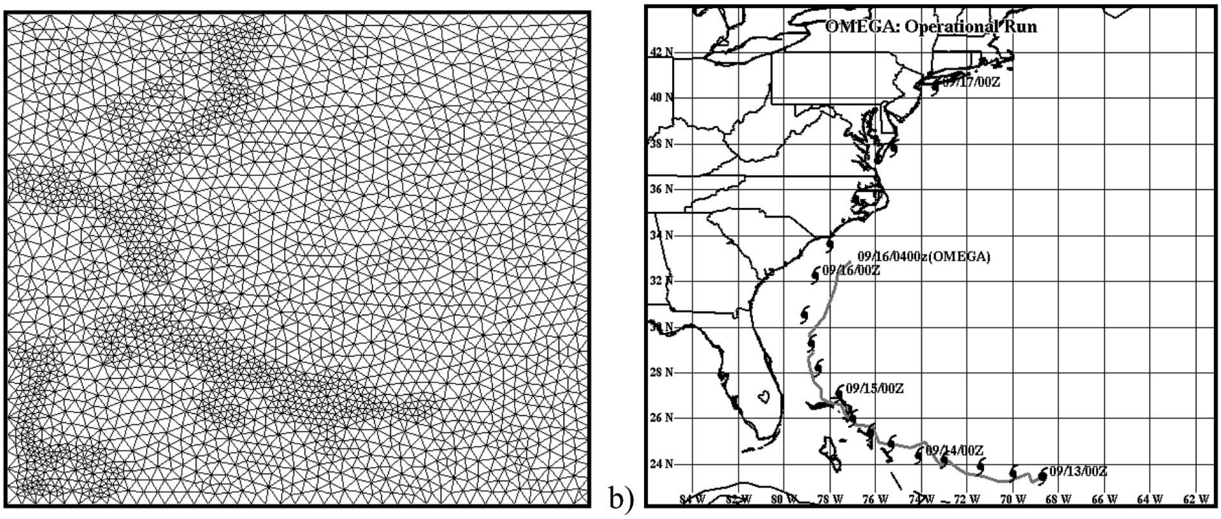

FIG. 4. (a) The OMEGA grid and (b) a closeup of the obs (symbol) and forecast (gray line) track for the first 72-h operational hurricane forecast (initialized at 0000 UTC on 13 Sep).

TABLE 1. Configuration of all 20 forecasts discussed in this paper.

Storm	Forecast ID	Analysis time	IC and BC	Resolution (km)	Comment
Georges (1998)	DYN24	0000 UTC 24 Sep	NOGAPS	15–80	Dynamic adapt
	DYN25	0000 UTC 25 Sep	NOGAPS	15–80	Dynamic adapt
Floyd (1999)	LRES12	0000 UTC 12 Sep	NOGAPS	25–80	Prior day
	LRES13	0000 UTC 13 Sep	NOGAPS	25–80	Baseline
	LRES14	0000 UTC 14 Sep	NOGAPS	25–80	Next day
	HRES14	0000 UTC 14 Sep	NOGAPS	15–80	High resolution
	HSST14	0000 UTC 14 Sep	NOGAPS	15–80	Elevated SST
	DYN14	0000 UTC 14 Sep	NOGAPS	15–80	Dynamic adapt
Beryl (2000)	LRES14	0000 UTC 14 Aug	NOGAPS	40–120	Operational
Chris (2000)	LRES18	0000 UTC 18 Aug	NOGAPS	40–120	Operational
	LRES19	0000 UTC 19 Aug	NOGAPS	40–120	Operational
Debby (2000)	LRES21	0000 UTC 21 Aug	NOGAPS	40–120	Operational
	LRES22	0000 UTC 22 Aug	NOGAPS	40–120	Operational
Florence (2000)	LRES11	0000 UTC 11 Sep	MRF	40–120	Operational
	LRES12	0000 UTC 12 Sep	MRF	40–120	Operational
	LRES13	0000 UTC 13 Sep	MRF	40–120	Operational
Helene (2000)	LRES20	0000 UTC 20 Sep	MRF	40–120	Operational
	LRES21	0000 UTC 21 Sep	MRF	40–120	Operational
Xangsane (2000)	LRES30	0000 UTC 30 Oct	MRF	25–120	Operational
	LRES31	0000 UTC 31 Oct	MRF	25–120	Operational

this problem a version of cumulus parameterization that was originally proposed by Kuo (1965, 1974) and later modified by Anthes (1977) is incorporated to account for the effect of subgrid-scale deep cumulus convection on the local environment. The coupling between the subgrid-scale cumulus parameterization scheme and the explicit cloud microphysics is still a great research area for numerical modelers. Recently, Molinari and Dudek (1992) proposed that the use of explicit cumulus physics representations becomes necessary for horizontal grid resolutions less than 3 km. At this scale, large deep convective clouds are often resolvable (e.g., Lilly 1990). For horizontal grid scales larger than 50–60 km, Molinari and Dudek suggested using cumulus parameterizations of convectively unstable grid points and explicit condensation at convectively stable grid points. The most troublesome scales for parameterizing convective processes are those between 3 and 50 km. Because of the continuous range of scales, OMEGA treats the crossover between cumulus parameterization and explicit microphysics by keeping both processes active and weighting the cumulus parameterization terms by a factor of the form

$$f = \min(1, A_i/A_c)$$

in which A_i is the area of the i^{th} OMEGA cell and A_c is the cutoff value (100 km^2). For large cells, this factor is unity and cumulus parameterization is fully weighted.

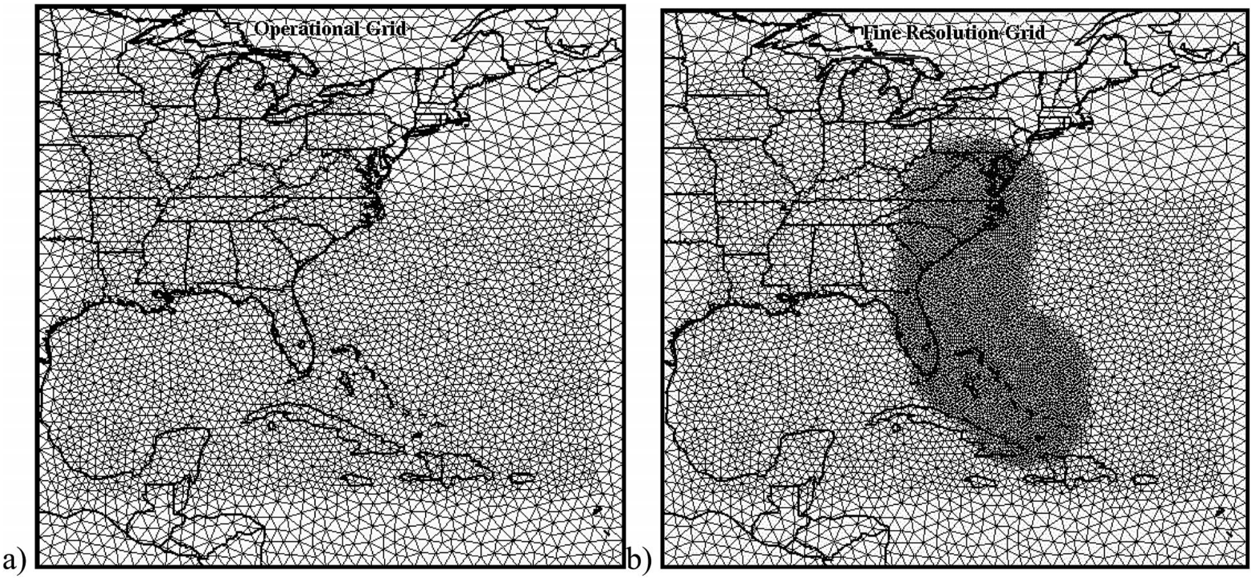

FIG. 5. The OMEGA grid for the low-resolution (LRES) runs (left) and the high-resolution (HRES) simulations (right).

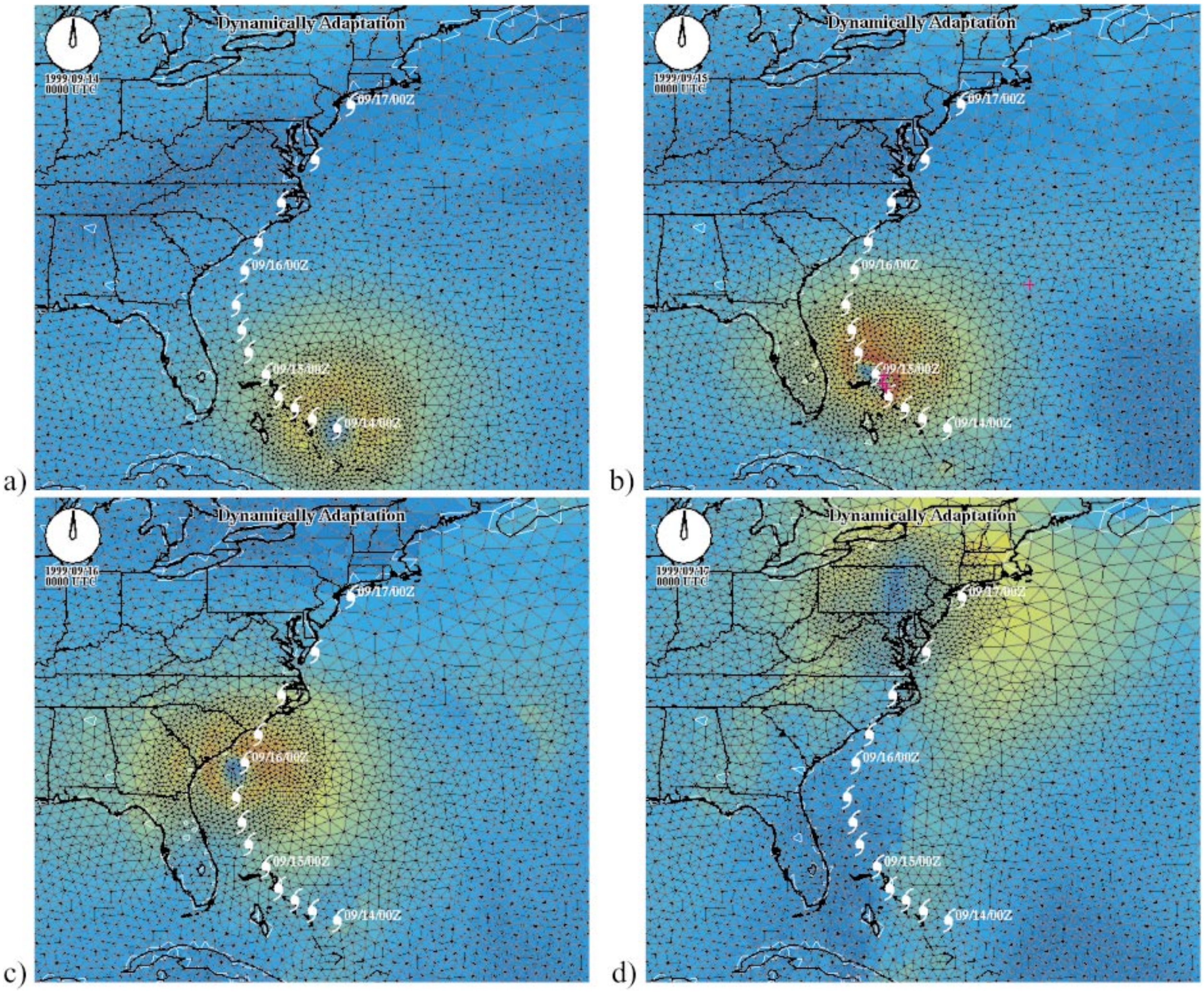

FIG. 6. The evolving grid of an OMEGA simulation (DYN14) of Hurricane Floyd superimposed over the 1-km wind speed (color) ranging from 10 to 120 kt. The obs track is indicated by the symbol; the four magenta crosses in (b) represent the locations of dropsondes discussed later.

In this situation, it is assumed that explicit microphysics will contribute little unless there is a stratiform situation that would not be considered by the cumulus scheme anyway. For small cells, the factor is near zero and cumulus parameterization is not a significant contributor to the system.

Another important component of the OMEGA system for hurricane forecasting is the *tracker* routine which postprocesses OMEGA output to determine the location of a tropical storm. Tracker is an automated system that performs the following steps to locate the storm center.

1) At analysis time, the observed storm location is used as the first guess location.
2) Tracker computes an interpolated modified dynamic pressure ($P_{dyn} = P' + \alpha\rho s^2/2$, where P' is the pressure perturbation, α is a factor set to 5, and s is the wind speed) onto a regular Mercator grid with spacing of 0.25°. A 9×9 point smooth is performed as part of this interpolation step.
3) The first guess location is used to identify the SW corner of the Mercator grid cell in which it lies. A 17×17 point ($4° \times 4°$) subdomain centered around this point is then specified. The minimum P_{dyn} at OMEGA level 15 (roughly 2 km elevation) within this subdomain is located and reported as the storm location.
4) The reported location is used as the first guess location for a new tracker analysis of the next set of OMEGA results, typically 1–3 h hence.

This routine has proven to be robust enough for automated processing, even in cases with strong shear.

4. Simulations of Hurricane Floyd (1999)

Hurricane Floyd (1999) (Fig. 3) was one of the deadliest natural disasters to strike the Atlantic coast of the

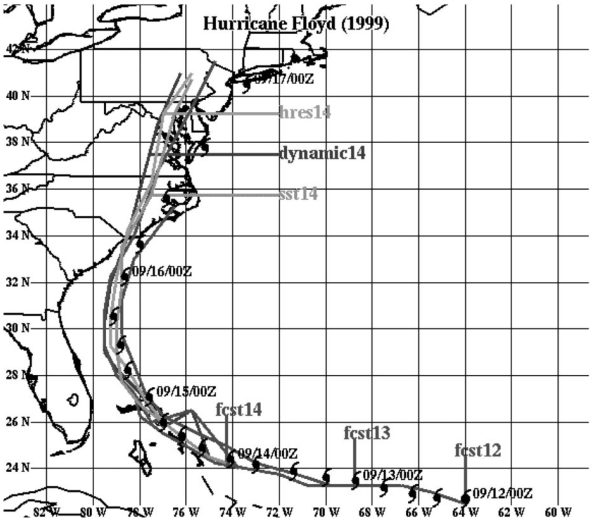

FIG. 7. OMEGA forecasted storm tracks for the initial sensitivity studies. All six tracks showed considerable skill out to 72 h.

United States since Hurricane Agnes (1972). Its landfall resulted in the loss of 57 lives and a total property damage of at least $3 billion (Pasch et al. 1999). The storm originated from a tropical disturbance and moved off the west coast of Africa on 2 September. It organized into a tropical depression on 7 September as it moved to about 1000 miles east of the Lesser Antilles. The system further strengthened into a tropical storm early the next day when it was located about 850 mi east of the Lesser Antilles. On 9 September, the storm intensified into a hurricane about 240 mi northeast of the northern Leeward Islands. Reports from NOAA (Pasch et al. 1999) suggest that Floyd turned from a westward to a northwestward course and its intensification trend temporarily halted before it eventually turned back to the west and strengthened into a major category 4 hurricane on the Saffir–Simpson hurricane scale on 13 September. The hurricane ravaged portions of the central and northwest Bahamas on 13–14 September, and posed a serious threat to Florida (Fig. 3, leftside).

Contrary to expectations, a mid- to upper-level trough approaching the eastern United States eroded the western periphery of the high that was initially steering Floyd westward towards Florida, thus creating a more northward steering current. Consequently, Floyd assumed a northwestward and later, northward course (Fig. 3, rightside) while slowly weakening, and eventually made landfall near Cape Fear, North Carolina, as a category 2 hurricane with estimated maximum winds near 90 kt around 0630 UTC 16 September. The simulations in this paper start on or after 13 September 1999 when Floyd was a fully developed hurricane.

a. *Operational simulation*

The first simulation of Hurricane Floyd was performed in an operational environment. The simulation was initialized from the NOGAPS analysis at 0000UTC 13 September 1999; the lateral boundary conditions were derived from the NOGAPS forecast. The static grid with a resolution ranging from 70 down to 30 km covered a domain from 13° to 40° and 58° to 89° W (Fig. 4a). The forecasted track (Fig. 4b) was compared against the reported cyclone locations (symbol) obtained from NOAA. (At the time of this simulation, the tracker routine did not exist and hence the OMEGA location was based on the minimum pressure.) The average track error for this forecast was 51 km for the first day, 61 km for the second day, and 78 km for the third day. The center pressure of the simulated cyclone, however, was significantly higher (roughly 50 mb) than observed. To understand the reason for the large underestimation of the hurricane intensity by the model, we performed the series of sensitivity studies presented in the next section.

b. *Sensitivity studies*

There are many factors that affect hurricane intensity forecasting. Three of the most significant are the model initialization, the grid resolution, and the model physics. These were the factors examined in our sensitivity study of this case.

A brief summary of all of the simulations discussed in this paper is provided in Table 1. The six simulations included three varying the initialization time, a variation using higher grid resolution, a test increasing the sea surface temperature, and a simulation using dynamic adaptation.

- The baseline grid for the Floyd sensitivity studies consisted of 35 vertical levels with a vertical resolution of 30 m near the surface increasing to 1.9 km at the top of the model domain (19.2 km). This grid is very similar to the operational run, extending from 12°–49°N and 60°–98°W with an effective horizontal resolution (based on the square root of the cell area) ranging from 80 to 25 km. This grid (referred to as LRES and shown in Fig. 5a) had 7993 triangular cells in each level.
- To study the potential impact of model initial conditions, the model was run with the baseline LRES grid initialized at 0000 UTC on the day before and the day after the baseline forecast (September 13). Except for the change in the time of initialization, all three of these cases used the same model configuration.
- To explore the impact of grid resolution, a simulation was conducted using a grid constructed by taking the baseline grid and allowing the resolution to go down to 15 km producing 12 711 cells. This grid was constructed by using dynamic adaptation with grid coarsening turned off and letting the grid adapt to the storm track. The final grid (referred to as HRES and shown

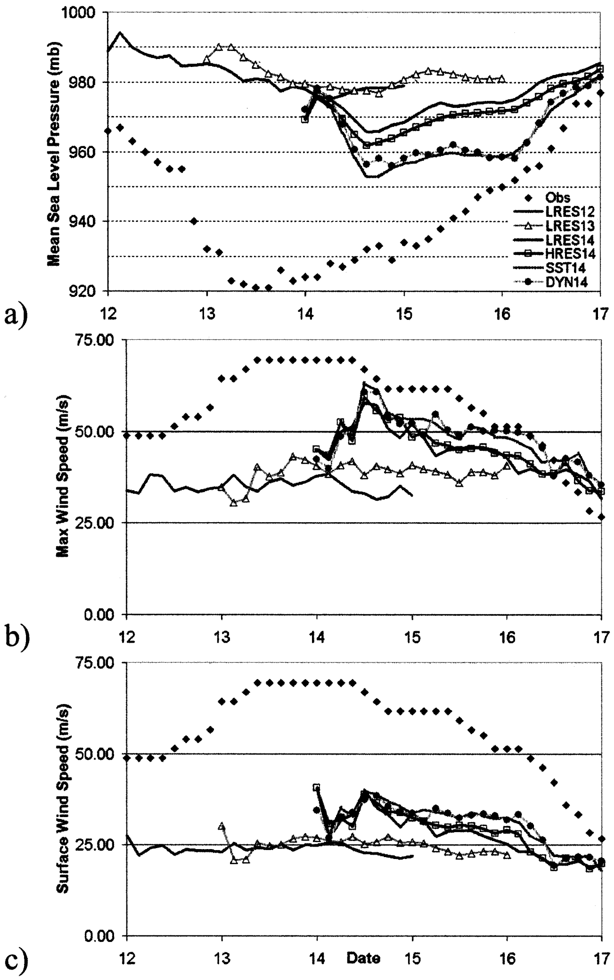

FIG. 8. Comparison of observations of Hurricane Floyd and the OMEGA forecasted (a) central pressure, (b) maximum wind, and (c) surface wind.

in Fig. 5b) was then used in this static adaptation simulation.

- As will be discussed later, a common feature of the simulations discussed previously was an intensity forecast that was weaker than the actual storm. Since the primary source of energy in hurricanes is the warm sea surface, we explored the impact of the sea surface temperature on the OMEGA forecast. This was accomplished by repeating a simulation performed on the HRES grid with the sea surface temperature field artificially increased by 1 K.
- Finally, to demonstrate the full power of the dynamic adaptation capability of OMEGA, a simulation was performed that used the same maximum and minimum grid resolution as the HRES grid but permitted grid coarsening, resulting in a much smaller number of grid cells. Note that dynamic adaptation involves a periodic changing of the grid, but it typically results in a 25%–30% reduction in the number of the highest-resolution grid cells, resulting in a similar reduction in computational time in spite of the overhead of adaptation. In this case, grid refinement was permitted every hour with grid coarsening occurring every 2 h. Figure 6 shows four snapshots of the dynamically adapting grid at the initial time and every 24 h for 3 days. This figure shows how OMEGA efficiently maintains high resolution over the storm without the necessity of carrying the same resolution everywhere.

The six simulations had very similar storm tracks (as extracted from the OMEGA forecast by the tracker routine). All of them are in close agreement with the observations (Fig. 7). The simulations reproduced the observed recurvature of the storm off the coast of Florida with an accuracy of less than 80 km. The four simu-

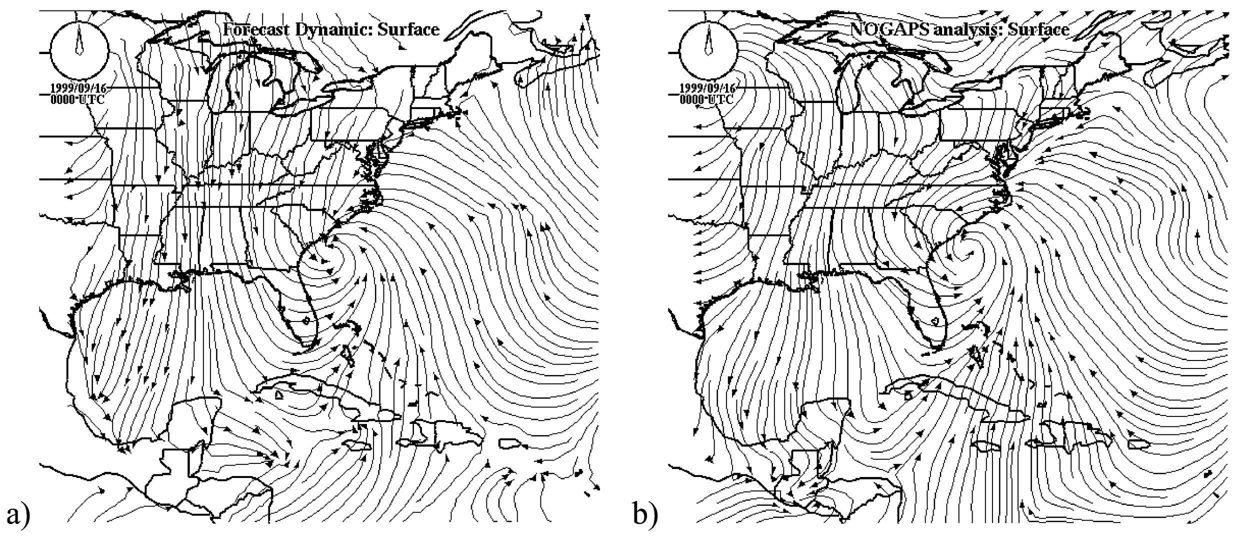

FIG. 9. Comparison of the streamlines obtained from (a) the OMEGA 48-h forecast streamlines, and (b) the NOGAPS analysis streamlines valid at the same time for Hurricane Floyd.

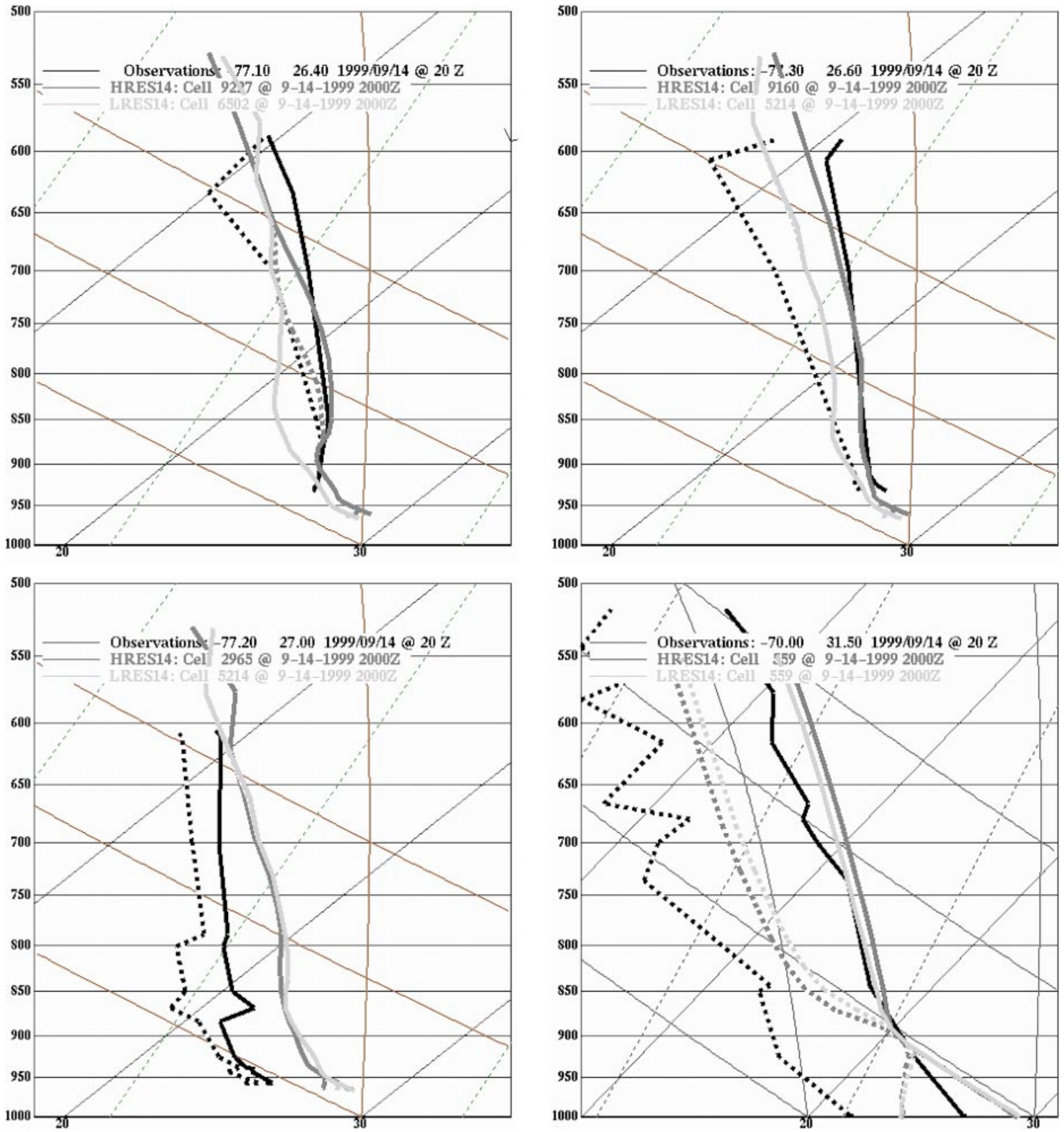

FIG. 10. Comparison of Floyd dropsonde data with OMEGA forecast profiles of temperature and dewpoint for the low- (LRES14) and high- (HRES14) resolution forecasts.

lations initialized at 0000 UTC 14 September reproduced the observed landfall near Cape Fear, North Carolina, at around 0700 UTC 16 September 1999 with an accuracy of less than 100 km. Although the track forecasts for these six simulations indicated excellent model performance of OMEGA given an initial error in cyclone center of roughly 25 km due to the large-scale analysis, a comparison of the observed and forecasted central pressure and maximum winds revealed that the model tends to forecast a much shallower low and weaker winds (Fig. 8).

The discrepancy in intensity forecast may be due in part to the lack of vortex bogus in the model initialization. The NOGAPS analysis did not accurately capture the low, leading to an excessively weaker storm in the OMEGA initial conditions. The 0000 UTC NOGAPS analyses on 12 and 13 September did not resolve the cyclone adequately resulting in a central pressure in

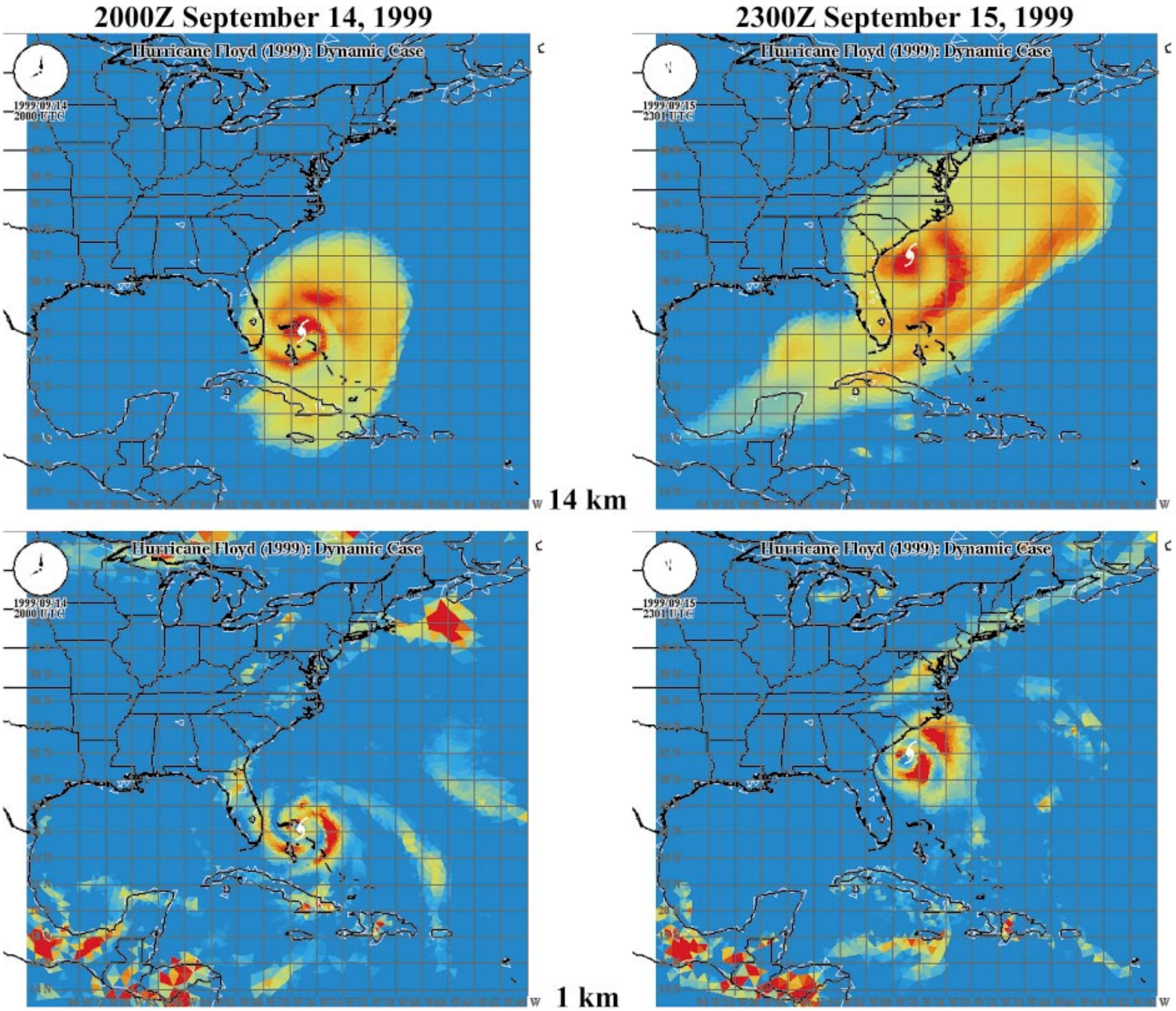

FIG. 11. OMEGA simulated cloud concentration at 14 km (top) and 1 km (bottom). The times of these figures (left and right) correspond roughly with those of Fig. 3, respectively.

the OMEGA analysis of over 20 and 50 mb higher than that observed, respectively. The analysis at 0000 UTC 14 September showed a better-resolved vortex with a low pressure roughly 20 mb below that of the day before. Even though this was still 40 mb above the observation, the better structure of the storm in the analysis results in a better intensity forecast.

In addition to the initial discrepancy, the OMEGA simulation did not exhibit as much intensification as observed, though the model did try to deepen the low (Fig. 8a, LRES14). This latter behavior could be related to the heating rate produced by the explicit microphysics or cumulus parameterization algorithms of the model (the evaluation of which was a major reason for performing these simulations), or the diffusion of the low due to either the numerics or the grid resolution. Analyzing the HRES14 simulation reveals that grid resolution can impact the intensity forecast. The OMEGA high-resolution simulation deepened the forecast low by an average of 3 mb, nevertheless the forecasted storm intensity still deviated significantly from the observations.

Three major factors influence the strength of a hurricane: 1) the thermodynamic state of the atmosphere through which it moves, 2) the storm's initial intensity, and 3) the heat exchange with the upper layer of the ocean under the core of the hurricane (Emanuel 1999). Having tested the impacts of model initialization and grid resolution on the storm intensity forecast, we turned our attention to the air–sea interaction. As mentioned earlier, the primary source of energy for the storm is the ocean and the controlling parameter in both the real and the modeled atmosphere is the SST. Consequently, the local variations in SST are expected to affect the

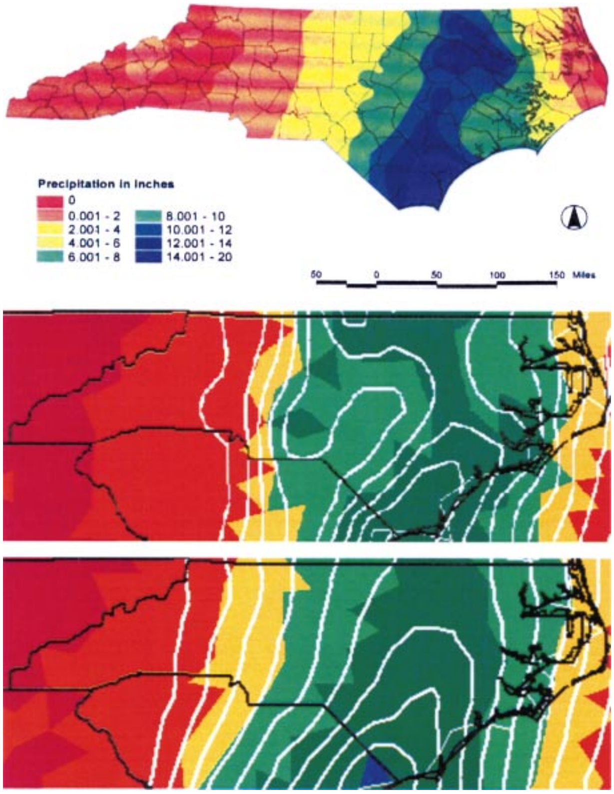

FIG. 12. Comparison of obs and simulated rainfall distribution valid 14–16 Sep 1999. The obs precipitation (top) is plotted in inches with max indicated in blue and min indicated in red; the simulated precipitation for cases LRES14 (middle) and HRES14 (bottom) are plotted in mm (1 inch = 25.4 mm) using the same color scheme. (Observations courtesy of Dr. Sethu Raman.)

intensity of the system. The NOGAPS SST field that was used to initialize the OMEGA model in the present study was available at a resolution of about 1°; this resolution appears to be too coarse to resolve local ''highs'' along the track of the storm. In addition, while the global SST analysis has a small overall bias, the standard deviation when compared with in situ field measurements is significant with a value of over 1.5 K reported by Casey and Cornillon (1999). Even high-resolution (9 km) Pathfinder analyses have a standard deviation of 0.85 K when compared with high fidelity in situ data (Kearns et al. 2000).

Whether the error in the flux calculation arises from an error in the input SST or from an error in the current surface flux models, to explore the sensitivity of the modeled storm intensification to increased surface flux, the HRES14 simulation was repeated with an SST field uniformly elevated by 1 K (referred as HSST14). As is seen in Fig. 8, warming the SST by 1 K results in 10 mb of additional deepening and roughly 10 kt increase in the maximum wind speed; however, the observed low was deeper still.

The grid adaptation discussed so far is statically adaptive, implemented in the grid generator prior to the beginning of an OMEGA simulation and the grid does not change during the simulation. While the application of such an unstructured static adaptive mesh in OMEGA allows for an increase in local resolution to better capture the important physical features of atmospheric circulation and cloud dynamics and topography (Bacon et al. 2000), the flexibility of unstructured grid in dynamically adapting to transient multiscale weather phenomena like the hurricane gives OMEGA a unique advantage over other atmospheric flow models in providing accurate solutions quickly in an operational setting without compromising on the scale interactions. To demonstrate this capability, we performed a dynamic adaptation forecast (referred to as DYN14), also using a 1-K elevated SST, which gave a very similar result to that of the HSST14 case, but using 25% fewer computational cycles (Figs. 6 and 8, DYN14).

Figure 6 depicts the dynamically adaptive OMEGA grids superimposed over wind speeds (in knots) at an altitude of about 1 km obtained at 0, 24, 48, and 72 h. It can be seen that the OMEGA forecasted storm track compares favorably with observations (white hurricane symbols) with track errors within a degree of accuracy (O(100 km)) until landfall. Furthermore, it should also be noted that the region of extreme pressure drop, which is usually constricted to a core region that is 15–50 km in radius, is well resolved by the dynamically adaptive grid. This demonstrates that the dynamically adaptive grid presents an efficient solution for operational forecasting of hurricanes.

A good hurricane track forecast is dependent upon a good prediction of the larger-scale environment of the storm. To evaluate the ability of OMEGA to reproduce the larger-scale environment, a comparison of the OMEGA forecast was made with global analyses and dropsonde data. The OMEGA 48-h forecasted streamlines and those derived from the NOGAPS analysis valid at the same time is shown in Fig. 9. It can be seen that the OMEGA 48-h forecast agrees well with the analysis valid at the same time. In order to compare the OMEGA results with dropsonde data, we extracted vertical profiles at the OMEGA cell centroid closest to and at the same time as the dropsonde observations. Figure 10 compares the LRES14 and HRES14 forecasts with four dropsondes 20 h after model initialization. While the high-resolution simulation has an incremental advantage over the baseline, both exhibit good agreement with the data.

Recent studies have shown that hurricane intensity evolution is also controlled by the inner core structure. Thus it is of interest to examine the internal thermodynamic and dynamic structure of the modeled storm. The OMEGA simulated low-altitude (1 km) and high-altitude (14 km) cloud concentration are shown in Fig. 11. The low and high cloud concentration fields shown are from the DYN14 case at 2000 UTC 14 September and 2300 UTC 15 September, respectively, which are close to the times of the satellite images shown in Fig.

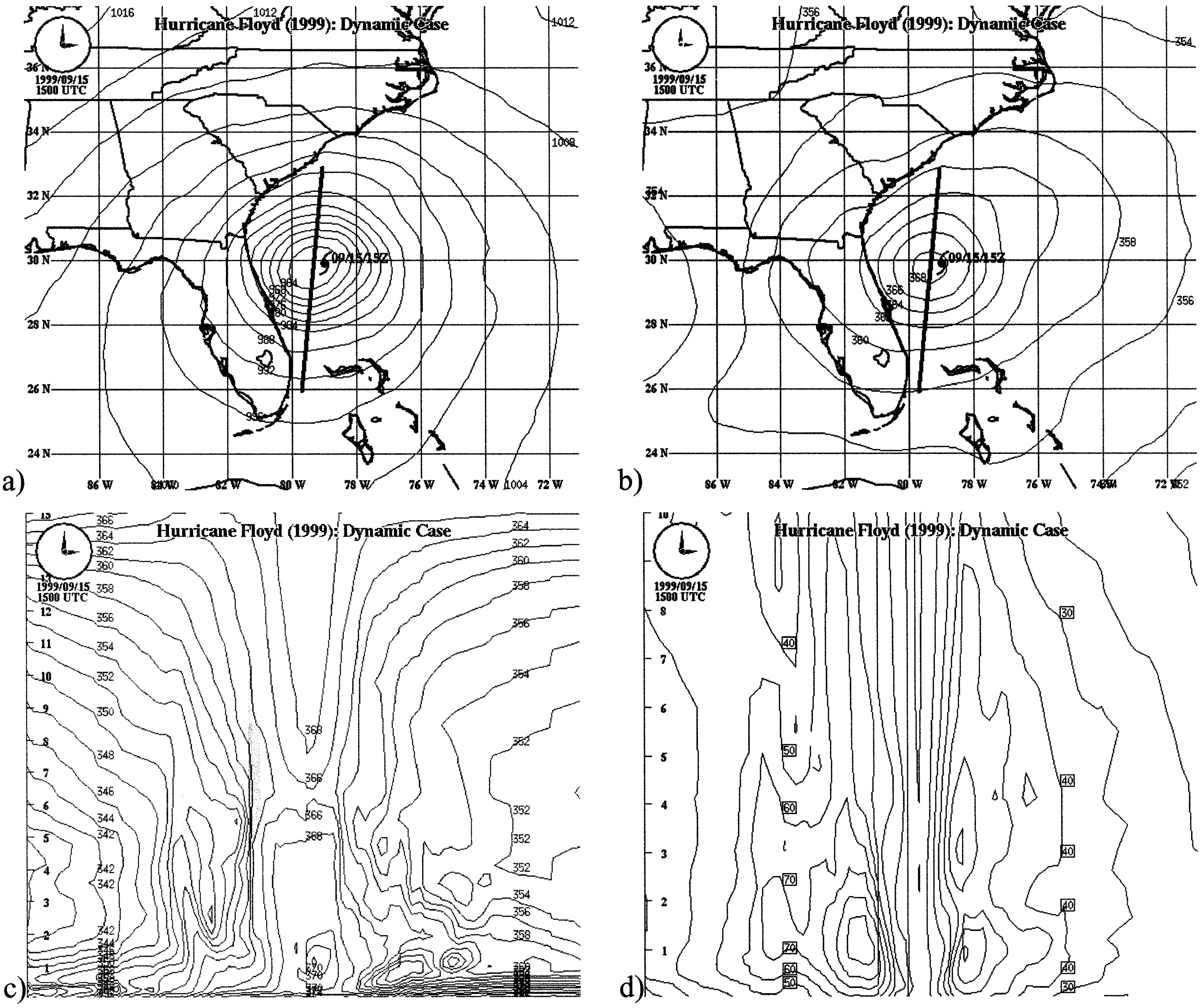

FIG. 13. Structure of the hurricane as simulated in the dynamic adaptation simulation at 1500 UTC 15 Sep 1999. Shown are (a) mean sea level pressure (mb); (b) θ_e (K) at approximately 12-km altitude; and vertical cross sections of (c) vertical velocity (grayscale) with θ_e contours superimposed; and (d) wind speed (kt) along a plane passing through the track of the hurricane. [The lines in (a) and (b) indicate the location of the cross sections in (c) and (d); the hurricane is approaching land from right to left.]

3. Comparing Figs. 3 and 11 shows that OMEGA is doing a good qualitative simulation of hydrometeor formation.

To examine the quantitative performance of the model, we compared the OMEGA simulated integrated precipitation with data obtained from the State Climatologist of North Carolina (S. Raman 2000, personal communication). Figure 12 compares the observations against both the low- and high-resolution OMEGA cases initialized at 0000 UTC 14 September. The agreement with the low-resolution results is reasonably good; the agreement with the high-resolution results is even better. OMEGA correctly forecast the geometry of the precipitation and the maximum value.

The sum of these qualitative and quantitative comparisons is a good validation of the microphysics and cumulus parameterization algorithms of OMEGA. However, apart from diabatic, latent heating produced by clouds, adiabatic warming in the region of subsidence, and diabatic warming due to sensible heat transfer at the ocean surface also contributes significantly to the total heating in a hurricane system.

A qualitative check of the net heating rate was performed by examining the thermodynamic structure of the simulated hurricane. Figure 13 shows the results of the dynamic adaptation simulation at 1500 UTC 15 September (39 h into the forecast). Shown are the mean sea level pressure (mb), θ_e (K) at approximately 12-km altitude, and vertical cross sections of the vertical velocity (m s^{-1}) with θ_e (K) contours superimposed, and wind speed (m s^{-1}). The minimum sea level pressure (Fig. 13a) is approximately 960 mb (vs 943 mb, observed).

The simulated heating ($\theta_e - \theta_e$ (env)) value at the center of the hurricane eye is approximately 14 K (369–

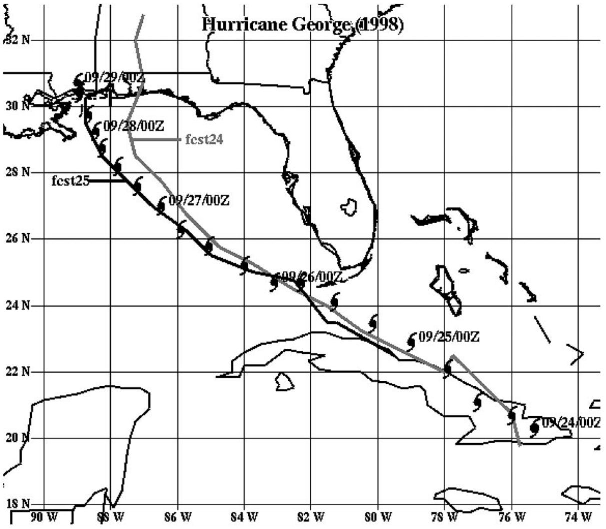

FIG. 14. OMEGA 4-day forecast storm tracks for Hurricane Georges. The gray and black track forecasts were initialized at 0000 UTC on 24 and 25 Sep, respectively.

355 K) at a height of about 12-km altitude and about 30 K (368–338 K) at a height of about 2-km altitude (Fig. 13c), which agrees well with the simulated values in some intense hurricanes (e.g., Hurricane Andrew; Liu et al. 1997). Note that the simulated structure of the hurricane's central core, as illustrated by the vertical cross section of θ_e fields (Fig. 13c), indicates the presence of a net subsiding motion of extremely dry and warm air (about 10–12 K warmer than the surrounding) from above, and a large increase in θ_e in the lower atmosphere due to the upward transfer of sensible and latent heat fluxes from the underlying warm ocean. An estimate of the hurricane intensity can be made on the basis of an empirical relationship developed by Malkus and Riel (1960)

$$\mathrm{P}_{\min} = 1000.0 - 2.5 \times (\theta_{e,\max} - 350.0),$$

which shows that the simulated $\theta_{e,\max}$ of approximately 368 K at 2-km elevation can produce a minimum central pressure of about 955 mb, which is consistent with the actual simulated central pressure of 960 mb.

In the eyewall region, the microphysical heating resulted in vertical velocity in excess of 1.5 m s^{-1} (Fig. 13c), and the horizontal wind speed is 31–62 m s^{-1} (60–100 kt; Fig. 13d). The simulated structure of the hurricane is consistent with those revealed by aircraft observations of other hurricanes (Gray and Shea 1973; Hawkins and Imbembo 1976; Anthes 1982; Jorgensen 1984; Willoughby 1998). Overall, the OMEGA model simulated the internal structure of the storm reasonably well. It remains to be seen if a higher resolution and a bogussed vortex at initialization time would be able to produce pressures more consistent with the observations. This will be the focus of future work.

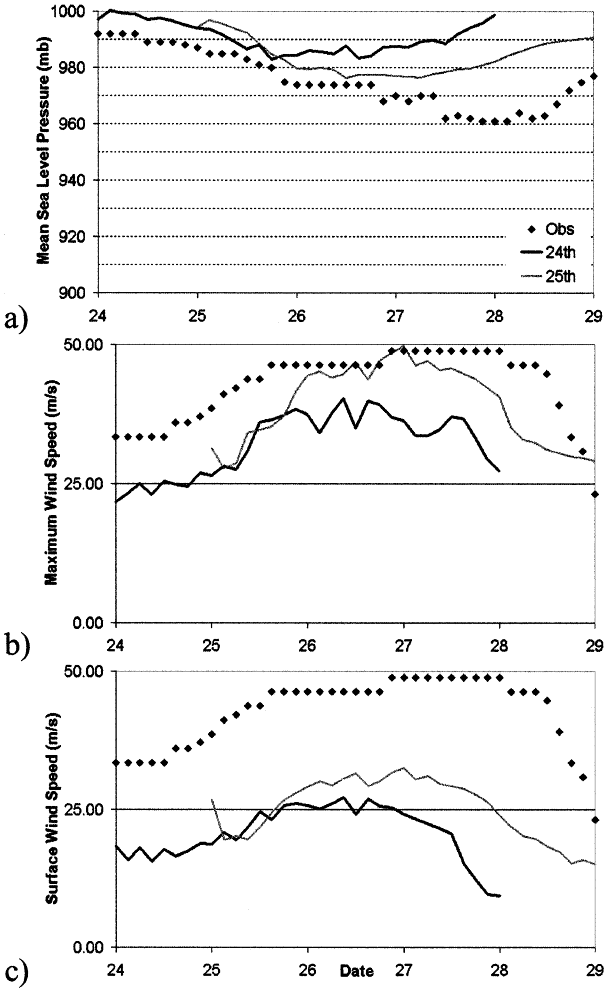

FIG. 15. Comparison of the OMEGA forecast (a) central pressure, (b) maximum wind, and (c) surface wind with observations.

5. OMEGA simulations of Hurricane Georges

As a further test of dynamic adaptation, a simulation of an additional historic storm was conducted. Hurricane Georges (1998) threatened the city of New Orleans in September 1998. More than 1.5 million people fled New Orleans and the surrounding area in light of forecasts of a 10–12-ft storm surge and up to 20 in. of rain (*New Orleans Advocate*, 27 September 1998). New Orleans has an orderly evacuation time exceeding 72 h and hence is heavily affected by an emergency of this type. For this reason, Hurricane Georges was a particularly good candidate to demonstrate the capability of dynamic adaptation and the ability of OMEGA to forecast beyond 72 h.

Two simulations were performed—one initialized at 0000 UTC 24 September (referred to as DYN24) and the other initialized at 0000 UTC 25 September (referred to as DYN25). Both simulations were initialized using NOGAPS global analysis and using the NOGAPS forecast fields for the lateral boundary conditions. These

TABLE 2. Summary of track error (km) as a function of forecast hour for all 20 OMEGA forecasts. The grayscale of the cells indicates the intensity of the storm at that time ranging from category 1 (lightest) to category 4 (darkest).

Forecast hour:	0	12	24	36	48	60	72	84	96
Georges (1998)									
DYN24	123	70	43	26	72	141	184	300	385
DYN25	39	67	72	92	152	108	93	78	99
Mean error	81	69	57	59	112	124	138	189	242
Floyd (1999)									
LRES12	49	60	43	23	76	62	52	28	83
LRES13	26	28	98	140	170	242	366	648	
LRES14	19	43	61	36	64	162	188		
HRES14	19	43	31	9	35	128	237		
HSST14	19	31	30	20	8	97	244		
DYN14	19	91	35	50	40	144	256		
Mean error	25	49	50	46	65	139	224	338	83
Beryl (2000)									
LRES14	48	101	94	192					
Mean error	48	101	94	192					
Chris (2000)									
LRES18	68	132	77	93					
LRES19		188							
Mean error	68	160	77	93					
Debby (2000)									
LRES21	193	89	144	411	439	429	305		
LRES22	56	213	269	334	317	160			
Mean error	124	151	206	372	378	294	305		
Florence (2000)									
LRES11	99	119	77	84	201	256	533		
LRES12	35	83	148	62	105	74	448		
LRES13	32	152	160	121	244	288	665		
Mean error	55	118	128	89	183	206	549		
Helene (2000)									
LRES20	54	115	191	201	114	70			
LRES21	53	115	110	159					
Mean error	54	115	150	180	114	70			
Xangsane (2000)									
HRES30	37	70	57	79	68	122			
HRES31	80	34	187	150					
Mean error	59	53	122	115	68				
Average error	56	92	101	120	140	165	298	264	189

forecasts were run using the same dynamic grid adaptation configuration as for Hurricane Floyd, including the elevated SST. In these simulations, however, the forecast period was extended to 96 h. Table 1 provides the configuration of these simulations and Fig. 14 shows the tracks for the two simulations.

The NOGAPS analysis produced an initial storm location error of roughly 80 km on the 24th and 60 km on the 25th. The average track error for the simulation initialized on the 24th was 55 km for the first day, 40 km for the second day, 120 km on the third day, and 280 km on the fourth day. For the simulation initialized on the 25th, the average track errors were roughly 60, 100, 115, and 75 km for the first through fourth day, respectively. These track errors indicate a considerable degree of skill of the model in track forecasts out to 72 h and some skill out to 96 h. The analysis of the central pressure and the maximum and surface winds (Fig. 15) indicated that the OMEGA model also forecast the intensity evolution reasonably well. It forecasts well the significant intensification of the storm in the first three days, though again not as strong as observed.

TABLE 3. OMEGA, GFDL, and CLIPER track error (km) for the nine selected storms.

Storm date/time		Forecast period (h) 0			12			24		
		OMEGA	GFDL	CLIPER	OMEGA	GFDL	CLIPER	OMEGA	GFDL	CLIPER
Georges:	DYN24		46	46	72	30	15	46	65	69
	DYN25		9	9	63	30	52	72	44	137
Floyd:	LRES12		15	15	59	11	15	41	30	83
	LRES13		11	11	30	11	22	100	43	83
	LRES14		15	15	39	15	56	57	78	176
Debby:	LRES21		15	15	93	54	159	144	161	259
	LRES22		44	44	211	98	78	269	115	89
Florence:	LRES12		20	20	83	30	30	148	24	48
	LRES13		24	24	150	56	39	156	115	130

6. Operational forecasts in 2000

The 2000 hurricane season was active, but many storms came and went in a very short period of time. During this season, we tried to run as many storms as possible operationally. In all, six storms were forecast using OMEGA: Tropical Storms Beryl and Chris, Hurricanes Debby and Florence, Tropical Storm Helene, and Typhoon Xangsane. Most of these simulations were run on a Beowulf cluster using 16 Pentium II processors (400 MHz). All of these operational runs used a static adaptive grid but because our goal was to explore the operational utility of the model, the grid was changed from storm to storm, and even sometimes between forecast cycles.

The Atlantic storms used grids with a horizontal resolution that ranged from 40 to 120 km; Typhoon Xangsane was forecast using a grid with resolution ranging from 25 to 120 km. At the beginning of the season (Beryl, Chris, and Debby), we used the NOGAPS analysis and forecast for initial and boundary conditions.

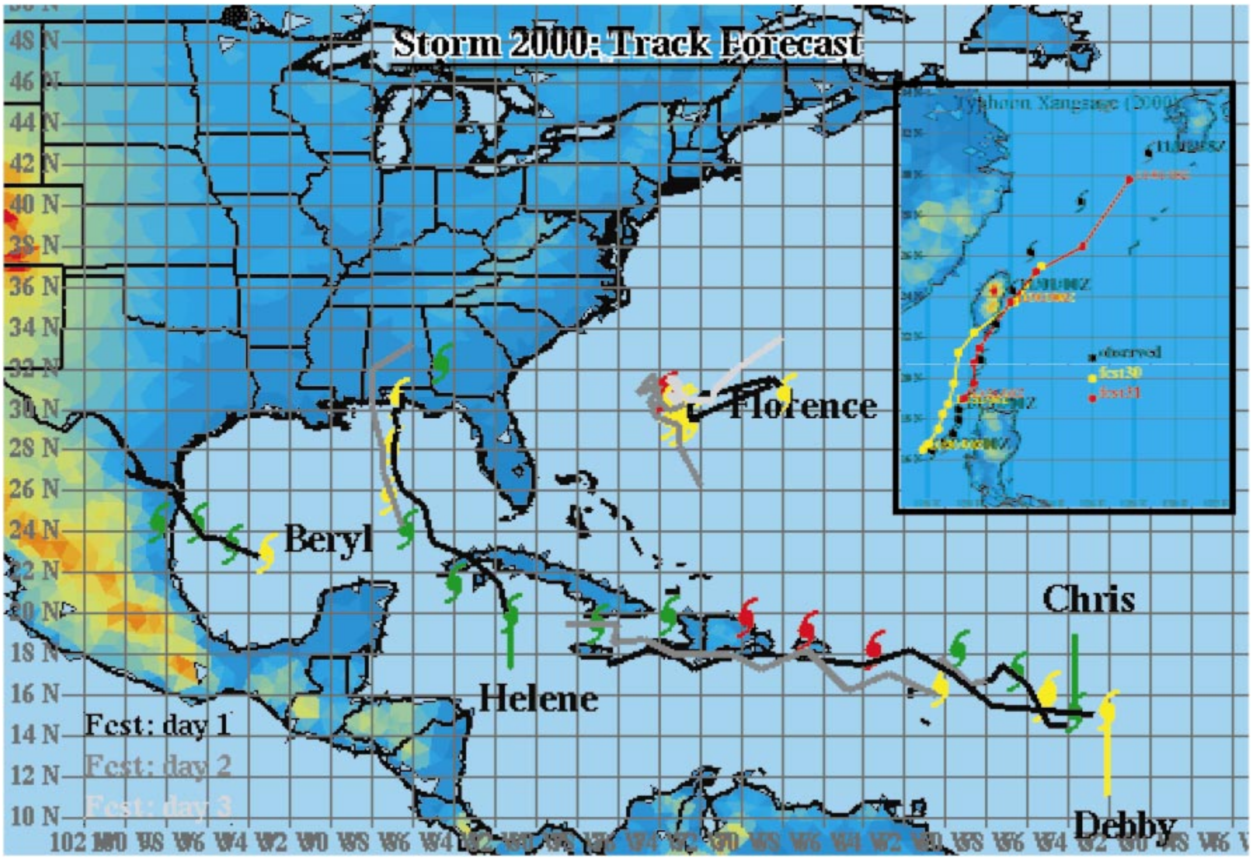

FIG. 16. OMEGA forecasts of the 2000 Atlantic storms and (inset) Typhoon Xangsane. The obs storm locations are color-coded by intensity (Tropical Depression: green, Tropical Storm: yellow, Hurricane: red).

TABLE 3. (*Extended*)

Forecast period (h)								
36			48			72		
OMEGA	GFDL	CLIPER	OMEGA	GFDL	CLIPER	OMEGA	GFDL	CLIPER
24	87	156	72	80	254	181	78	474
91	44	250	150	87	354	89	254	611
19	39	196	74	69	343	50	93	556
135	91	141	167	120	163	363	150	352
33	165	322	65	269	535	183	593	1352
415	167	359	435	204	461	307	306	798
332	91	52	313	94	193			
57	20	48	100	19	157	448	232	480
117	213	254	239	361	380	661	467	657

Later in the season (Florence, Helene, and Xangsane), we substituted the Medium-Range Forecast analysis and forecast for the NOGAPS data stream. Available rawinsonde and surface observations, but not dropsonde data, were included in the optimum interpolation analysis.

Tracker was used to identify the storm location in all cases. Figure 16 shows the OMEGA forecast tracks for the Atlantic storms with an inset showing the forecast tracks for Typhoon Xangsane.

7. Analysis of OMEGA track error

The mean track error for each of the eight storms documented in this paper (George, Floyd, Beryl, Chris, Debby, Florence, and Xangsane) was calculated individually, and then averaged to provide an overall performance metric for the OMEGA system (Table 2).

The average track error of the entire suite of eight storms is 56, 101, 140, 298, and 189 km for the analysis and the 24-, 48-, 72-, and 96-h forecasts, respectively. Given the small sample set, these numbers must be considered in context. For example, only three forecasts (two for Georges and one for Floyd) went out to 96 h, and four storms (Beryl, Chris, Helene, and Xangsane) did not remain organized long enough to forecast for 72 h. Nevertheless, the 24-, 48-, and 72-h errors compare favorably with the 1998 NHC average errors (McAdie and Lawrence 2000) of 156, 268, and 374 km, respectively.

Looking at the two historic cases (Georges and Floyd) in detail, it appears that OMEGA has performed quite well when compared with the NHC suite of models for these storms. The OMEGA 24-, 48-, and 72-h track errors for Hurricane Georges of 57, 112, and 138 km are roughly 25% less than the NHC official error for that storm (Guiney 1999) of 91, 161, and 217 km, respectively. Similarly, the OMEGA track errors for Hurricane Floyd of 50, 65, and 224 km compare favorably with the NHC official error (Pasch et al. 1999) of 98, 135, and 193 km.

Examining the operational forecasts, there were too few forecasts associated with Tropical Storms Beryl, Chris, or Helene for the NHC to perform any meaningful forecast evaluations. Hurricane Debby, on the other hand, had an NHC official forecast error (Pasch 2000) of 139, 157, and 244 km, which was considerably better than the OMEGA forecast error of 206, 378, and 305 km. The OMEGA forecast in this case had the storm divert to the south when it hit Hispañola, rather than to the north as observed. The OMEGA forecast for Hurricane Florence had mean track errors of 128, 183, and 549 km at 24, 48, and 72 h; the NHC official track errors for this storm were 144, 263, and 311 km, respectively (Franklin 2000). This storm vacillated between a tropical storm and a minimal hurricane during the period of our forecasts.

Nine of the OMEGA/Tracker forecasts (listed in Table 3) were independently verified at the NOAA Tropical Prediction Center (M. Lawrence 2001, personal communication). Only cases where the maximum 1-min sur-

TABLE 4. Average track error (km) for OMEGA, GFDL, and CLIPER for the nine cases in Table 3.

	Forecast time (h)					
	0	12	24	36	48	72
OMEGA	61*	89	115	136	179	285
GFDL	22	37	75	102	145	271
CLIPER	22	52	119	198	315	660

* Based on the SAIC analysis.

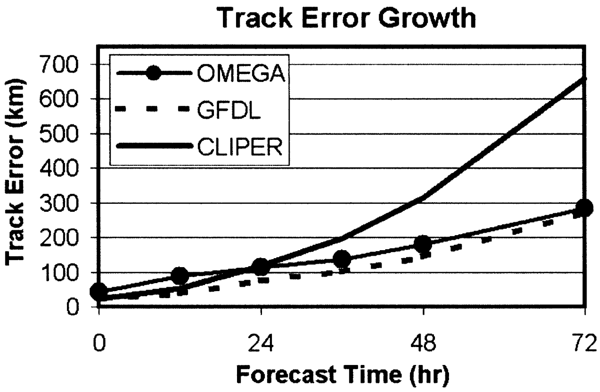

FIG. 17. Average track error (km) for the nine cases in Table 3.

face wind speed was higher than 17 m s^{-1} were verified (Hurricanes Georges, Floyd, Debby, and Florence). The OMEGA track errors were then compared with a homogeneous set of errors from the operational forecasts of the NOAA Geophysical Fluid Dynamics Laboratory model (Bender et al. 1998) and the statistical Climatology and Persistence (CLIPER) model (Neumann 1972).

The results of the independent assessment are presented in Table 3 and summarized in Table 4 and Fig. 17. Note that the track errors presented in Table 2 and the NHC track errors in Table 3 are slightly different since the NHC standard position location format is only accurate to 0.1° which led to a maximum potential position error of roughly 5 km. A significant difference exists in the initial location error. This is because the OMEGA forecast analysis relies basically on the NOGAPS/MRF global fields, while the GFDL and CLIPER models (along with most of the rest of the suite of NHC models) use a prescribed initial storm location, intensity, and structure. This initial error may be partly responsible for the early time (0–24 h) track error in the OMEGA forecasts. However, it is interesting that the 48- and 72-h OMEGA forecasts are comparable to the GFDL model forecast in spite of this initial error.

8. Summary and conclusions

The Operational Multiscale Environmental model with Grid Adaptivity (OMEGA) represents a significant departure from the traditional methods used in numerical weather prediction and real-time hazard prediction. The advanced numerical and adaptive grid generation methods embodied in OMEGA have now been applied to hurricane simulation. OMEGA was used for 20 forecasts encompassing eight storms. Overall, OMEGA and the automated tracker routine produced storm tracks that were more than 20% better than the 1998 NHC average, indicating significant skill of the model out to 72 h. The OMEGA results, however, were not as good as the GFDL model for those cases in which a direct comparison was made. This finding is tempered by the fact that the OMEGA initialization did not include any modification to the global analysis fields other than the inclusion of the rawinsonde observations in the reanalysis on the OMEGA grid.

Six sensitivity simulations of Hurricane Floyd, including one with a dynamically adaptive grid, were performed. All six simulations reproduced reasonably well the observed track, including the recurvature off the east coast of Florida, and the landfall near Cape Fear. The model simulated the larger-scale environment in which Hurricane Floyd was embedded reasonably well. In addition, comparison of the total precipitation valid for 14–16 September over the state of North Carolina, where the hurricane made a landfall, indicated good agreement between observations and predictions.

High resolution in the region of hurricane was important in generating better-organized cloud and flow fields and a well-defined eye with a central pressure lower than its environment by some 50 mb, which was still some 25 mb higher than the observations. Another strong sensitivity was demonstrated with the elevation of the sea surface temperature by 1 K. This resulted in the deepening of an initially weak vortex with a central pressure of 966 mb (vs 924 mb observed) obtained from the NOGAPS analysis on 14 September 1999 into a category 4 hurricane in about 12 h and, consequently, producing wind intensities closer to the observations. Finally, dynamically adapting to the evolving tropical storm produced similar results to the high-resolution simulations at a considerable savings in computational resources.

The OMEGA model is undergoing continual development. We believe that the hurricane intensity and track errors will be reduced still further through our ongoing efforts including: 1) an improved initialization scheme for OMEGA model using an analytic vortex specification with the storm center location determined using satellite imagery, 2) improved physical models including the air–surface flux and cumulus parameterization, 3) coupling of an ocean model with OMEGA to better simulate the two-way interaction between ocean and the core of the hurricane system, and 4) increased parallelization in order to increase the number of processors that can be utilized and hence increasing the resolution possible in an operational situation.

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