Effectiveness of Adaptive Observations in Improving Numerical Weather Forecasting

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ABSTRACT

Over the past 40 years there have been significant improvements in weather forecasting. These improvements are primarily due to (1) improved model physics and increased numerical grid resolution made possible by ever-increasing computational power, and (2) improved model initialization made possible by the use of satellite-derived remotely sensed data. In spite of these improvements, however, we are still not able to consistently and accurately forecast some of the most complex nonlinear diabatic mesoscale phenomena, such as propagating tropical mesoscale convective systems/cloud clusters, tropical storms, and intense extratropical storms. These phenomena develop over very fine spatial scales of motion and temporal periods and are dependent on convection for their existence. Poor observations of convection, boundary layer dynamics, and the larger scale pre-convective environment are often the cause of these substandard simulations and thus require improved observational data density and numerical forecast grid resolution.

This paper performs a set of Observing System Simulation Experiments (OSSE). The objective of the OSSE experiments is to demonstrate that an adaptive (targeted) observational strategy can improve forecast accuracy over existing more conventional observational strategies in terms of enhancing the initial conditions and subsequent accuracy of the simulations of a numerical weather prediction model. For the proof of this concept, hurricane Floyd (1999) is chosen as a test case. The set of experiments starts from a baseline high-resolution forecast of hurricane Floyd using the Operational Multiscale Environment model with Grid Adaptivity (OMEGA). This baseline run serves as the truth set for the OSSE under a "perfect model" assumption. From the baseline run, atmospheric vertical profiles were extracted to simulate pseudo-observations using different adaptive strategies. These data extracts were used to create new coarse-resolution forecasts of hurricane Floyd that were then compared against the both baseline and real atmospheric observations. In general, the experiments show that additional adaptive observations in sensitive areas can help to reduce hurricane forecast errors significantly from a Numerical Weather Prediction (NWP) model.

1. Introduction

Numerical forecasts of chaotic systems like the atmosphere are limited by the use of imperfect models and imperfect initial conditions. Lorenz (1963, 1969) pointed out that any minor discrepancies, between either the natural system and its model or the actual and the analyzed state of the system at the initial time of a forecast, will lead to a loss of predictability within a finite time period. The size of these discrepancies will, in general, determine the time period for which useful forecasts can be made. Improving numerical models and the analysis of the atmosphere used as initial conditions are hence the two basic avenues through which progress is made in Numerical Weather Prediction (NWP).

Over the last two decades, with the advancements in supercomputers and improvements in the formulation of atmospheric physics and dynamics, NWP models have been continuously improved. For example, for medium range weather prediction, model deficiencies have become less important compared to the initial uncertainties. In fact, analysis errors are now being considered as the main source of the forecast errors for the NWP models (Lorenz, 1990). As for the atmospheric analyses, their quality depends on two main factors. First, the quality of the analysis is limited by the technique through which the analysis is derived. Both the NWP model used to generate first guess fields for the analysis, and the statistical estimation method that combines information from the first guess and observations are built using approximations because of limits in our knowledge and computational capabilities. The second dominant factor regarding the quality of the analysis is data coverage. Observations providing better geographical coverage, higher quality and/or more comprehensive data should lead to improved atmospheric initial conditions and in turn improved NWP forecast guidance, provided that these observations can be assimilated rapidly enough to be useful.

The Earth's atmosphere comprises roughly 10^{10} km^3 ($4 \times \pi \times [6400 \text{ km}]^2 \times 20$ km). Detailed surface observations often show features that are roughly one kilometer in scale size, hence there are over 10^{10} degrees of freedom in the atmosphere. The current *in-situ* atmospheric measurement system is woefully inadequate to determine the current state of the atmosphere and hence our ability to forecast is limited by this constraint. Every hour, fewer than 8,000 WMO surface sites collect surface observations; assuming that these provide information valid over 1 km^2 and valid up to 1 km, the total coverage is less than 2×10^{-5} of the surface of the earth and less than 10^{-6} of the volume of the atmosphere. Every 12 hours fewer than 1,000 WMO rawinsonde sites release balloons; assuming that these provide information valid over a volume of roughly 10 km $\times$ 10 km $\times$ 20 km, we see that these balloons sample less than 2×10^{-7} of the volume of the atmosphere.

The total data volume taken by the global conventional observation network is roughly 25 MB per day. These observations at regular time intervals and at fixed geographical locations have been able to observe the large-scale features of the atmospheric system and have served the interests of climatologists, synoptic forecasters, and early NWP forecast systems. However, there is still need for additional resolution to resolve *critical* features in the atmosphere (such as the details of a frontal boundary, convective structure of the hurricanes, *etc*.). The next generation of satellite-based atmospheric observations (*e.g.*, ATOVS, COSMIC, GIFTS) promise to provide an expansive increase in our observational coverage. The spatial and temporal resolution of the retrieved atmospheric properties will increase and the total coverage of the Earth will increase. The net result on the data flow is an increase of several orders of magnitude.

While these datasets will always have value for research in weather and climate, their value in operational weather forecasting is dependent on developing ingest, analysis, and assimilation systems that can utilize the data in a timely fashion. In recent years, there has been a trend towards 3-D and 4-D variational assimilation systems in order to make the maximal use of a limited amount of data; in the future, we will find ourselves at sea in an ocean of data searching for landmarks. This paradigm shift requires a similar shift in our utilization of data. Instead of using all data in an egalitarian and brute-force method, we need to consider adding some form of intelligence to our data processing system to *identify, extract*, and *utilize* just the necessary *critical* information for a given forecast cycle.

In recent years, there has been growing interest in enhancing the efficiency and accuracy of both NWP models and observational systems by employing adaptive strategies. From a numerical modeling point of view, since higher resolution in three dimensions requires a consistent increase in temporal resolution, it is very expensive and computationally demanding to significantly improve horizontal resolution in numerical models. The cost of improved resolution can be as much as N^3, where N is the effective increase in resolution. Since high resolution is often important only over brief periods of time and relatively small regions (*e.g.*, convection is short-lived and small scale), much of the extra resolution is wasted on large-scale circulation systems.

Bacon *et al.* (2000) has demonstrated the feasibility of employing a dynamically adaptive grid numerical model (Operational Multiscale Environment model with Grid Adaptivity, OMEGA). The OMEGA model focused the model's horizontal grid resolution on regions of complex mesoscale phenomena (*cf.*, Figure 1) to improve the overall quality and efficiency of simulations from which forecasts can be derived. In OMEGA, efficiency is not compromised because the model grid contracts in scale or adapts to the region where the resolution was unambiguously required. This new concept in atmospheric modeling has clearly shown that improvements in quality and efficiency are possible from the same modeling system, as the increased 4-dimensional resolution is highly focused in space and time.

Similarly, there has been also a growing interest in adaptive observational systems. Presently, rawinsonde balloons, space-based (*e.g.*, satellites), and ground-based (*e.g.*, doppler radars and wind profilers) sensors provide data to initialize numerical models. These observational tools provide operational data sets that are fixed in space and time and provide a predictable discrete data set *independent of the existing weather phenomenology*. In order to overcome the perceived inadequacies of the existing observation network, Joly *et al.* (1997), Emanuel and Langland (1998), Albertson and Franklin (1999), Zhang and Krishnamurti (2000) have recently reported on the use of adaptive observations, which are non-uniformly distributed as *a function of the observed distribution of atmospheric mesoscale phenomenology*. As the atmosphere contracts the scale of circulation systems, a disproportionate number of the observations are focused on the fine scale phenomena. This concept has actually been tested in the recent FASTEX field study (*e.g.*, Emmanuel and Langland, 1998) over the North Atlantic Ocean.

In this paper, the feasibility of employing the adaptive (targeted) observation concept in NWP models will be discussed using the OMEGA model. A set of Observing System Simulation Experiments (OSSE) was performed. The objective of the OSSE experiments was to demonstrate that an adaptive observational strategy can improve forecast accuracy over existing more conventional observational strategies in terms of enhancing the initial conditions and subsequent accuracy of the simulations of a numerical weather prediction model. To prove this concept, hurricane Floyd (1999) was chosen as a test case. The set of experiments starts from a baseline high-resolution forecast of hurricane Floyd. This baseline run serves as the truth set for the OSSE under a "perfect model" assumption. From the baseline run, atmospheric vertical profiles were extracted to simulate pseudo-observations using different adaptive strategies. These data extracts were used to create new coarse-resolution forecasts of hurricane Floyd that were then compared against both the baseline and real atmospheric observations.

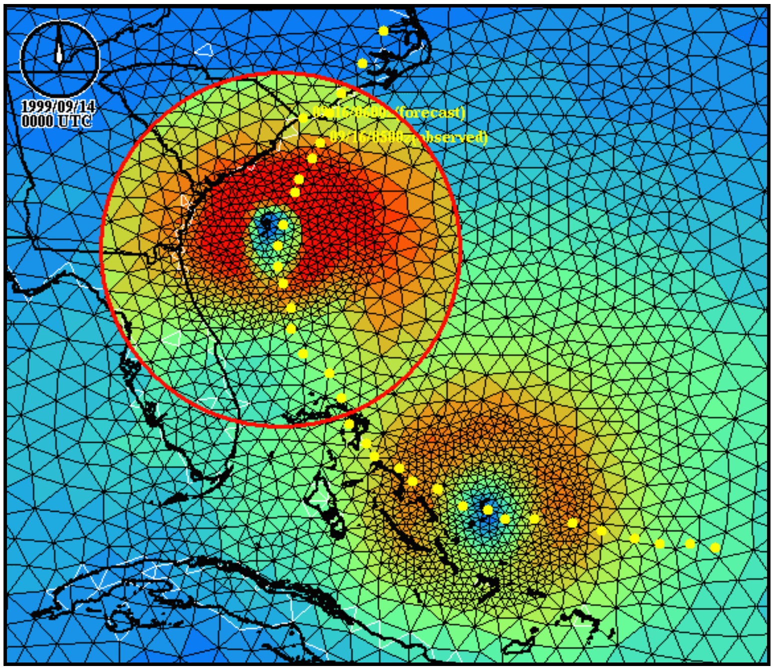

Figure 1. Dynamic grid adaptation puts high resolution only where needed, leading to the accurate and computationally efficient prediction of high wind speed (color) and track of hurricane Floyd. The initial conditions are shown with an inset showing the high-resolution area at 48 hours into the forecast. The yellow dots show the observed storm track.

The results of this study demonstrated that it is possible to achieve a considerable error reduction over areas/cases selected based on the largest potential weather related threat to society with the use of about 25 targeted observations over the sensitive data sparse areas. These results raised the possibility that the judicial use of the adaptive observation approach, in addition to the regular and opportunity driven part of the observational network, may bring substantial further benefits to NWP models.

2. The concept of adaptive observations

The regular and opportunity driven observations constitute the backbone of the global observing network and they are expected to do so in the foreseeable future. Satellite derived atmospheric properties, however, will soon have the accuracy, coverage, and resolution to dominate our understanding of the dynamics of the atmosphere. The utilization of this data, however, will require either massive increases in our data processing capability, or a change in our approach. The selective extraction of adaptive (targeted) observations is one method to make maximal utilization of the satellite derived information and is the focus of this study. The adaptive observational strategy is defined here as an approach where the location, time, and/or observed variable is actively chosen in order to optimize the numerical weather prediction quality. Optimization is interpreted here in the broadest sense, including measures like the global performance of short-range forecasts in general. Targeted observations represent a subcategory under adaptive observations where data collection is optimized to improve a particular forecast aspect, like a three day hurricane track forecast.

With the continuous improvements in the NWP models over the last two decades, model deficiencies have become less important compared to the initial uncertainties (Lorenz, 1990). The problem of initial uncertainties was addressed by Lorenz (1963, 1965). In his pioneering works, Lorenz pointed out that in a nonlinear dynamical system, slightly different initial states may lead to considerably different final solutions. The atmosphere is a prime example of this kind of chaotic dynamical system. In a NWP model, the initial uncertainty is mainly associated with the low resolution of the observation network. These initial analysis errors are unavoidable and will grow during the coarse of model integration through a self-amplified mechanism. Model forecast skill will, therefore, decrease with increasing forecast time, even if the NWP model is perfect.

From an observational point of view, initial uncertainty can be reduced by increasing the resolution of the existing global observational network. However, the timely ingest, analysis, and assimilation of data from a high-resolution observational network may be too expensive and not practically possible. It may be more practical, to use intensive observations only over some particular areas for specific weather systems; this is the objective of adaptive observation. In other words, the prediction will be more sensitive over some areas as compared to others, or the inaccuracy of analysis over some locations will affect the forecast errors more than in other locations. Thereby, the concept of adaptive (targeted) observation can improve forecast skill by reducing the uncertainties in the initial stages.

Not all situations will benefit from adaptive observations; stable dynamical systems are generally easily observed and forecasted. In a different vein, events with potentially large societal impact should be prime candidates, given a substantial uncertainty in these forecasts. The identification of a feature for which forecasts are to be improved is only the first step in the process of targeted observations. Next, the location, time, and type of observations to be taken need to be identified. In practice, given information on the case selected, a future adaptive observation time is typically chosen based on practical considerations (*e.g.*, deployment limitations).

The type of observation is also determined by technical factors. It follows that the primary concern of targeting is the identification of a region, and within it a pattern that can optimize the effect of targeted observations with respect to the selected forecast feature. The final step in targeted observations is the assimilation of the targeted data, along with those available from the regular and opportunity driven part of the observing network. The impact of the data is usually evaluated by running a control analysis/forecast cycle in parallel that differs from the operational cycle only in that it excludes all targeted data. The difference between the operational (including targeted data) and parallel (control) analysis and forecast fields thus reveals the effect of the targeted data.

Although the concept of adaptive observations is new, it has a relatively long history. For example, the hurricane reconnaissance program, which was initially tasked to collect critical information on the location and intensity of hurricanes, started in 1947. In 1982, NOAA's Hurricane Research Division began research flights in the data-sparse regions around tropical cyclones in order to improve numerical model forecasts of their tracks. Burpee *et al*. (1996) found that such flights allowed for an improvement in hurricane track forecasts of approximately 25%, and as a result, NOAA procured the Gulfstream-IV (G-lV) aircraft for operational synoptic surveillance flights for hurricanes threatening landfall in the United States and its territories east of the dateline.

Hurricane related adaptive observational work has been, however, limited to the tropics and subtropical areas and until recently had been based on subjective techniques. Objective targeted observational techniques were first developed and considered for extratropical use within the FASTEX field program (Joly *et al.*, 1997). Following a workshop (Snyder, 1996), various groups developed and applied targeted observational strategies that were later used in FASTEX and follow-up field programs (Buizza and Montani, 1999; Gelaro *et al*., 1999; Bergot *et al*., 1999; Szunyogh *et al*., 1999). This paper focuses on demonstrating the value of such a radical change in our data collection and analysis system design on NWP models.

3. The OMEGA modeling system

A complete description of OMEGA can be found in Bacon *et al.* (2000); however the basic features of the model are provided in Table 1. OMEGA is a fully non-hydrostatic, 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 (Kuo, 1965; Anthes, 1977) and Kain-Fritsch (Kain and Fritsch, 1990) schemes to parameterize cumulus effects, and an extensive bulk-water microphysics package derived from Lin *et al*. (1983). OMEGA models the shortwave absorption by water vapor and longwave emissivities of water vapor and carbon dioxide using the computationally efficient technique of Sasamori (1972). 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. OMEGA is based on a triangular prism computational mesh that is unstructured in the horizontal dimension and structured in the vertical. The rationale for this mesh is the physical reality that the atmosphere is highly variable horizontally, but always stratified vertically. 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 topography or 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 structured logical grid approach used in more traditional codes (Baum and Löhner, 1989).

Two types of grid adaptation options are available in OMEGA: static and dynamic adaptation. In static adaptation, the numerical grid resolves 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 dynamic adaptation, the grids are additionally allowed to adapt to regions that require high resolution during the course of a simulation, *e.g.*, frontal zones, hurricane circulation (*cf*., Figure 1), pollutant plumes, *etc*.

Table 1. An Overview of OMEGA

Governing equations	Fully non-hydrostatic
Dimensionality	3D
Grid structure	Unstructured triangular prisms
Grid adaptivity	Both static and dynamic grid adaptation
Coordinate system	Rotating Cartesian coordinates
Numeric	Finite volume
PBL	Treated separately as viscous sublayer, surface layer, and transition layer
Turbulence closure	1.5 order turbulent kinetic energy closure
Cumulus par.	Modified Kuo scheme and Kain-Fritsch scheme
Microphysics	Extensive bulk-water
Radiation	Shortwave absorption by water vapor and longwave emissivities of water vapor and carbon dioxide
Lower boundary	Based on Monin-Obukhov similarity theory
Upper boundary	Rigid, free-slip surface
Lateral boundaries	Radiative boundary condition, large scale nudging boundary condition
Initialization	Based on 4D data assimilation
Transport and diffusion	Embedded Eulerian and Lagrangian (Monte Carlo particle and probabilistic puff) aerosol dispersion algorithms

4. Case study – Hurricane Floyd of 1999

The United States is more vulnerable to tropical cyclones now than at any time in its history. Millions of people live and vacation along the coastline and are exposed to the threat of tropical cyclones including wind, rain, storm surge, and severe weather. During this century, improved forecasts and warnings, better communications, and increased public awareness have reduced the loss of life associated with tropical storms. However, despite large reductions in track forecast errors from dynamical models, operational hurricane forecast errors have not reached estimated predictability limits.

The gains made over the last 40 years in our understanding and forecasting of tropical storms have depended critically on the mix of observations. New strides in our abilities have always paralleled the development of new research tools, from instrumented aircraft, to radar, to satellite. Each improvement in tropical storm forecasting has been achieved by taking advantage of the available observations. The fact that a tropical storm spends the majority of it's life over the tropical ocean, where there is very little data available, has forced the community to pioneer adaptive observing strategies in order to provide critical observations of the storm's location and strength. To take full advantage of these new observations, techniques need to be developed to objectively analyze these observations, and initialize models aimed at improving prediction of hurricane track and intensity from global-scale and mesoscale dynamical models.

For example, hurricane Floyd was one of the deadliest natural disasters to strike the Atlantic coast of the United States. Its landfall resulted in the loss of 69 lives and a total 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 September 2, 1999. It organized into a tropical depression on September 7, 1999 about 1,000 miles east of the Lesser Antilles. The system further strengthened into a tropical storm early the next day when it was located about 850 miles east of the Lesser Antilles. On September 9, 1999, the storm intensified into a hurricane about 240 miles northeast of the northern Leeward Islands. 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 four hurricane on September 13, 1999.

During the period between 1200 UTC 14 September and 0000 UTC 15 September, hurricane Floyd is surrounded by convection within a deep cyclonic vortex circulation extending from the surface through the 300-mb level. This can be seen in the 0000 UTC 15 September NWS ETA 300-mb wind and height analyses and inferred from the satellite imagery depicted in Figure 2. It is during this time that the storm approaches the Bahamas Island chain and that it begins to show the first signs of weakening as it turns from its nearly due westerly to a northwesterly trajectory of motion. However, it is still an intense storm under a symmetric vortex and is surrounded by deep convection.

Shortly after this time, at 1200 UTC 15 September, as the storm turns northward along the eastern Florida coast and accelerates in its forward velocity, the upper vortex begins to erode on its western periphery. The storm weakens as it becomes less symmetric, and the convection in its southwestern quadrant begins to diminish. This occurs because the western quadrant of the upper vortex is stretched and destroyed by the approaching southeastern part of the polar jet entrance region located over the southeastern United States. The elongated flow, accompanying the southwesterly winds of the polar jet entrance region, acts to deform the 300-mb level vortex surrounding the hurricane inducing a new vertical wind shear profile on the western flank of the storm.

This stretching by the southwesterly flow of the larger polar jet stream entrance region results in an open 300-mb vortex structure which prevents the unidirectional vertical shear accompanying the storm from being maintained as it was at 0000 UTC 15 September. Such a transition from unidirectional to significant directional vertical wind shear disrupts the deep convective symmetry accompanying a tropical vortex circulation. Hence, the western flank of hurricane Floyd becomes deformed and exposed; it is therefore no longer surrounded by a deep symmetric vortex aloft. This stretching by the polar jet entrance region east of northern Florida disrupts the symmetric pattern of convection on the southwestern side of the storm thus resulting in a diminishment of the deep surface pressure fall due to latent heating which had sustained the storm all the way from Africa to the Bahamas prior to 0000 UTC 15 September.

Such a disruption of deep vortex structure is typically associated with the shift in storm trajectory to the north and its accelerated forward velocity in mid-latitudes thus requiring a fine scale representation in numerical weather prediction models, if it is to be accurately simulated. It should be emphasized that all discussion in this work pertains to simulations starting on or after September 13, 1999, when Floyd was a fully developed hurricane posing a threat to the southern and mid-Atlantic coastal regions of the United States.

Hurricane Floyd of 1999 will be studied in this paper as an example to test the proposed observation targeting strategy. One of the reasons for choosing hurricane Floyd case is that the

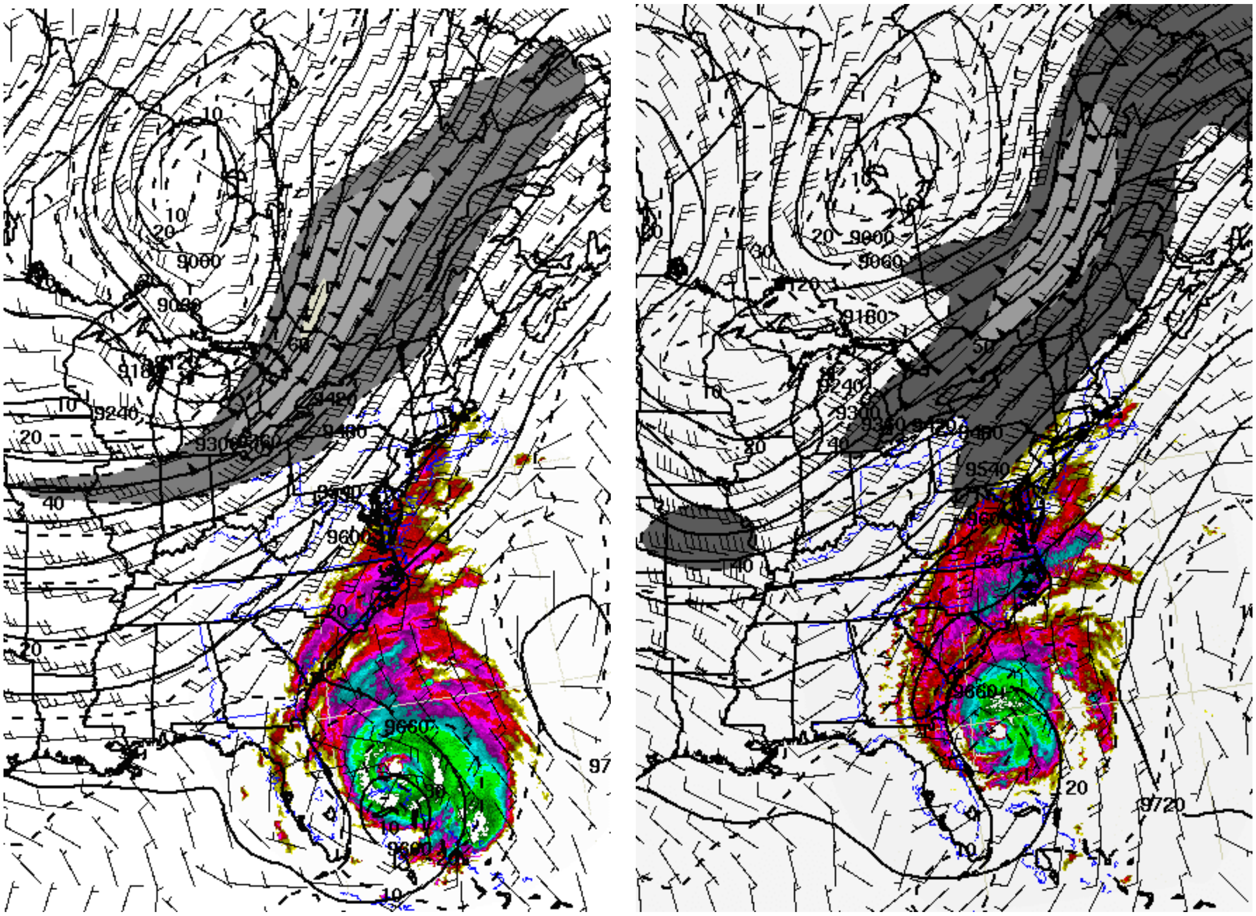

Figure 2. 300-mb wind and height ETA analysis roughly overlaid on the enhanced infrared image of hurricane Floyd at 0000 UTC (left) and 1200 UTC (right) on September 15, 1999.

OMEGA model had a very good track forecast as compared to the observed best track (*cf*. Figure 1). This allows us to make the necessary "perfect model" assumption. The other important reason is that it is well known that the hurricane movement is dictated by mid-level, large-scale steering wind. Dong and Neumann (1986) calculated correlations between storm motion and geostrophic steering flow at different levels. They found that the initial wind field at upper levels between 700-mb and 300-mb is important, especially for the hurricane track forecast. In the case of hurricane Floyd, as we discussed previously, a complex polar jet steering flow played an important role in the track of the storm (*cf.*, Figure 2). This feature allows us to examine the inaccuracy of analysis over the steering flow areas using adaptive observation strategy and its impact on the forecast track error.

5. Experimental Design

This study proposes a concept that can be used to make estimates of the potential forecast value of new adaptive data sources, so that the benefits of such new data sources can be assessed on a rational basis. The concept combines the OMEGA model with an adaptive approach to target observations over areas where the hurricane predictions are very sensitive to the initial analysis of the model. In order to demonstrate the feasibility of such a concept, we focus on a set of Observing System Simulation Experiments (OSSE) to show the potential for an adaptive observation strategy to improve forecast quality.

A brief description of the experiments is presented in Table 2. The OSSE starts from a baseline high-resolution (with an average 10 km horizontal grid resolution) OMEGA forecast of hurricane Floyd performed using the standard procedure for the initial analysis and generation of the lateral boundary conditions. Note that, at this point, it is necessary to make an assumption of a "perfect model" and that all of the forecast errors come solely from the uncertainty of the initial state. Under the perfect model assumption, this baseline run serves as the truth set for the OSSE. The second experiment is a coarse-resolution run (with an average 100 km horizontal grid resolution), which serves as a typical operational hurricane run. Note that the only difference between these two runs is the difference in the horizontal grid resolution. This second coarse-resolution run serves as the control set for the rest of the adaptive observation simulations.

From the baseline truth run, we extract vertical profiles (pseudo adaptive/targeted observations) to simulate observations using different adaptive strategies. Mainly, initial storm location and storm outflow jet location are chosen to be the sensitive areas that could have a significant impact on the storm track. These different data extracts are used in initial analysis of the coarse-resolution control run to create new OMEGA forecasts (adaptive runs). The storm track forecasts from these adaptive runs are then compared against the results from truth and control runs and the observations to determine the benefits of such new adaptive data sources.

5.1. High-Resolution Truth Simulation

The OMEGA model for the truth simulation was run for an 84 hour forecast period starting at 0000 UTC 13 September. The computational domain and the static grid configuration (the grid does not change during the integration) used in this simulation are shown in Figure 3. An average horizontal grid resolution of 10 km was used in the simulation with 54,162 horizontal grid cells. The OMEGA model used 35 vertical grid levels for the simulation, with a vertical resolution ranging from 15 m near the ground to 2 km at the top of the domain. The top of the simulation domain was set to 20 km.

The OMEGA model was initialized using the Navy Operational Global Atmospheric Prediction System (NOGAPS) gridded data. The environment outside the computational domain was also derived from the same gridded forecast data fields (not from NOGAPS analysis fields). Boundary conditions at 12 hr intervals were based on these large-scale gridded forecast fields, and linear interpolation was used to determine boundary values at intermediate times**.**

An important feature of the OMEGA model is its worldwide datasets. The OMEGA model has eight major worldwide databases for terrain elevation, land/water distribution, soil type, land

Table 2: A brief description of the Observing System Simulation Experiments (OSSE).

OSSE Runs	Initialization Time	Average Grid Res.	Number of Targeted Obs.	Location of Targeted Obs.
Truth Run	9/13, 00 Z	10 km		
Control Run	9/13, 12 Z	100 km		
Adaptive Run1	9/13, 12 Z	100 km	635	Initial storm
Adaptive Run2	9/13, 12 Z	100 km	100	Initial storm
Adaptive Run3	9/13, 12 Z	100 km	25	Initial storm
Adaptive Run4	9/13, 12 Z	100 km	11	Initial storm
Adaptive Run5	9/13, 12 Z	100 km	35	Storm Outflow Jet

use/land cover, climatological vegetation index, climatological sea surface temperature, climatological subsurface temperature, and climatological soil moisture. In this simulation, OMEGA used its 30 arc-seconds (1 km) resolution terrain elevation and land/water datasets. The other characteristics were obtained from different sources. For example, one-degree global soil type database (12 types), created from the GLOBAL Ecosystems Database (Webb *et al.*, 1992), were used in this simulation. Similarly, 19 land-cover categories from the Biosphere-Atmosphere Transfer Scheme (BATS) with a 30 arc-second (1 km) resolution were used for land use/land cover data. Finally, sea surface temperatures were obtained from the NOGAPS analysis.

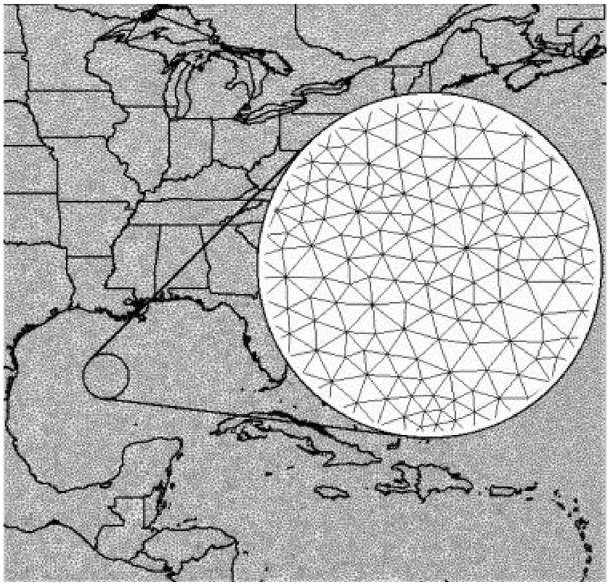

Figure 3. OMEGA domain and grid configuration for the high-resolution truth run. The inset shows a detail of the 5-15 km grid.

The OMEGA model forecasted track of hurricane Floyd track is compared against the reported storm track (black symbols) in Figure 4. Note that the reported storm location starts from 0000 UTC 14 September, while the forecasted hurricane track starts from 1200 UTC 13 September. This comparison shows that the model predicts the track of the hurricane Floyd extremely well compared with the observational track. This nearly perfect track forecast required an extraordinary amount of computation. The predicted center pressure of the simulated storm, however, was significantly higher (roughly 50 mb) than the observed central pressure. The main reason of this discrepancy is due to the model initialization from NOGAPS. The NOGAPS analysis did not accurately capture the storm intensity, leading the initial pressure in OMEGA to be high (by roughly 50 mb) at the initial time. This large initial error is the reason that we will only concentrate on the track of the storm for the purposes of this study.

5.2. Coarse-Resolution Control Simulation

The OMEGA model for this case was run for a 72 hour forecast period starting at 0000 UTC 14 September. The 12 hour difference in initialization time is caused by the need for OMEGA forecasted pseudo-soundings (adaptive/targeted observations) from the high-resolution truth run for the adaptive observation OSSEs. The computational domain and the static grid configuration used in the simulation are shown in Figure 5. An average horizontal grid resolution of 100 km was used in the simulation with 5,850 horizontal grid cells. The OMEGA model used 35 vertical grid levels for the simulation, with a vertical resolution ranging from 15 m near the ground to 2 km at the top of the domain. The top of the simulation domain was set to 20 km. The OMEGA model was again initialized using the NOGAPS gridded analysis. The environment outside the computational domains was also derived from the corresponding gridded forecast fields. Note that the only difference between the baseline truth and this control run is the difference in horizontal grid resolution and the time of initialization.

Figure 6 shows the predicted track as compared to the observed track of the storm. The results indicate that the coarse resolution track forecast shows a significant track location error. This is due to fact that the model now uses an average 100 km horizontal grid resolution. At this

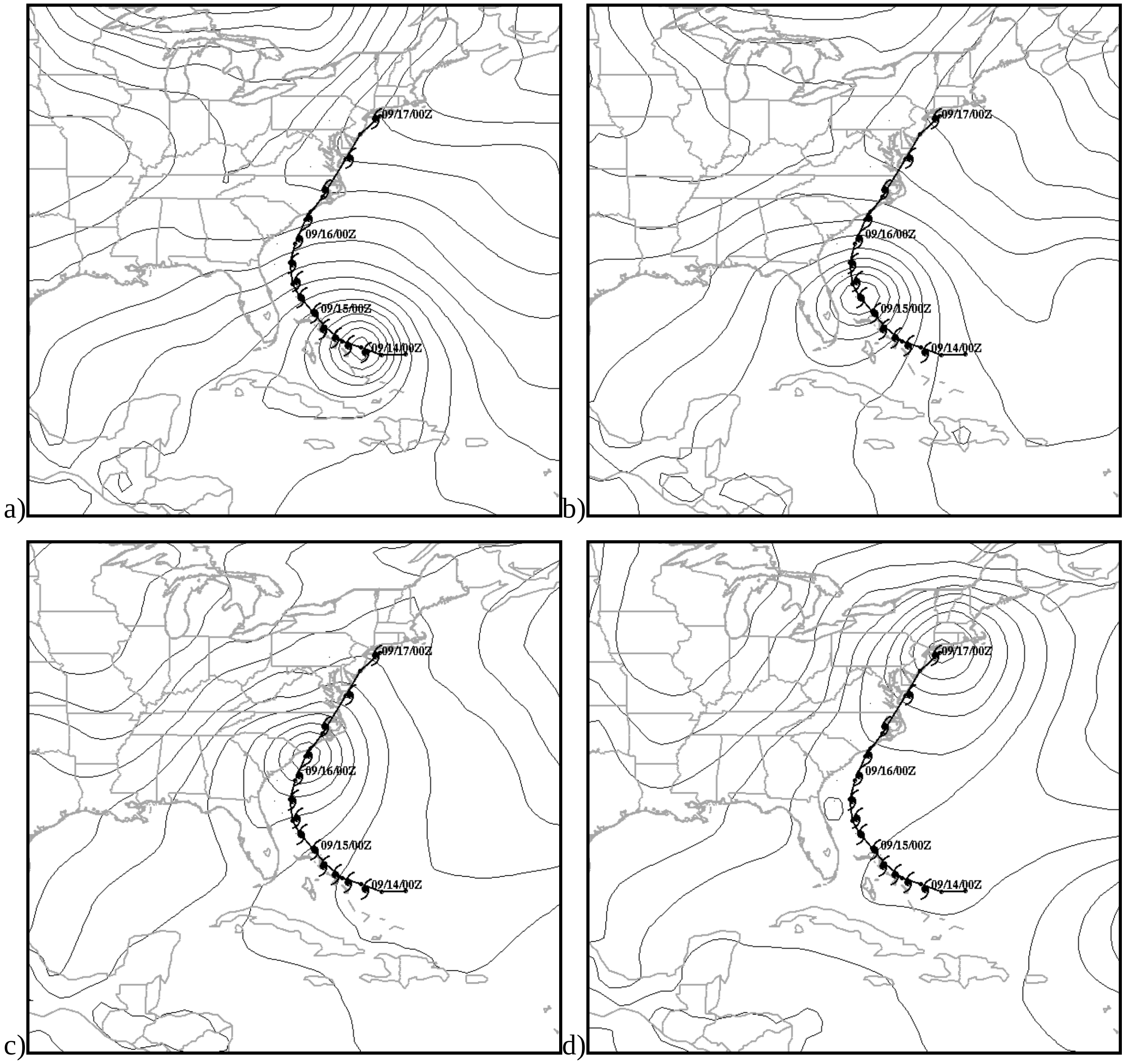

Figure 4. The OMEGA forecasted mean sea level pressure for hurricane Floyd at 12, 36, 60, and 84 hr after initialization. Also shown is the OMEGA forecasted track (solid black line) and the observed track (black hurricane symbols).

resolution, very fine spatial scales of motion and temporal periods and dependence on convection cannot be resolved accurately. Since the hurricane structure heavily depends on the convection, boundary layer dynamics, and the larger scale pre-convective environment, it requires improved observational data density to more accurately forecast the hurricanes.

Note that in general, a hurricane is an intense atmospheric vortex with a horizontal scale of over several hundred kilometers and a vertical scale of fifteen to twenty kilometers formed over warm oceans and driven by convective cells with horizontal scales of a few kilometers. The structure and evolution of the system are characterized by strong multi-scale interactions. Past early numerical studies, starting from those by Kasahara (1961); Kuo (1965), Yamasaki (1977), Kurihara (1973), Gray (1979) have all led to a better understanding of the structure and evolution of hurricanes. Yet, to date there is not a single operational model that has the capability of forecasting tracks of hurricanes reasonably well (Willoughby, 1999). Given accurate sea surface temperatures (SST), 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.

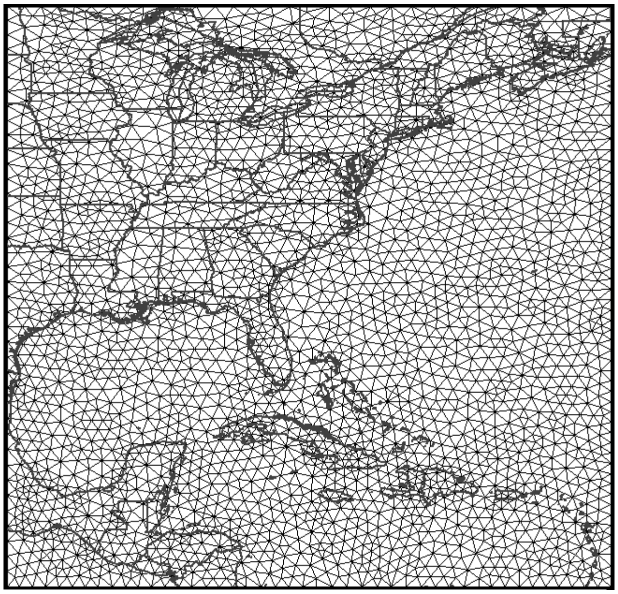

Figure 5. OMEGA domain and grid for the coarse (35-145 km) resolution control run.

However, to adequately resolve the fine structure of a hurricane, model resolution on the order of 10 km or less is required. In general, computational limitations make it impractical to treat the entire model with this fine resolution. In this study, we, therefore, assume that the coarse resolution run represents a more typical operational hurricane run and in that supplementary role serves as a control run for the adaptive runs. In the next section, we will examine the potential for an adaptive observation strategy to improve the hurricane Floyd track forecast accuracy.

6. Discussion of Results

Given the truth and control results, experiments were then performed that explored the benefit of different adaptive observation strategies. The first series of experiments explored the benefit of additional observations at initialization time over specific regions of interest. Accurate modeling of tropical cyclone motion requires both realistic numerical models and accurate representation of meteorological fields through the depth of the troposphere on a variety of scales. Adaptive (targeted) observations are atmospheric data that are obtained in certain areas that are believed to be critical for improvements to initial conditions used in numerical weather prediction models. For practical applications of an adaptive observation strategy, forecast improvement is equally important to placing the data impact at the right place, at the right time. Whether the forecast improves due to the targeted data depends primarily on the quality of the assimilation procedure.

It is a challenging task for the analysis to use isolated patches of targeted data to its full potential. In fact, since the assimilation schemes are statistical in nature, it is never guaranteed, no matter how good an analysis scheme is that good quality extra data would improve the forecasts in every single case. What we can expect from these sensitivity experiments is that, as the assimilation schemes get more advanced, a higher proportion of targeting cases would be associated with improved forecasts. There are not only numerous targeting strategies that one might consider testing, each with numerous conceivable variants. There are also many ways in which one might design and experiment to test a given variant of a given strategy. To keep our total effort within bounds, we consider the initial structure and location of the hurricane to be critical in terms of its accurate forecast.

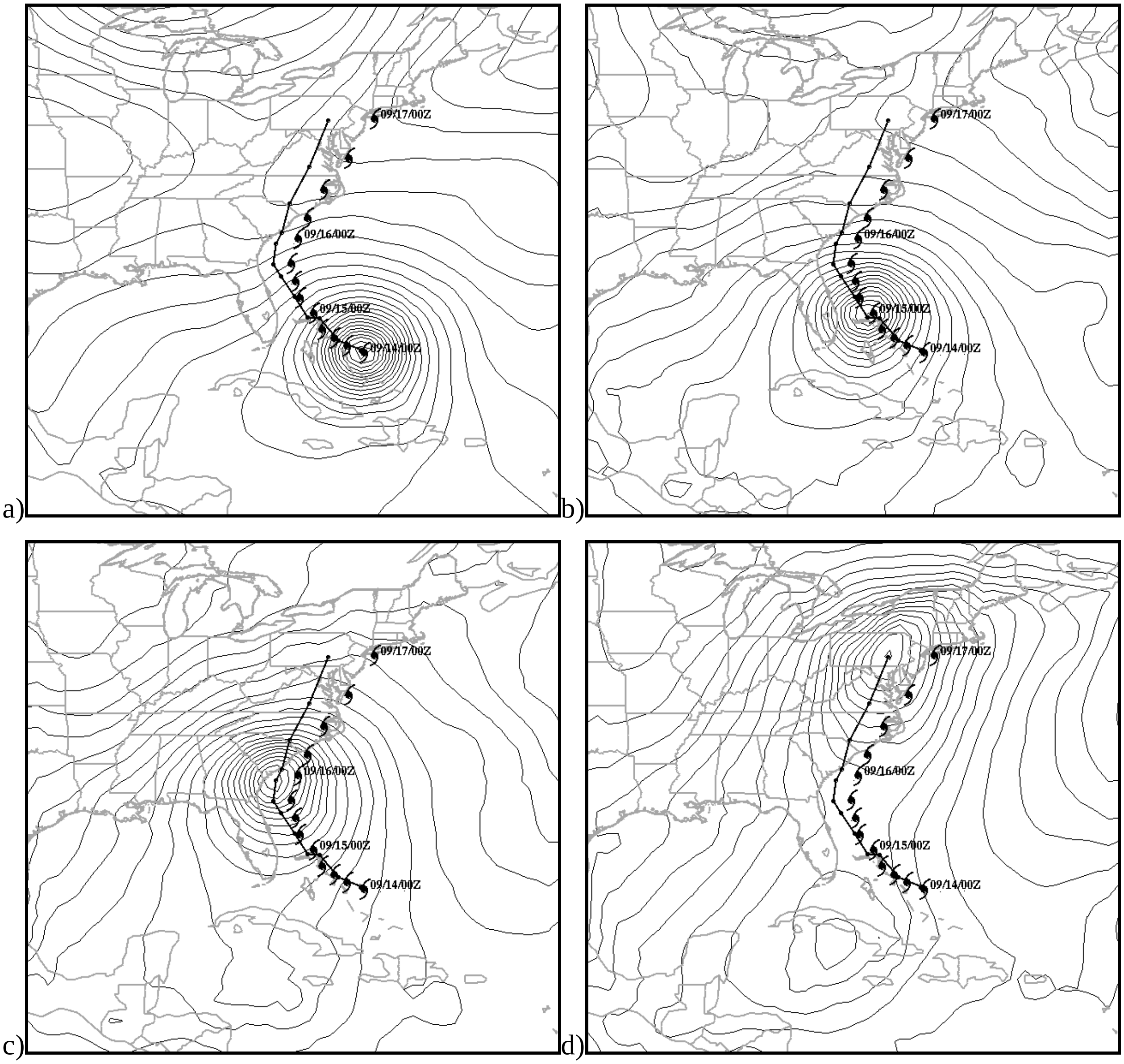

Figure 6. The OMEGA mean sea level pressure for the coarse resolution control run of hurricane Floyd at initialization and at 24, 48, and 72 hr into the forecast. Also shown is the OMEGA forecasted storm track (solid black line) and the observed track (black hurricane symbols).

6.1. Adaptive Observation Simulation #1

In the first adaptive observation run, 654 irregularly spaced high-density pseudo soundings (adaptive measurements) from the high-resolution truth run were extracted from the region of hurricane Floyd at 14 September 0000 UTC. Figure 7 shows the locations of the extracted pseudo adaptive soundings. These adaptive pseudo-measurements were treated as special measurements made in response to an identified need in a defined area and time. These soundings were then used in the initial analysis to create a better representation of the hurricane structure at the initial time. Note that the coarse resolution grid, presented in Figure 5, was still utilized.

Figure 8 shows the simulated hurricane Floyd track for this adaptive observation case (dashed line) and the truth run track (eastern track), and the control run track (western track). The results are compelling and strongly supportive of the impact of the use of adaptive observations in NWP models. These results show that the adaptive observations have greatly reduced the hurricane track forecast error during the 72 hours forecast period. It is clear from this experiment that additional observations can help to reduce hurricane track error from an NWP model.

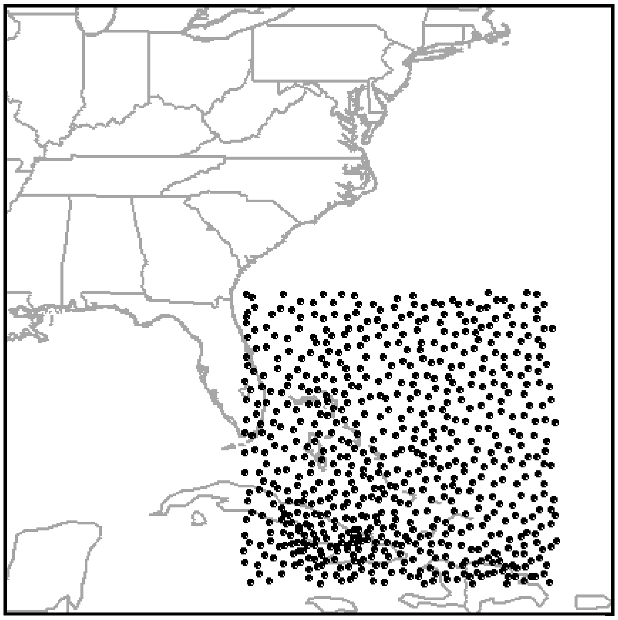

Figure 7. The location of 654 irregularly spaced pseudo-soundings that have been extracted from the truth run. These soundings are used in the adaptive observation run #1.

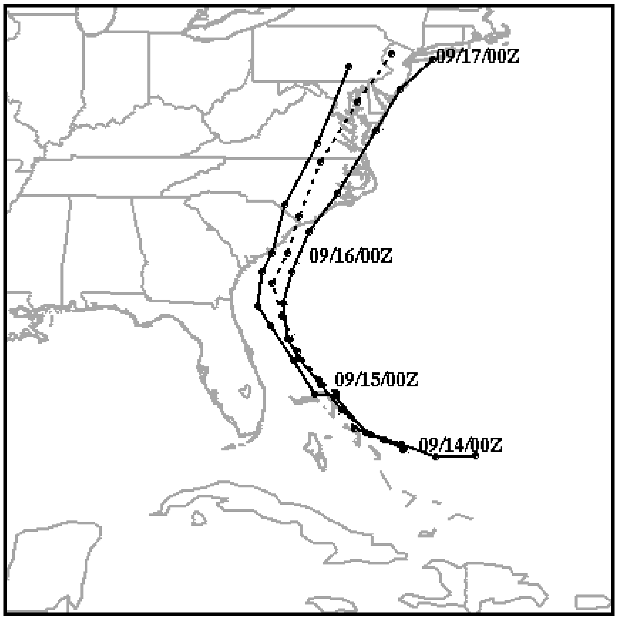

Figure 8. OMEGA forecasted track for hurricane Floyd track for the adaptive observation run #1 (dashed line) as compared to the truth run (eastern track), and the control run (western track).

6.2. *Adaptive Simulations #2-5*

The first adaptive simulation demonstrated that a high-density adaptive observation network can reduce the initial uncertainty of the tropical storm position and hence its subsequent forecast error. However, from a practical point of view, it is important to understand the minimum set of adaptive observations that is necessary in a given situation. For this reason, we conducted additional OSSEs to determine if the same reduction of track error could be achieved using a lesser number of adaptive observations to provide the crucial fine scale information controlling Floyd's track. Four additional sensitivity experiments were performed in all. The first three of these experiments involved adding successively fewer targeted observations around the initial location of the storm to the reanalyzed 0000 UTC 14 September model initial state; the final experiment explored the use of adaptive observations in the region of the storm outflow jet location.

The locations of the adaptive observations is shown in the left panel of each of Figures 9-12. They involve: (1) a group of 100 pseudo-observations in a square matrix evenly distributed about 150 km apart and covering the same region as the original 654 point pseudo-observation adaptive experiment (Figure 9a); (2) a group of 25 pseudo-observations spread out along the storm track covering the region east of Florida and over the Bahamas (Figure 10a); (3) a group of 11 pseudo-observations spread out

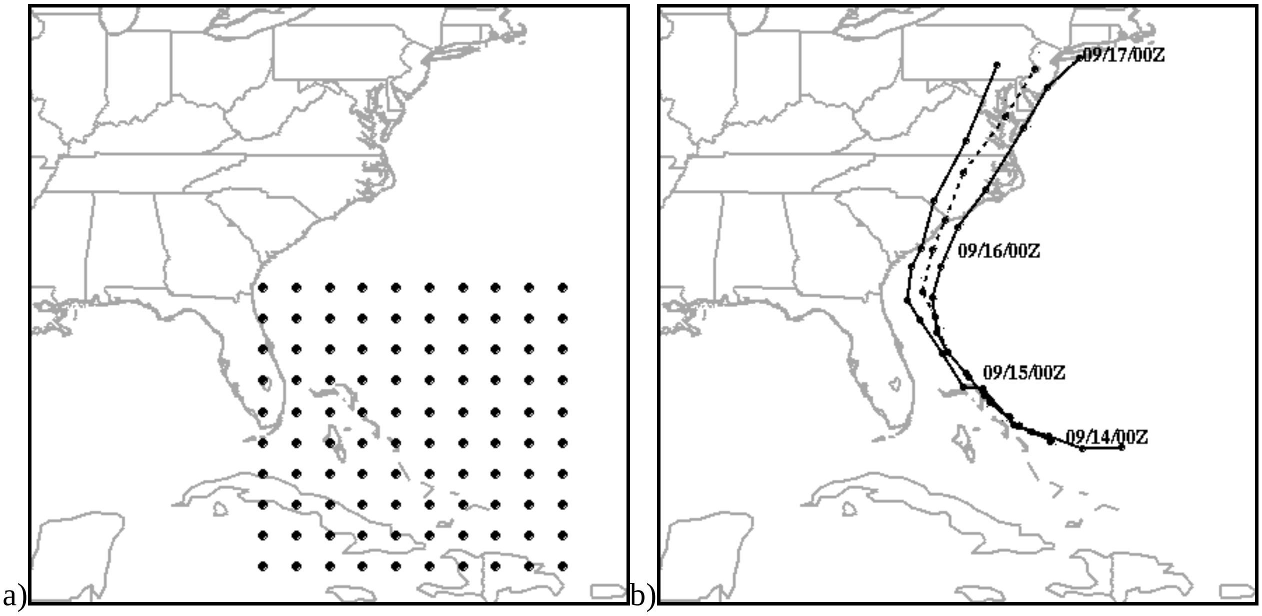

Figure 9. a) The location of 100 regularly spaced pseudo-soundings that were extracted from the truth run and used as targeted observations and b) the OMEGA forecasted hurricane Floyd track for this Adaptive Observation simulation #2 (dashed line) as compared to the truth run (eastern track), and the coarse resolution control run (western track).

along the storm track and shifted even farther southeastwards near the location of the hurricane prior to the target time (Figure 11a); and (4) a group of 35 pseudo-observations spread out along the storm's convective outflow jet region east of Florida, Georgia, and South Carolina coast lines (Figure 12a). The strategy involved in performing these additional experiments being first, to

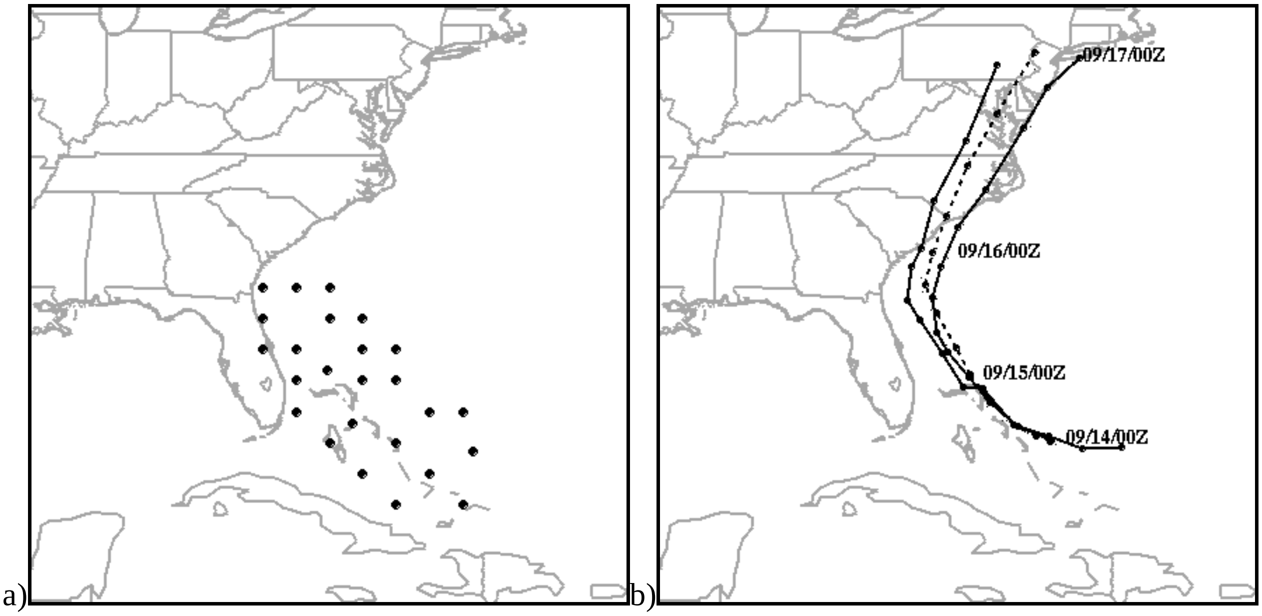

Figure 10. a) The location of 25 pseudo-soundings that were extracted from the truth run and used as targeted observations and b) the OMEGA forecasted hurricane Floyd track for this Adaptive Observation simulation #3 (dashed line) as compared to the truth run (eastern track), and the coarse resolution control run (western track).

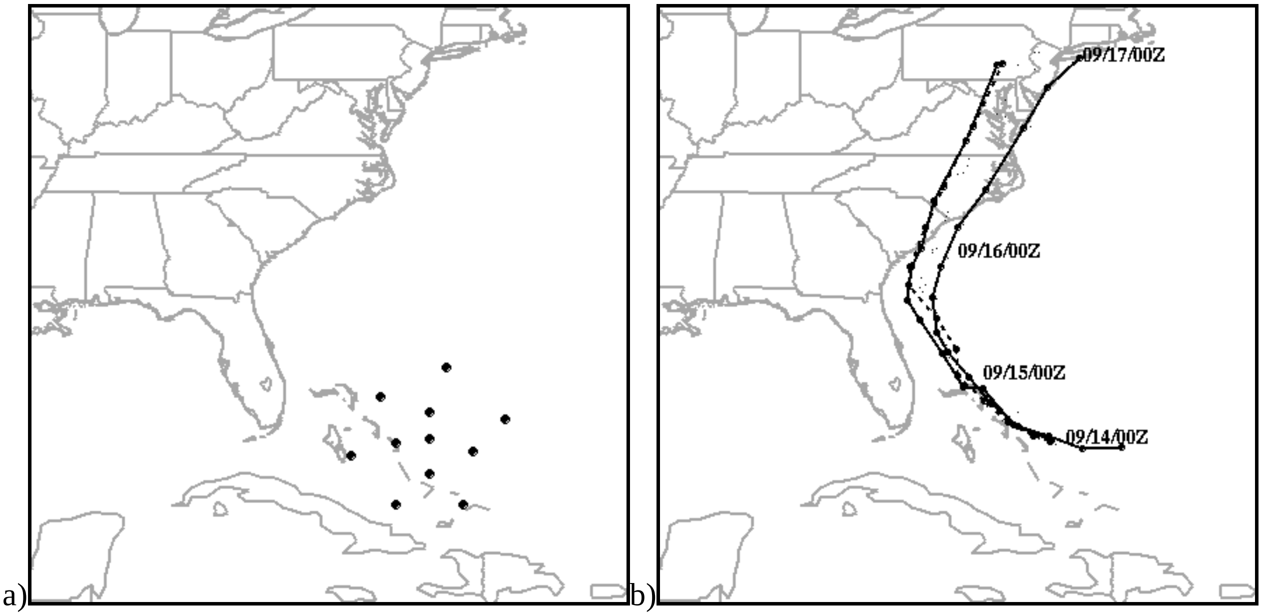

Figure 11. a) The location of 11 pseudo-soundings that were extracted from the truth run and used as targeted observations and b) the OMEGA forecasted hurricane Floyd track for this Adaptive Observation simulation #4 (dashed line) as compared to the truth run (eastern track), and the coarse resolution control run (western track).

determine whether the resolution of new pseudo-observational data and second, whether the distribution of new pseudo-observational data at the initial time but in a different sensitive area had a significant impact on the forecasted hurricane track.

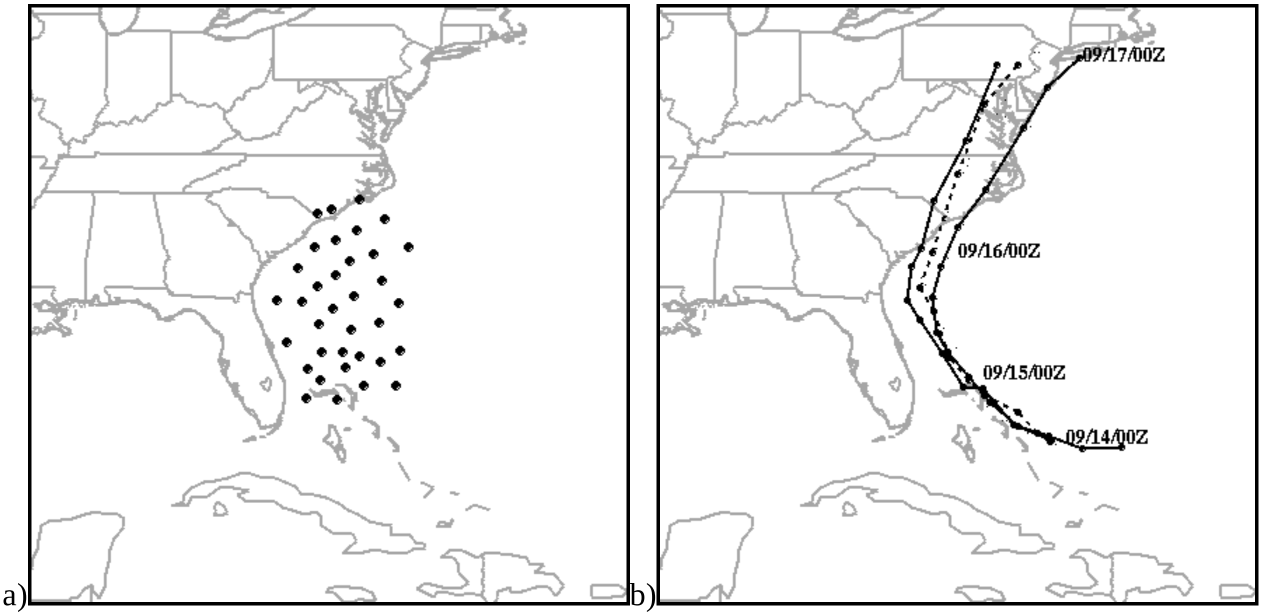

Figure 12. a) The location of 35 pseudo-soundings that were extracted from the truth run and used as targeted observations and b) OMEGA forecasted hurricane Floyd track for this Adaptive Observation simulation #5 (dashed line) as compared to the truth run (eastern track), and the coarse resolution control run (western track).

A comparison of simulated tracks for each new sensitivity experiment relative to the baseline (truth) and coarse mesh (control) simulations is shown in the right panel of Figures 9-12. The first and second sensitivity experiments, which employed 100 (Figure 9b) and 25 (Figure 10b) new pseudo-observations, had a very similar outcome as the original adaptive observation simulation, which employed 654 new pseudo-observations at the target time. That impact was to cut the simulated storm track error approximately in half over the region from the offshore coastal waters of northern Florida to the Middle Atlantic coast. These results indicate that as few as 25 to 100 pseudo-soundings with about 150 km spacing had a nearly equivalent impact on the storm track as did the original targeting strategy using much higher horizontal sampling. The next subsequent experiment with 11 pseudo-soundings (Figure 11b), however, resulted in a much weaker improvement.

The final experiment explored the value of data from a different location, the storm outflow jet. In this case, we used the truth simulation to identify the region of the outflow jet and then selected 35 pseudo-observations from this region (Figure 12a). This experiment allowed us to examine the inaccuracy of analysis over the steering flow areas, while the other experiments allowed us to examine the inaccuracy of analysis over the initial location of the storm using adaptive observations and their impact on the forecast track error.

The most significant impact of this adaptive strategy experiment was to reduce the downstream error more than that in the region of model initialization, although the overall impact was considerably less than the more dense matrix of targeted pseudo-observations. The implication is that the additional pseudo-observations located over the northern part of the grid were more crucial to the improvement in storm track downstream but lacked the resolution to improve it as much as the denser resolution pseudo-observational datasets. Since the location and the number of pseudo-observations were varied in these three experiments, the cause of the variability is somewhat more complex than if only a single variable (*e.g.*, location and number of observations) where changed; however, the general point is clear.

By reviewing Figure 2, one can infer a possible explanation for the results of these targeted data experiments. Figure 2 depicts the 300-mb NWS ETA wind and height analyses from which one can infer the ageostrophic wind at 0000 UTC and 1200 UTC 15 September. Evident is a dramatic variation in the structure of the ageostrophic wind above the low-level hurricane vortex. The anticyclonic outflow jet above the low-level vortex is important in regulating the mass removed from the storm, and hence the intensity and trajectory of the vortex (*i.e.*, by removing mass along the track of the storm the path of least resistance or storm blocking is altered). It is apparent that an approximately 300 km wide anticylonic outflow exists over the waters adjacent to the Georgia/South Carolina coastal regions and later adjacent to the North Carolina coastal regions at 0000 UTC and 1200 UTC 15 September, respectively. If one assumes that there is a subtle difference in storm track depending upon the influence of the polar jet entrance region over land and the outflow jet over water, then resolving the spatial and temporal variation of these features is a crucial delimiter of the subsequent storm trajectory. Furthermore, the outflow jet is a persistent feature of these tropical storms and is likely accompanying Floyd in its trajectory from the Bahamas to the Carolinas as can be inferred from Figure 2.

Consistent with this hypothesis is the concept that the optimum interpolation objective analyses scheme requires a minimum of at least two grid points in both x and y-space to resolve the signal of the about 300 km × 300 km outflow circulation. Hence, based on said hypothesis, one would anticipate that at least a 150 km horizontal grid representation of this feature from the fine mesh (truth) simulation is necessary to resolve it sufficiently in the reanalyzed initial state to alter the track of the storm. From Figure 2 one can infer the 300-mb ageostrophic wind magnitude and direction at the 1200 UTC 15 September time. It is at this approximate time that the simulated vortex errors begin to significantly develop in all but the baseline truth simulation. Consistent with the aforementioned hypothesis and based upon the magnitude of the outflow jet accompanying the anticyclonic circulation above the low-level vortex, about 30 targeted pseudo-observations is capable of resolving this feature while the coarser distribution of targeted observations smooth its signal considerably and the coarse mesh simulation truncates it virtually entirely. The implication is that the outflow jet is crucial to enhancing the mass removed from the column and forcing the trajectory of the storm to the right of the advection accompanying the polar jet's entrance region.

7. Summary and Conclusions

In this paper, the concept of using adaptive (targeted) observations to improve numerical weather prediction forecasts has been explored. Adaptive or targeted observations are assumed to be data that have the ability to significantly impact upon the quality of a forecast simulation and that are chosen by selectively targeting the location, time, and data type. A set of observing system simulation experiments was conducted using the adaptive grid OMEGA model to create a baseline high-resolution simulated atmospheric event (the "truth" simulation). Hurricane Floyd (1999) was chosen as the test problem for the proposed adaptive observational strategy. Using different adaptive observation strategies, "data" was synthetically extracted from the truth simulation in the form of *pseudo*-soundings. This data was inserted into a series of coarse-resolution hurricane Floyd simulations to evaluate the efficacy of the different observation strategies.

The main purpose of these OSSEs was to determine if we could significantly improve upon the hurricane track simulation by judiciously inserting synthetic observations at a specified target time into the simulation of a hurricane in a model with degraded physics (in this case, coarser resolution). The hypothesis is that a small number of pseudo-observations (vertical soundings) might be very effective at improving track forecasting, if judiciously positioned in space and time. This would be evident if a model with degraded horizontal resolution could reduce the error of the simulated hurricane's location out to 12-36 hours or more by simply targeting observations in the right place and time during the evolution of the simulation.

The results of the OSSEs were compelling and strongly supportive of the hypothesis that adaptive observations can improve forecasts. The high-resolution truth run produced a nearly perfect track forecast of hurricane Floyd; a necessary requirement for the use of the truth simulation as a source of pseudo-observations for the OSSEs. The baseline coarse resolution (control) simulation showed a marked western bias in the hurricane track. The adaptive observation experiments clearly showed that the addition of specific information into even a coarse resolution model can markedly improve the track forecast. The number of points necessary for this improvement can be as few as a couple of dozen strategic observations. The control configuration used only 10% of the number of grid cells as the truth simulation, yet the addition of 25 additional observations improved the track forecast all the way out to 72 hours. The improvement gained from adaptive observations represented a nearly 50% track error reduction beyond 24 hours for the 654, 100, 35, and 25 observational points adaptive runs. An additional subsequent experiment of 11 observational points, however, failed to have a substantial impact on the long period track forecast.

This numerical experiment highlights the potential benefit of targeted observations on the simulation of atmospheric circulation. While it is only a preliminary indicator, it leads naturally to a paradigm shift from the ingest, analysis, and assimilation of the entire spectrum of meteorological data to a more selective approach. Since data assimilation tends to be an order N^2 operation, as the volume of useful satellite-derived data increases by one to two orders of magnitude over the next 10 years and as the resolution of our models increases by an order of magnitude, the assimilation cost will increase by four to six orders of magnitude. Moore's law for computation states that computer processing power increases by a factor of two every 18 months or a factor of 100 over 10 years, hence we will be at least a factor of 1000 shy of our needs. The approach of adaptive observations can significantly reduce the processing requirements while still enabling the desired improvement in performance accuracy.

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