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The Potential Role for Cloud-Scale Numerical Weather Prediction for Terminal Area Planning and Scheduling

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THE POTENTIAL ROLE FOR CLOUD-SCALE NUMERICAL WEATHER PREDICTION FOR TERMINAL AREA PLANNING AND SCHEDULING

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1. INTRODUCTION

A number of operations in the aviation industry, particularly in the terminal area, are weather-sensitive to local conditions in the short-term (3 to 18 hours). Often, they are reactive due to unavailability of appropriate predicted data at the required temporal and spatial scale. Hence, whatever planning that may be applied to these processes to enable proactive efforts utilize either historical weather data as a predictor of trends or the results of synoptic- to meso-beta-scale weather models. Since this time range is beyond what is feasible with modern nowcasting techniques, near-real-time assessment of observations of current weather conditions may have the appropriate geographic locality, by its very nature is only directly suitable for reactive response.

According to the Air Transportation Association, air traffic delays caused by weather cost the airlines about $4.2B in 2000, of which $1.3B was estimated to be avoidable. Hence, meso-gamma-scale numerical weather models operating at higher resolution in space and time with more detailed physics may offer greater precision and accuracy within a limited geographic region such as a terminal area, for problems with short-term weather sensitivity (e.g., Mass et al, 2002; Gall and Shapiro, 2000).

Conceptually, improvements in the quality and lead-time of local weather forecasts derived from such models could enable air traffic controllers and dispatchers to develop more effective alternative flight paths to reroute aircraft around hazardous weather. Airline officials could initiate recovery plans before weather-induced disruptions actually occur, rescheduling passengers and aircraft in affected areas, thereby improving safety and efficiency. Airport terminal operators could more efficiently schedule and staff aircraft deicing and snow removal operations during the winter (e.g., Changnon, 2003 and Dutton, 2002).

Many of these ideas were recognized in the past, although practical deployment with a sufficient balance of physics and throughput has been limited until recently. For example, Carpenter et al 1999 discusses the use of the Advanced Regional Prediction System (ARPS) to support airport terminal operations. They implemented nested forecasts at 27, 9 and 3 km resolution focusing on specific large airports in the midwestern United States.

2. PREVIOUS WORK

To begin to address these issues, we build upon our earlier work, the implementation of an operational testbed, dubbed "*Deep Thunder*", which has been customized for transportation applications. This prototype provides nested 24-hour forecasts, which are typically updated twice daily, for the New York City metropolitan area to 1 km resolution utilizing explicit, bulk cloud microphysics. The work began with building a capability sufficient for operational use. In particular, the goal is to provide weather forecasts at a level of precision and fast enough to address specific business problems. Hence, the focus has been on high-performance computing, visualization, and automation while designing, evaluating and optimizing an integrated system that includes receiving and processing data, modelling, and post-processing analysis and dissemination. Part of the rationale for this focus is practicality. Given the time-critical nature of weather-sensitive transportation operations, if the weather prediction cannot be completed fast enough, then it has no value. Such predictive simulations need to be completed at least an order of magnitude faster than real-time. But rapid computation is insufficient if the results cannot be easily and quickly utilized. Thus, a variety of fixed and highly interactive flexible visualizations have also been implemented, including ones focused on support of operational decision-making in transportation. The concept behind *Deep Thunder* in this context is clearly to be complementary to what the National Weather Service (NWS) does and to leverage their investment in making data, both observations and models, available. The idea, however, is to have highly focused modelling by geography and application with a greater level of precision and detail than what is ordinarily available (Treinish and Praino, 2004).

Deep Thunder has recently been extended to also provide forecasts for the Chicago, Kansas City, Baltimore and Washington metropolitan areas at 2 km resolution. Therefore, high-resolution (1-2 km) coverage of eleven airport terminal areas is currently being provided (i.e., JFK, LGA, EWR, HPN, ORD, GYY, MDW, DCA, IAD, BWI, MCI). All of the processing, modelling and visualization are completed in one to two hours on relatively modest hardware to enable sufficiently timely dissemination of forecast products for terminal area applications at reasonable cost.

2.1 Forecast Model Description

The model used for the *Deep Thunder* project is non-hydrostatic with a terrain-following coordinate system and includes interactive, nested grids. It is a highly modified version of the Regional Atmospheric Modeling System (Pielke et al, 1992), the details of which are described in Treinish and Praino, 2004. It includes full bulk cloud microphysics (e.g., liquid and ice) to enable explicit prediction of precipitation. Operationally, a 3-way nested configuration is utilized via stereographic projection. Each nest is a 62 x 62 grid at 16, 4 and 1 km resolution, respectively (i.e., 976 x 976 km^2, 244 x 244 km^2 and 61 x 61 km^2), focused on New York City. For the other three geographic areas, the three-way nests are

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66 x 66 at 32, 8 and 2 km resolution, respectively. All of the operational domains are illustrated in Figure 1. The specific locations of the various configurations were chosen to include the major airports operating in the particular metropolitan area within the highest-resolution (1 or 2 km) nest. Figure 1 places all of the forecast domains in a geographic context, which shows a map of the eastern two-thirds of the continental United States. On the map are three regions associated with each of the four aforementioned metropolitan areas. They correspond to the triply nested, multiple resolution forecasting domains used to produce each high-resolution weather forecast. The outer nests are in gray, the intermediate nests are in magenta and the inner nests are in white.

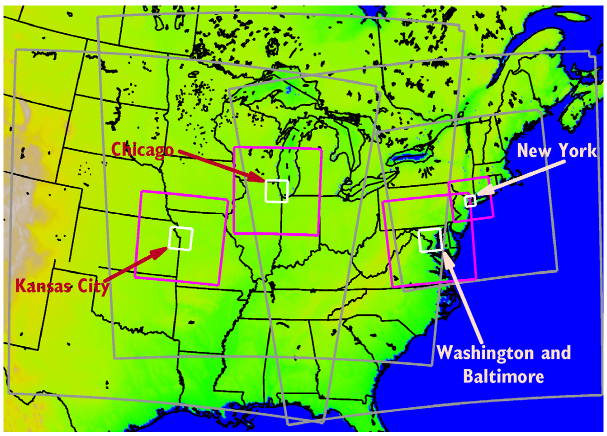

Figure 1. Model Nesting Configurations.

The three nests employ 48, 12 and 3 second time steps, respectively for New York and 100, 25, 6.25 second time steps, respectively for the other areas. The time steps were chosen to ensure computational stability and to also accommodate strong vertical motions that can occur during modelling of severe convection. Each nest employs the same vertical grid using 31 stretched levels with the lowest level at 48 m above the ground, a minimum vertical grid spacing of 100 m, a stretch factor of 1.12 and a maximum grid spacing of 1000 m. At the present time, two 24-hour forecasts are produced daily, typically initiated at 0Z and 12Z for New York, while the others are initiated at 6Z and 18Z. Additional runs are scheduled with initialization at other times either on-demand or during interesting weather events.

3. APPROACH

In order to evaluate the potential utility of this class of numerical weather prediction for terminal operations, we pose a question: could the availability of such forecasts enable some weather-related ground delays to be avoided? We begin by determining particular days in 2002 and 2003, when there was a significant ground delay associated with weather at any of the three large airports run by the Port Authority of New York and New Jersey, all of which are within the 1 km forecasting region (i.e., EWR, JFK and LGA). We then classify these days into two categories. The first is days when severe or otherwise significant weather was reported in this geographic region by the local office of the National Weather Service (NWS) at Upton, NY and/or the NOAA Storm Prediction Center (SPC, 2004). We then need to determine what type of and when specific weather forecast information was available for potential use in airport operations. Since we do not have access to the direct forecasts utilized by either the Federal Aviation Administration (FAA) nor the Port Authority for such purposes, we utilize the zone forecasts produced by the Upton NWS office as a proxy. We attempt to address the questions, do these forecasts point to sufficiently severe weather or not? If the latter, then were the delays possible due to the FAA not having sufficient information needed to impose the appropriate traffic flow management restrictions?

The second category is days when there was a NWS forecast of severe weather, which resulted in the FAA issuing a ground delay, but the disrupting weather never materialized. For both categories, we compare forecasts produced for those specific days by *Deep Thunder*. In the first case, we consider if our forecasts indicated weather sufficiently severe to impact terminal operations. In the second, we determine if our forecasts illustrate a lack of severe weather in this geographic region.

4. WEATHER DELAYS FOR 2002 AND 2003

For both 2002 and 2003, there were many days with a large number of weather-related delays reported by the OPSNET for EWR, JFK and LGA (FAA, 2004), which are used to evaluate the quality of available forecasts. This information is summarized in Tables 1 and 2, for 2002 and 2003, respectively. For each year, they list the top ten days with the total number of delays at the three airports. The number of delays reported are for each occurrence that is greater than 15 minutes in length.

Although these data are considered at face-value, there are a few issues. For example, there appears to be less weather sensitivity at JFK in comparison to the other two airports. This will need to be investigated further, but is beyond the scope of this initial paper.

The sixth column in each table is a summary of the reported weather with information. It should be noted that for the most part, these days do not correspond to those cited as having severe weather by NWS or SPC. Many of the significant convective events and winter events have been compared to the forecasts produced by *Deep Thunder* (e.g., Praino and Treinish, 2004, and Treinish and Praino, 2005). Some of these will be discussed later in this paper.

The seventh and eighth columns summarize the *Deep Thunder* forecast and the NWS forecast as well as the approximate time of their availability in parentheses. Since one or more forecasts may be relevant for the weather on a particular day, the sequence of forecasts and their updates are indicated in both columns.

Date 2002	EWR Delays	LGA Delays	JFK Delays	Total Delays	Actual Weather	*Deep Thunder* Forecast *	NWS Forecast *
7/9	265	241	201	707	•Fog, haze •Windy (41 mph peak at EWR) •Light rain, some thunderstorms	• (1630Z) evening thunderstorms, EWR wind peak of 41 mph, heavy rain	•(day before) scattered showers and thunderstorms late in day, may be gusty
5/13	301	244	111	656	•Fog •Moderate rain (~.75"), some thunderstorms •Peak winds > 25 mph	•(1630Z day before) morning fog thunderstorms, heavy rain •(0430Z) fog, thunderstorms, heavy rain, winds > 40 mph •(1630Z) fog, thunderstorms, heavy rain, peak winds > 35 mph	•(0233Z) occasional rain, dense fog advisory •(0900Z) flood advisory, heavy rain, change of thunderstorms late in day, foggy
5/2	247	365	23	635	•Hail •Moderate rain (< .5") •Peak winds 20-25 mph	•(1630Z day before) morning fog, moderate rain •(0430Z) fog, moderate rain, peak winds > 30 mph	•(1212Z day before) rain, fog in morning, likely strong thunderstorms with damaging winds
10/11	163	202	240	605	•Fog •Heavy rain (> 2.5")	•(1630Z day before) morning fog, heavy rain •(0430Z) fog, heavy rain, peak winds > 30 mph •(1630Z) fog, heavy rain, peak winds > 25 mph	•(day before) occasional rain, heavy at times late in day
6/26	266	241	90	597	•Fog, haze •Some thunderstorms	•(1630Z) afternoon thunderstorms, peak winds > 40 mph	•(0832Z) scattered showers may contain damaging winds and hail •(1847Z) severe thunderstorm watch
4/19	215	190	139	544	•Fog •Very windy (peak of 69 mph LGA, 76 mph EWR) •Some thunderstorms •1" hail	•(0430Z) fog •(1630Z) evening thunderstorms	•(1928Z day before) chance of showers and thunderstorms in afternoon •(1950Z) chance of showers and thunderstorms with small hail and gusty winds
8/5	208	250	79	537	•Fog, haze •Peak winds > 25 mph	•(1630Z) afternoon and evening thunderstorms, peak winds > 30 mph	•(1930Z) showers and thunderstorms likely, may contain damaging winds and hail
10/16	197	209	100	506	•Fog •Moderate rain (~1") •Peak winds > 30 mph	•(1630Z day before) morning fog, moderate rain, peak winds ~30mph •(0430Z) fog, > 1", peak winds > 40mph	•(0906Z day before) flood watch, rain heavy at times, windy •(2022Z day before) rain heavy at times, very windy, patchy fog
7/19	195	138	148	481	•Fog, haze •Moderate rain (~1") •Some thunderstorms •Peak winds > 30 mph	•(1630Z day before) morning thunderstorms, peak winds > 25 mph •(0430Z) strong afternoon thunderstorms, peak winds > 25 mph (50 at LGA) •(1630Z) thunderstorms, peak winds > 30 mph	•(0927Z) chance of showers and thunderstorms •(1901Z) chance of scattered shower and thunderstorms, patchy fog
4/28	211	156	111	478	•Fog •Moderate to heavy rain (>1.5") •Some thunderstorms •Peak winds > 25 mph	•(1630Z day before) > 1.5î morning rain, fog, peak winds > 25 mph •(0430Z) ~1.5" morning rain, fog, peak winds > 30 mph •(1630Z) evening thunderstorms	•(0059Z) rain, may be heavy, possible thunderstorms •(1432Z) late showers and thunderstorms, may produce gusty winds and hail •(1902Z) added patchy fog •(2337Z) dense fog advisory

Table 1. Summary of 2002 Results for Highest Number of Weather Delays
(* with Approximate Times for Posting of Forecast in UTC: EDT + 4 hours, EST + 5 hours).

Date 2003	EWR Delays	LGA Delays	JFK Delays	Total Delays	Reported Weather	*Deep Thunder* Forecast *	NWS Forecast *
9/4	394	413	3	810	•Fog, haze, low visibility •Light rain, some thunderstorms	• (1630Z day before) morning moderate showers, fog •(0430Z) fog •(1630Z) light rain, fog	•Occasional showers
6/4	450	252	57	759	•Fog •Heavy rain (>2”), flooding •Some thunderstorms	•(0430Z) heavy rain (>2”), fog	•(day before) flood watch •Moderate to heavy rain (1-2”)
11/5	367	263	79	699	•Fog, low visibility •Light to heavy rain (.2 - 1.1”), some thunderstorms	•(0430Z) light rain, fog •(1630Z) moderate rain and fog	•(0910Z) areas of fog, light rain •(1747Z) dense fog advisory
9/3	244	293	81	618	•Fog •Moderate rain (~.3”), some thunderstorms	•(1630Z day before) morning moderate to heavy rain, fog •(1630Z) fog	•(day before) light rain, patchy fog •(1005Z) heavy rain likely
7/11	306	296	0	602	•Fog, haze, low visibility •Moderate rain (~.3î), some thunderstorms	•(1630Z day before) fog •(0430Z) some thunderstorms, fog •(1630Z) some afternoon thunderstorms, fog	•(0129Z) occasional shower and chance of heavy thunderstorms •(0746Z) showers likely with scattered, gusty thunderstorms
12/11	316	232	1	580	•Fog, low visibility •Heavy rain (~.5-1”) •Peak winds > 40 mph	•(1630Z day before) morning moderate showers, fog, peak winds > 40 mph •(0430Z) moderate to heavy rain (.5-1”), winds > 40 mph, fog •(1630Z) moderate rain (.1-.5”), peak winds > 30 mph, fog	•(1143Z day before) heavy rain expected, fog •(1730Z day before) flood watch, heavy rain •(1700Z) dense fog
9/15	280	276	0	556	•Fog, low visibility •Light to moderate rain (0-.4”)	•(1630Z day before) fog •(0430Z) light rain, fog	•(0151Z) chance of showers, patchy fog •(0758Z) chance of showers, thunderstorms
7/21	285	162	107	554	•Fog, haze •Thunderstorms •Peak winds 30-40 mph	•(0430Z) light rain, fog, winds 25-32 mph •(1630Z) fog, peak winds 25-32 mph	•(1855Z) severe thunderstorms possible •(2030Z) severe thunderstorm watch, gusts to 70 mph, hail
5/11	283	188	78	549	•Fog, haze, low visibility •Light rain (LGA) •Peak winds 20-30 mph	•(1630Z day before) morning thunderstorms •(0430Z) fog, light showers, peak winds 20-30 mph) •(1630Z) fog, light showers (LGA), peak winds 25-35 mph	•(0530Z) slight risk for severe thunderstorm late afternoon/ evening •(2015Z) dense fog advisory
3/6	182	244	118	544	•Fog •Ice, glaze •Significant snow (~3”, ~.5” liquid)	•(1630Z day before) morning light rain, changing to snow, fog •(0430Z) mixed precipitation (~1” liquid), fog •(1630Z) mostly snow (~.5”liquid), freezing during the late afternoon and evening, fog	•(1926Z day before) possible snow (2-3”) •(0145Z) winter weather advisory •(0958Z) snow, may be heavy, starting with rain/sleet

Table 2. Summary of 2003 Results for Highest Number of Weather Delays
(* with Approximate Times for Posting of Forecast in UTC: EDT + 4 hours, EST + 5 hours).

From the data used to prepare Tables 1 and 2, it is clear that the most common weather that leads to delays at these airports is fog (19 out of 20 cases). In 15 out of the 20 examples, *Deep Thunder* forecasted the observed fog. In contrast, NWS forecasted fog in only eight cases, half of which were significantly later than the *Deep Thunder* forecasts. In only one case, July 19, 2002, did NWS correctly predict fog when *Deep Thunder* did not.

On only three days did *Deep Thunder* miss a forecast of some significant weather at the airports (May 2, 2002: thunderstorms, April 19, 2002: very high winds, July 21, 2003: thunderstorms). However, other aspects of the reported weather on those days were correctly predicted. The NWS forecasts incorrectly indicated information about winds for December 11, 2002; July 21, 2002; May 13, 2003; May 2, 2003 and August 5, 2003. On the other hand, the NWS forecasts had long lead times for several precipitation events, especially those more on a synoptic scale (e.g., June 4, 2002; March 6, 2002; July 9, 2003; October 11, 2003 and October 16, 2003).

5. SPECIFIC CASE STUDIES

None of the examples outlined in Tables 1 and 2 showed a delay for which there was no significant weather. While further analysis of other days with delays of a lesser magnitude will uncover that situation, it is also worth considering a few other days in 2002 and 2003 during which severe weather or significant delays did occur.

5.1 August 2, 2002

The reported weather delays for August 2, 2002 were relatively minor compared to the examples cited earlier (162, 27 and 126 for EWR, JFK and LGA, respectively). However, the average ground stop reported in OPSNET for that day was quite high (almost 127 minutes average for a total of 18026 minutes in the region, mostly at EWR). In particular, severe thunderstorms occurred between 2000 EDT and 2300 EDT that evening at EWR with heavy rainfall (> 1.6”) and wind gusts over 30 mph as well as hail. The National Weather Service forecasts provided the following information in time sequence:

- The day and evening before:scattered showers and thunderstorms
- 1100 EDT: strong thunderstorms possible late this afternoon
- 1336 EDT: strong thunderstorms possible late this afternoon with gusty winds
- 1652 EDT: severe thunderstorm watch, damaging winds and hail

In contrast, consider Figures 2 and 3, which show the *Deep Thunder* forecasts for that evening. Figure 2 is for a model run initialized at 0Z and was available at about 0030 EDT. Figure 3 is for a model run initialized at 12Z and was available at about 1230 EDT. Both figures represent a type of meteogram that is oriented toward interpretation by the non-meteorologist. Each consists of three panels showing surface data and one panel to illustrate upper air data. In all cases, the variables are shown as a function of time interpolated to a specific location (EWR -- Newark International Airport). The plots on the left each show two variables while those on the right show one. The top left plot presents temperature (blue) and pressure (red). The bottom left panel shows humidity (blue) and total precipitation (red).

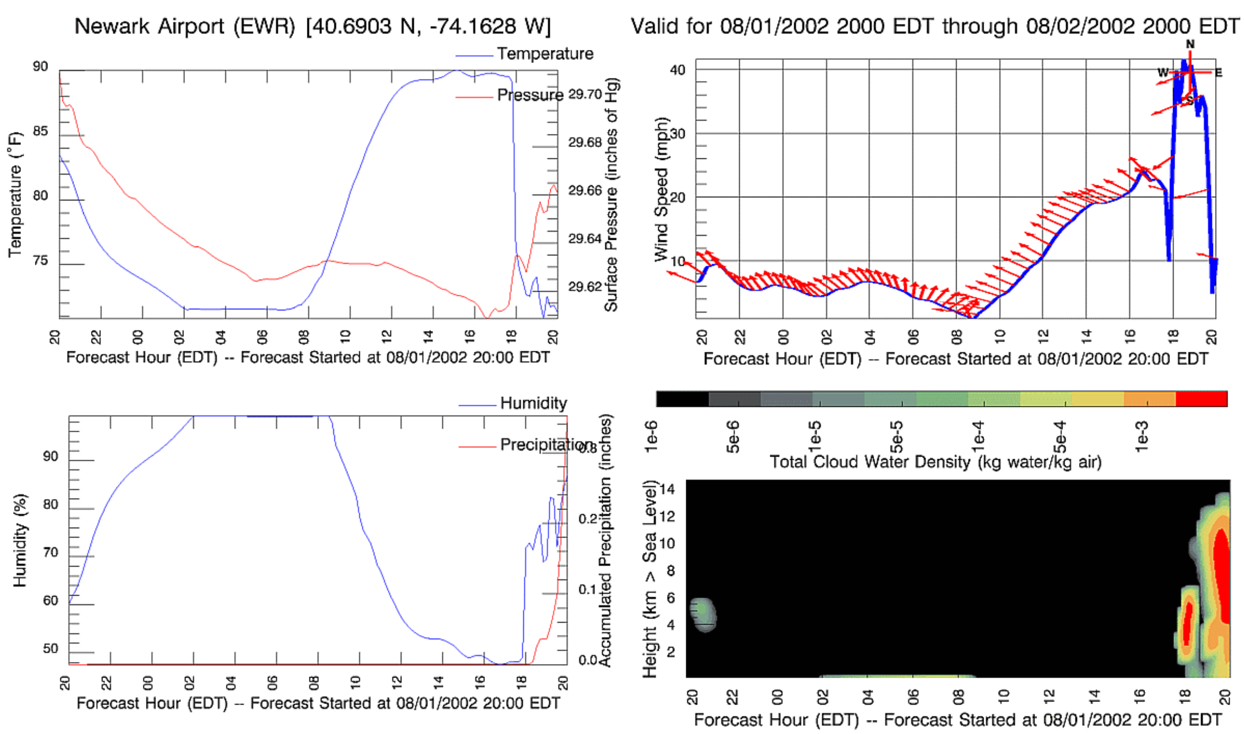

Figure 2. *Deep Thunder* Forecast for EWR -- August 2, 2002 Initialized at 0Z.

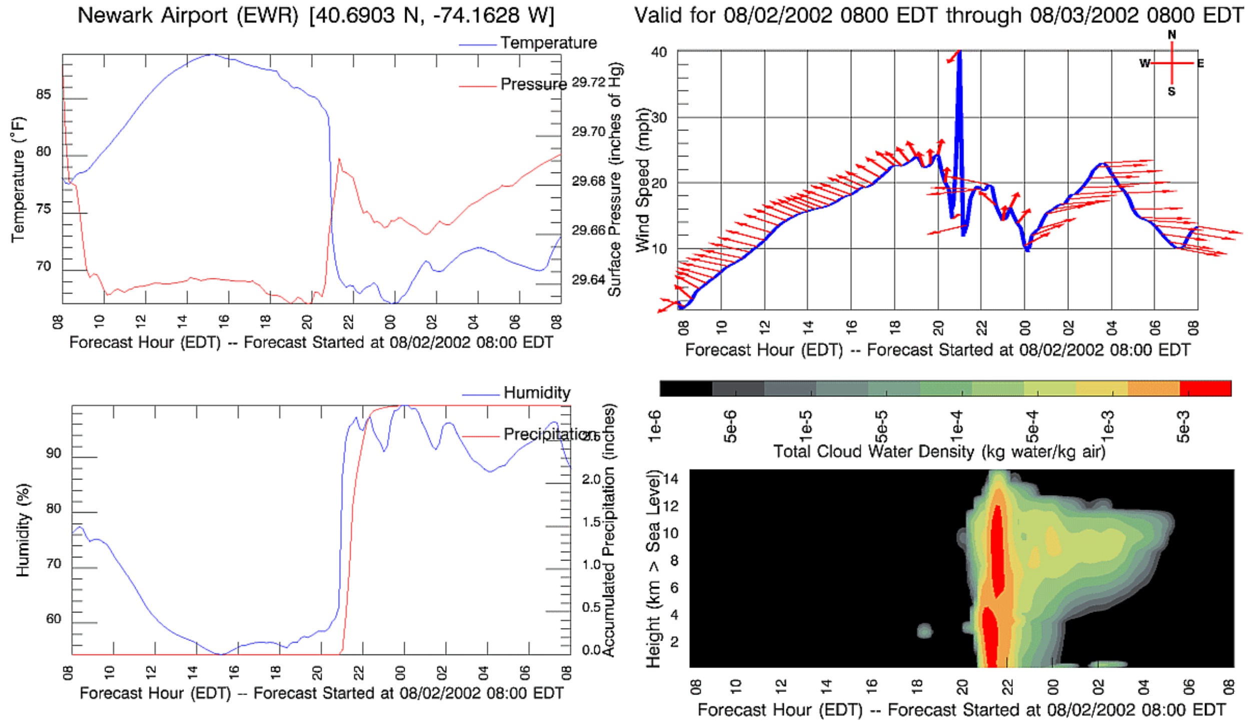

Figure 3. ***Deep Thunder*** **Forecast for EWR -- August 2, 2002 Initialized at 12Z.**

Since the precipitation is accumulated through the model run, the slope of the curve will be indicative of the predicted rate of precipitation. Therefore, when the slope is zero, it is not raining. In addition, the model calculations require some time to "spin-up" the microphysics to enable precipitation. Therefore, there will typically be no precipitation in the first hour or two of model results. The top right plot illustrates forecasted winds -- speed (blue) and direction (red). The wind direction is shown via the arrows that are attached to the wind speed plot. The arrows indicate the predicted (compass) direction to which the wind is going. The bottom right plot is a colored log-contour map of forecasted total (water and ice) cloud water density as a function of elevation and time. This "cross-sectional" slice can provide information related to storms, fog, visibility, etc. predicted at this location. Portions of the plot in black imply time or elevations where there are little or no clouds. Areas in yellow, orange and red imply when and where the relatively densest clouds are forecasted, following the color legend on the top of the panel.

Using these figures, the earlier model run shows the thunderstorm beginning at about 1815 EDT. The latter forecast corrects the timing with precipitation beginning at about 2100 EDT and stopping at about 2345 EDT. The overall magnitude of the predicted storm has a positive bias. The total precipitation is high (2.9 inches vs. 1.62 inches) and the peak winds have a positive bias of about 10 mph. On the other hand, the timing is correct within the temporal resolution of the weather station observations.

5.2 September 23, 2003

As a weak cold front approached the east coast of the United States on the morning of September 23, 2003, showers and thunderstorms developed just ahead of it. Many of them evolved into severe thunderstorms, spawning two F1 tornadoes in northeastern New Jersey between 0805 EDT and 0835 EDT, and two additional F1s in eastern Pennsylvania. There were reports of high winds with gusts up to 80 mph. In addition, about 2.5 inches of rain fell in the area in about 30 minutes. There were over 100 trees uprooted as well as a number of damaged buildings and downed power lines.

The *Deep Thunder* forecast for this event is summarized in Figure 4. Both panels show a terrain map, colored by a forecast of total precipitation, where darker shades of blue indicate heavier accumulations. The map is marked with the location of major cities or airports as well as river, coastline and county boundaries within the 4 km nest. In addition, there are colored arrows indicating predicted winds, with the lighter color being faster winds and the arrow direction corresponding to the direction to which the wind is flowing. Above the terrain is a forecast of clouds, represented by a three-dimensional translucent white surface of total cloud water density (water and ice) at a threshold of 10^{-3} kg water/kg air. Within the cloud surface is translucent cyan surface of forecast reflectivities at a threshold of 45 dbZ. This combination is indicative of a well-formed squall line associated with strong convection.

The top panel of Figure 4 is from a model forecast initialized at 0Z on September 23, 2003. Operationally, this forecast provided approximately a seven-hour lead-time for the event with initialization data from 12 hours before the event. However, the forecasted squall line was biased toward the north and roughly 90 to 120 minutes late. A subsequent run, initialized with 6Z data, corrected both of those biases and is illustrated with the corresponding visualization in the bottom panel. Operationally, the lead time is reduced to 90 to 120 minutes.

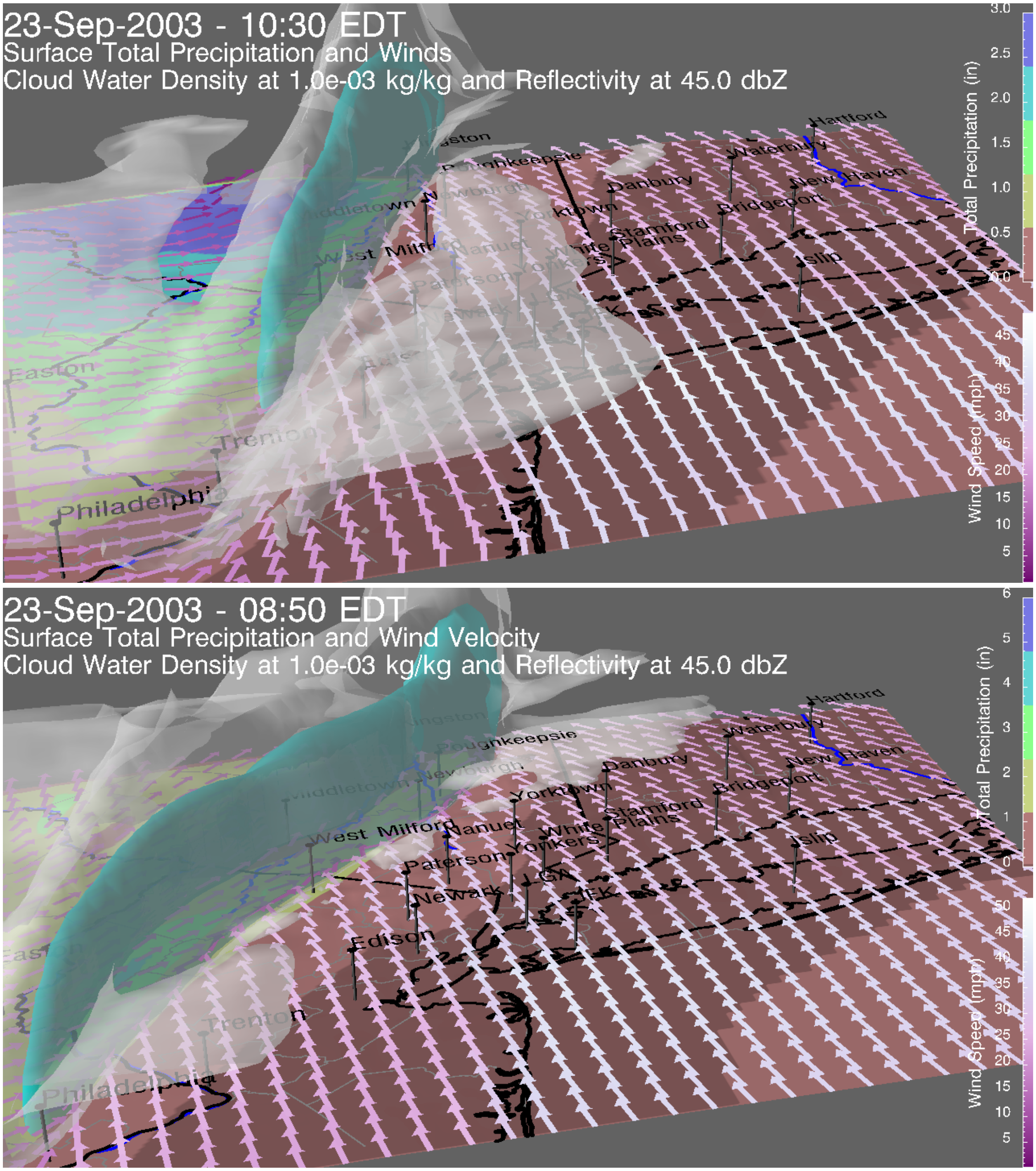

Figure 4. ***Deep Thunder*** **Forecasts of Severe Thunderstorm Event of September 23, 2003.**

In contrast, the overnight forecast from the National Weather Service indicated that there was "a chance of thunderstorms, rain may be heavy". At 0826 EDT, a tornado warning was issued. In addition, Allan et al, 2004, cite this same event with a very short term forecast of radar echo tops as an extension of their on-going Terminal Convective Weather Forecast program deployed at the same airports discussed in this paper. However, their forecast is complementary in that it provided information with a lead time of only up to an hour.

6. DISCUSSION

Much of the work focused on improved weather forecasts in terminal areas is dedicated to the analysis of local radar observations. The goal is complementary to the effort discussed herein -- for near-real-time response in the 0 to 2 hour time frame (e.g., Wolfson et al, 2004 and Evans, Allan and Robinson, 2004).

6.1 Other Recent NWP Efforts

Given the near-real-time availability of input data, lowered cost of high-performance computing systems and growing quality of modelling codes, the capability of operating high-resolution numerical weather prediction systems has become more feasible in recent years. Only a few have focused on potential applications for applied such modelling to winter forecasting (Xu et al, 2004). In particular, they have attempted to improve the quality of short-term forecasts by assimilating the results of the type of radar used for the aforementioned nowcasting. They cite a snow event on December 11, 2002 and the limitations in their ability to predict the key features of that event covering the New York City metropolitan area at 3.3 km. In contrast, the operational *Deep Thunder* forecasts for LGA for that event are shown in Figure 5 (0Z and 12Z, respectively). The 0Z forecast has the snow beginning about two hours earlier than the local observations report with the 12Z correcting that time. The 12Z forecast has the snow ending about two hours before the actual snow stopped. There was a positive bias in the liquid equivalent (1.2 inches vs. 0.9 inches) In addition, the 12Z forecast also captured the two snow bands observed by radar.

Xu et al ran their system operationally for the winter 2004 season focused on Baltimore at 3.3 km resolution, but also included the New York area at 10 km resolution. They cite a late winter snowstorm on March 16 in which their forecast was late in predicting the start of the event by one to two hours. The operational *Deep Thunder* forecasts for this event are shown in Figure 6 for both BWI (at 16 km resolution) on the left-hand side as well as LGA (at 1 km resolution) on the right-hand side, for three model run cycles, initialized at 0Z (top), 6Z (middle) and 12Z (bottom). The first two forecasts included the start of the snow, and correctly predicted the time at both airport locations within the temporal resolution of the available observations. The 12Z cycle also had the start time correct for LGA. Both the 6Z and 12Z forecasts had the snow ending a couple of hours earlier than was observed at both airports. The 12Z forecast for LGA has the snow tapering off for a few hours, which was not observed. For both airports, the forecasted liquid equivalent was about twice what was observed.

6.2 Forecast Assessment

The example events discussed herein show significant and consistent skill associated with *Deep Thunder*'s forecasts of fog, convective thunderstorms and winter snow events compared to other sources of forecasts. This would appear to be the result of using both a high-resolution grid and a more sophisticated cloud microphysics scheme compared to what Xu et al or what is available to the NWS from the National Centers for Environmental Prediction. The overall architecture of the system has permitted the practical operation of this capability in the New York City metropolitan area for over three years (Treinish and Praino, 2004).

A delay occurrence in the OPSNET data for one airport may mean that some aircraft were delayed on the ground more than 15 minutes at another airport due to an anticipation of bad weather at the destination in the next few hours. This factor has not been considered in the analysis discussed herein, which could be manifested by not having significant weather at the time of the delay. Therefore, the determination of whether or not the FAA fails to impose a traffic flow management restriction when bad weather was forecasted but did not occur has not been fully addressed.

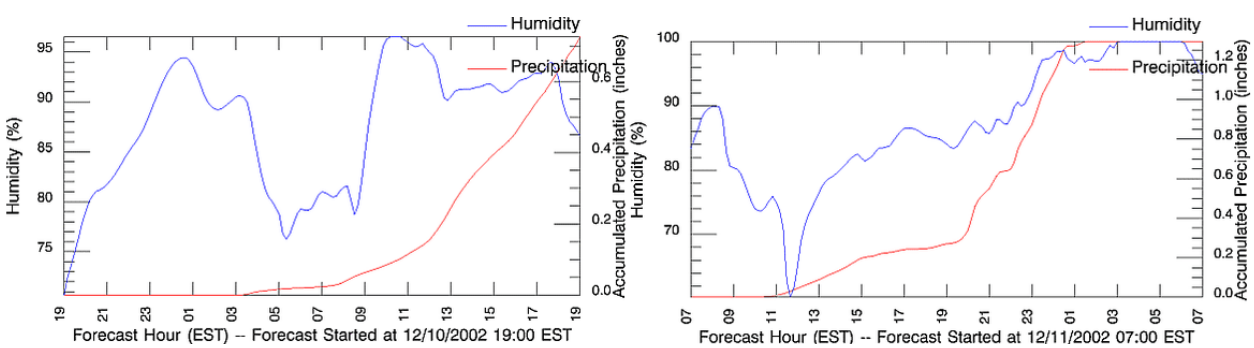

Figure 5. *Deep Thunder* Precipitation and Humidity Forecast for LGA for December 11, 2002 Initialized at 00Z (left) and 12Z (right).

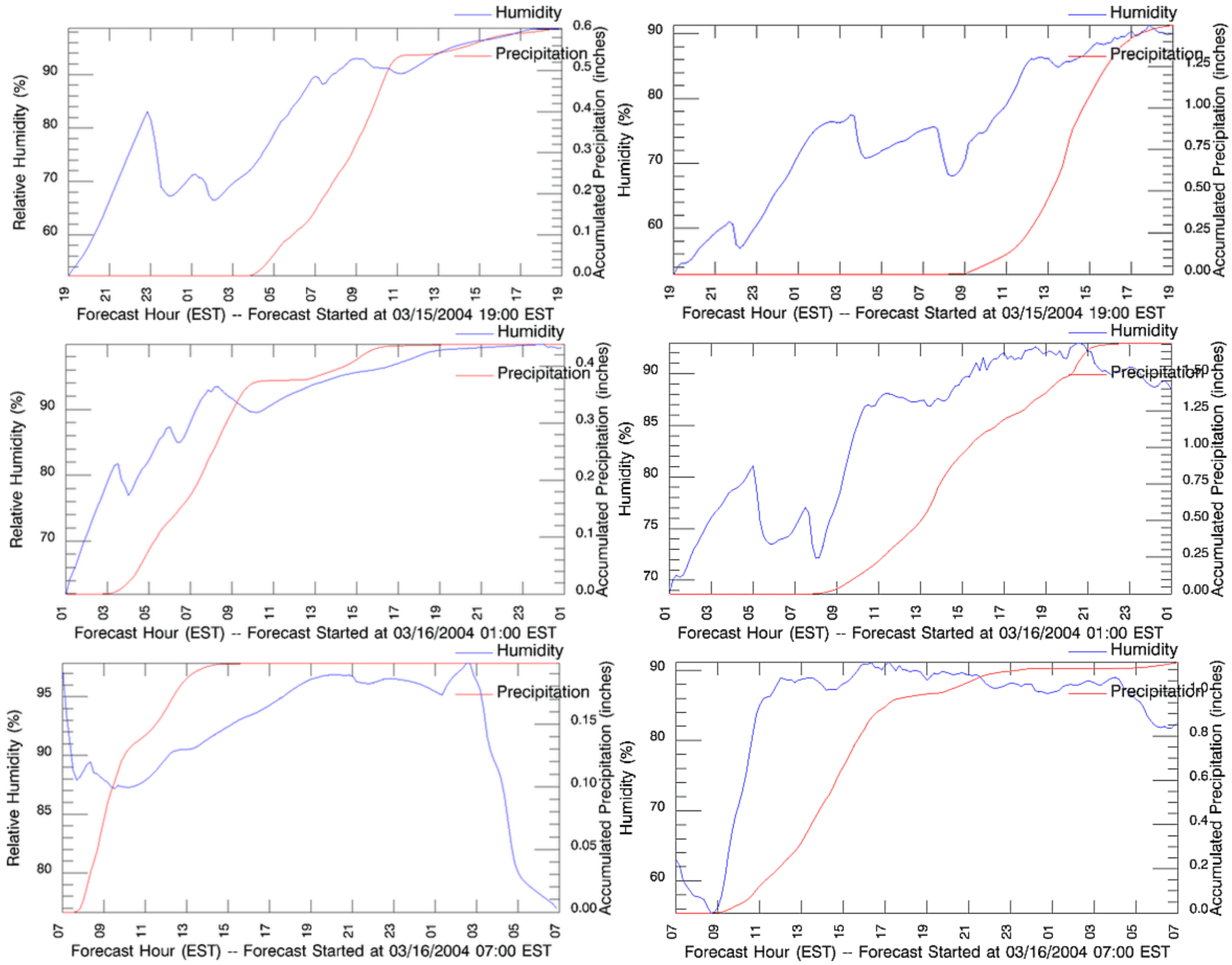

Figure 6. *Deep Thunder* Precipitation and Humidity Forecast for BWI (Left at 16 km Resolution) and LGA (Right at 1 km Resolution) for March 16, 2004 Initialized at 00Z (top), 06Z (middle) and 12Z (bottom)..

7. CONCLUSIONS AND FUTURE WORK

This is an on-going effort. The results to date illustrate a practical implementation with good skill at forecasting weather events of relevance to airport terminal operators. But they also point to several next steps.

The first step focuses on improvements in overall forecast quality, especially for storm timing and precipitation totals. Initially, new, higher-resolution data sets becoming available via NOAAport (e.g., 12 km Eta and daily sea surface temperature) with other data sets will be utilized improve the model initial conditions. Further tuning of the microphysics will also be addressed to reduce its efficiency in aggregation.

Additional analysis of the New York forecasts and delays at the airports is required as well as their extension to the other major terminal areas now being addressed by *Deep Thunder*. The goal of this planned work is to better estimate the economic benefit of this class of numerical weather prediction in two separate categories.

1. The standard forecast used at a terminal area results in a traffic flow management alarm. Hence, the FAA issues ground delays in anticipation of bad weather that does not materialize. As a result, many aircraft are needlessly delayed on the ground and flights are cancelled, leading to massive disruptions and unnecessary costs to the airlines. Would *Deep Thunder* have correctly predicted safe weather for such days?
2. The standard forecast used at a terminal area results in a missed alert when the FAA issues little or no ground delays and bad weather materializes. In this situation, many aircraft are delayed in the air and/or are diverted to other airports. This also results in disruptions and unnecessary costs. Would *Deep Thunder* have correctly predicted the hazardous weather for such days?

Hence, the next step is to further identify days with exceptionally high and low ground delays and then compare them to predicted weather. Days with a high incidence of ground delays but no bad weather would be case 1. Days with little or no ground delays with bad weather would be case 2.

8. ACKNOWLEDGEMENTS

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