THE USE OF ADAPTIVE (TARGETED) OBSERVATIONS IN OPERATIONAL 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

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 increase 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.

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) plane for operational synoptic surveillance flights for hurricanes threatening landfall in the United States and its territories east of the dateline.

In recent years, there has been growing interest in enhancing the efficiency and accuracy of NWP models by employing adaptive strategies. From a numerical modeling point of view, since higher resolution requires a consistent increase in temporal resolution, it is very expensive and computationally demanding to significantly improve horizontal resolution in numerical models. 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.

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 provide a predictable discrete data set *independent of the existing weather phenomenology*. In order to overcome the shortness of the existing observation network, Albertson and Franklin (1999), Zhang and Krishnamurti (2000) have recently reported on the use of adaptive observations. As the atmosphere

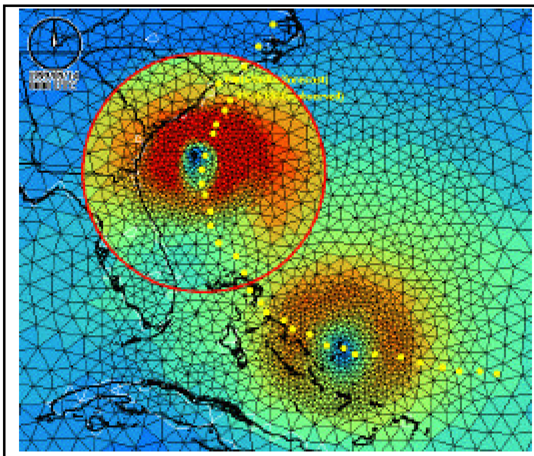


Figure 1. Dynamic grid adaptation puts high resolution only where needed, leading to the accurate and computationally efficient prediction of high wind speed (color) and track of hurricane Floyd. The initial conditions are shown with an inset showing the high-resolution area at 48 hours into the forecast.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

contracts the scale of circulation systems, a disproportionate amount of the observations are focused on the fine scale phenomena. This concept has 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. We perform a set of Observing System Simulation Experiments (OSSE). The objective of the OSSE experiments is 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. 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. 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.

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 OMEGA MODELING SYSTEM

A complete description of OMEGA can be found in Bacon *et al.* (2000) and Boybeyi *et al.* (2001). 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.

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.*

3. CASE STUDY – HURRICANE FLOYD

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.
For example, hurricane Floyd (*cf.* Figure 2) 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 eventually organized into a major category four hurricane northeast of Cuba on September 13, 1999.

Hurricane Floyd 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 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. 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.

4. DISCUSSION OF RESULTS

The OSSE experiments starts from a baseline high-resolution (with an average 10 km horizontal grid resolution, Figure 3a) OMEGA forecast of hurricane Floyd performed using regular initial analysis. Note that at this point, it is necessary to make an assumption of a "perfect model" to assure 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, Figure 3b) which serves as a typical operational hurricane run. Note that the only difference between these two runs is the difference in the grid resolution. This second coarse-resolution run serves as the control set for the rest of the adaptive observation runs.

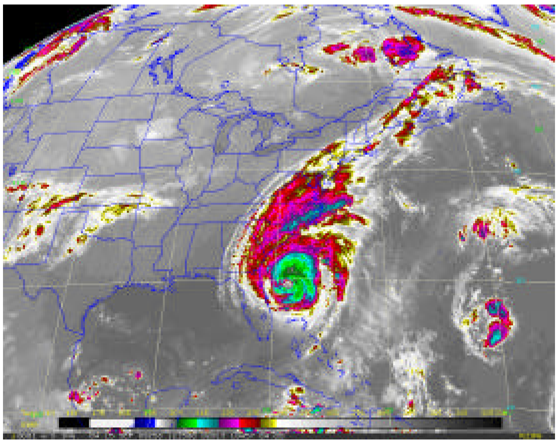


Figure 2. Enhanced infrared image of hurricane Floyd on September 15, 1999 at 12:00 UTC.

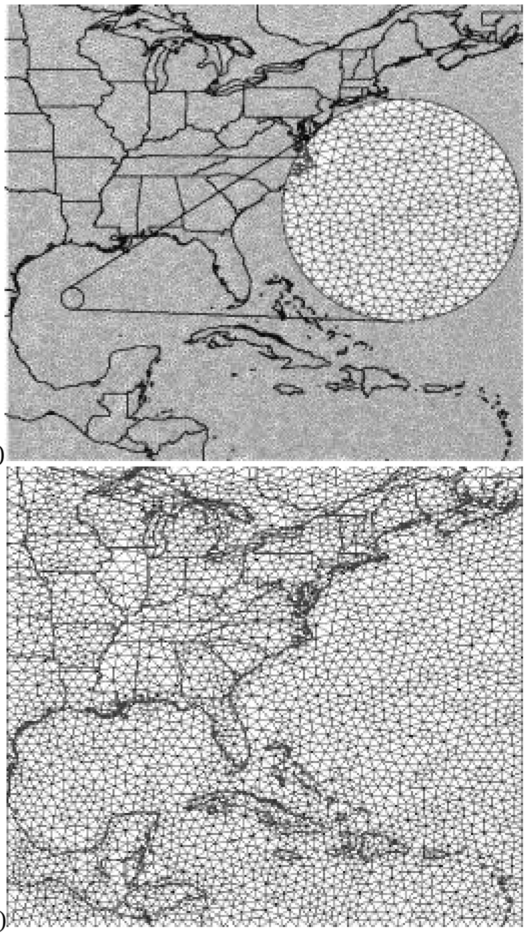
From the baseline truth run, we extract vertical profiles (pseudo adaptive/targeted observations) to simulate observations. Mainly, initial storm location is chosen to be the sensitive area that could have a significant impact on the storm track. These different data extracts are used in initial analysis 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.

4.1 High Resolution Truth Run

The OMEGA model for this case was run for 84 hours forecast period starting on 13 September, 0000 UTC. An average horizontal grid resolution of 10 km was used in the simulation with about 55,000 horizontal grid cells (*cf.* Figure 3a). 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. Finally, sea surface temperatures obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS) analysis.

The OMEGA model forecasted hurricane Floyd track (red dots) is compared against the reported storm track (white dots) 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.



a)

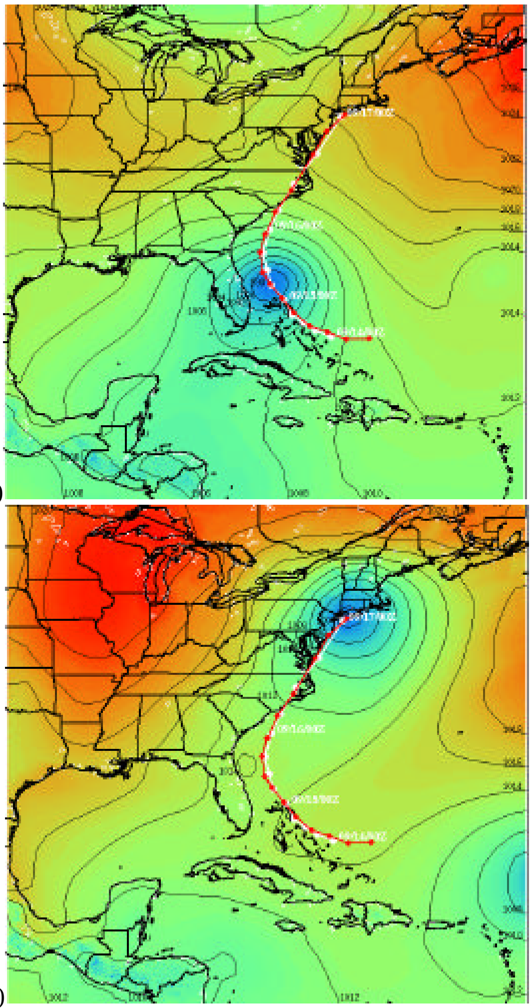
b)

Figure 3. OMEGA domain and grid for (a) the baseline high-resolution and (b) coarse resolution control run.

4.2 Coarse Resolution Run

The OMEGA model for this case was run for 72 hr forecast period starting on September 14, 00:00 UTC. This is due to the fact that pseudo soundings (adaptive/targeted observations) from the baseline truth run will be used later for the adaptive observation runs. Therefore, we allowed 12 hours spin up time for the OMEGA model. An average horizontal grid resolution of 100 km was used in the simulation with about 5,500 horizontal grid cells (*cf.* Figure 3b).

Figure 5 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 resolution, very fine spatial scales of motion and temporal periods and dependence on convection can't be resolved accurately. Since 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.



a)

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Figure 4. The OMEGA forecasted Hurricane Floyd for high resolution truth run at 36, and 84 hr (respectively, 15 September 0000 UTC; and 17 September 0000) and its track (red dots) as compared to observed track (white dots). Background contoured field shows the predicted mean sea level pressure field.

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. Therefore, predictions of hurricanes can 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 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 (targeted) runs. In the next section, we will examine the potential for an

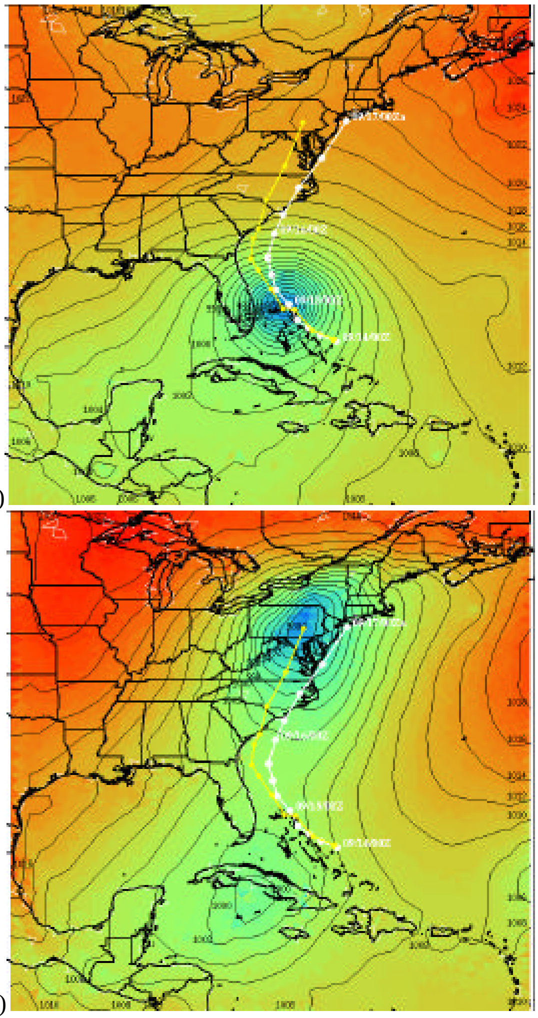

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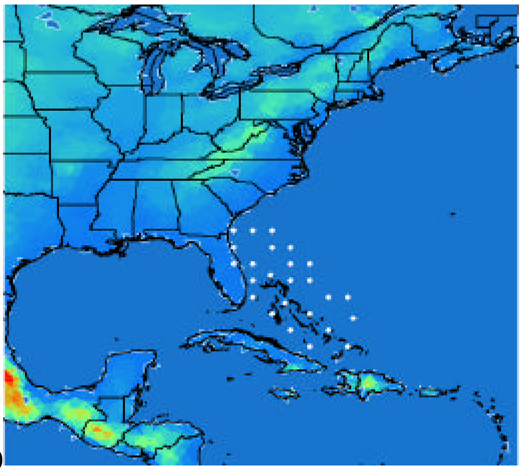
Figure 5. The OMEGA forecasted Hurricane Floyd for coarse resolution run at 24, and 72 hr (respectively, 15 September 0000 UTC; and 17 September 0000) and its track (yellow dots) as compared to observed track (white dots). Background contoured field shows the predicted mean sea level pressure field.



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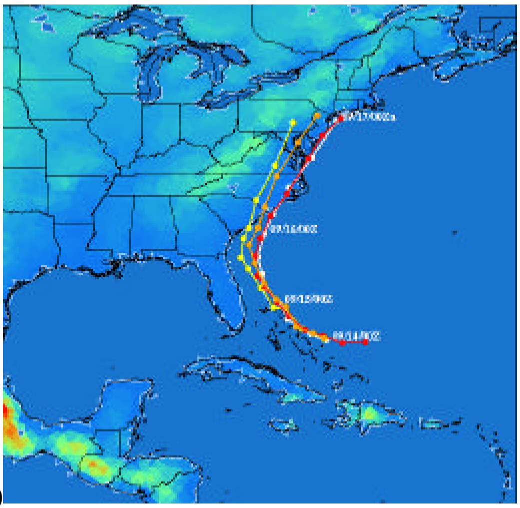

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Figure 6. a) The location of 25 pseudo-soundings that have extracted from the control run, b) OMEGA forecasted hurricane Floyd track for this adaptive observation run (orange) as compared to the observed track (white), the control run track (red), and the coarse resolution run (yellow).

adaptive observation strategy to improve the hurricane Floyd track forecast accuracy.

4.3 Adaptive (Targeted) Observation Runs

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. 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, primarily we consider the initial structure and location of the hurricane to be critical in terms of its accurate forecast.

Therefore, in our first adaptive observation run, we extracted about 650 irregularly spaced high-density pseudo soundings (adaptive measurements) from the high-resolution truth run where initially hurricane Floyd was located on 14 September 0000 UTC. In an effort to better understand the sensitivity of the adaptive observation simulations to targeted observational strategies, three additional sensitivity experiments were performed. These additional experiments involved adding successively fewer targeted pseudo-observations to the reanalyzed 0000 UTC 14 September model initial state at the storm's initial location. 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 650 point pseudo-observation adaptive experiment (2) a group of 25 pseudo-observations spread out along the storm track covering the region east of Florida and over the Bahamas; (3) a group of 11 pseudo-observations spread out along the storm track and shifted even farther southeastwards near the location of the hurricane prior to the target time. The strategy involved in performing these additional experiments being first, to determine whether the resolution of new pseudo-observational data had a significant impact on the forecasted hurricane track.

The second and third sensitivity experiments, which employed 100 and 25 new pseudo-observations, had a very similar outcome as the first adaptive grid simulation, which employed about 650 new pseudo-observations at the target time. Therefore, for brevity, a comparison of simulated tracks for 25 new pseudo-observations experiment relative to the observed, baseline truth, and coarse mesh control simulation is only shown here (Figure 6). The results indicate that the simulated storm track error was cut approximately in half over the region from the offshore coastal waters of northern Florida to the Middle Atlantic coast. The results also indicate that as few as 25 pseudo-soundings with about 150 km spacing had a nearly equivalent impact on the storm track as did the other targeting strategy using much higher horizontal sampling (100 and 650). The next subsequent experiment with 11 pseudo-soundings, however, resulted in a much weaker improvement (not shown here).

5. CONCLUSIONS

The results of the OSSEs were compelling and 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 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 100 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 of 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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