The Blizzard of 25-27 December 2010: Forecast Assessment

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Executive Summary

A powerful blizzard struck the Northeast United States on 26-27 December 2010, severely affecting the New York City metropolitan area, New Jersey and portions of New England. The New York City metropolitan area was paralyzed by blizzard conditions combining twenty to thirty inches of snow with winds gusting in excess of 50 to 60 mi h^{-1}. New York City officials conducted a review of the city's poor snow removal response after the storm. The report concluded that the inadequate response was linked, in part, to "sudden changes to the weather forecasts", leading up to the storm on the 26th and 27th of December. To address these concerns, this report documents the forecasts leading up to the storm with a focus on the numerical weather predictions that provided a basis for the NWS medium range to short range forecasts 5 to 1 days prior to the onset of the blizzard conditions in and around the New York City metropolitan area.

Ensemble model forecasts provided early indications of a possible major snowstorm almost a week in advance. While there were a considerable number of ensemble members that led many forecasters to believe that the storm would stay too far offshore to affect anyone other than eastern New England, there were always a wide range of solutions, including some which pointed to a significant snow event in New York City. As early as 1200 UTC 24 December, a significant number of model ensemble solutions began to point to a higher probability of a significant snow event although many forecasters remained skeptical since there still was considerable model divergence. Furthermore, the "model of choice", the European Center or ECMWF model, continued a trend from earlier runs to track the system further off the East Coast. These ECMWF

runs on 23 and 24 December minimized the threat of heavy snowfall, even while the Global Forecast System (GFS) was trending with a deeper low tracking northeastward closer to the coast, accompanied by heavy snow. By 1200 UTC 24 December, the GFS tracked a deep low immediately along the coast, a track which was corroborated by subsequent NAM runs, putting New York City squarely in blizzard conditions on 26 December.

The entire suite of European, Canadian and U.S. models didn't converge on the correct forecast scenario until 36 to 48 hours prior to the onset of the heaviest snow, generally late on the 24th through early on the 25th. Furthermore, the significant model differences on 24 December 2010 contributed to forecaster uncertainty. Many of the GFS/GEFS and SREFS members trended with a storm system closer to the coast and therefore a heavier snow solution for New York City. Meanwhile, the ECMWF forecasts kept the track farther offshore, suggesting the storm would not be too severe, even though earlier ECMWF forecasts indicated more of a threat several days before the storm. It wasn't until the 1200 UTC 25 December model cycles that all the models converged on a solution that put New York City squarely in the area of heavy snowfall and blizzard conditions on 26 December.

The uncertainties in the models and the lack of an overall convergence toward a consistent forecast scenario until the 24th to 25th model cycles impacted the consistency of forecasts issued by NWS offices and led to sudden changes in the forecasts between December 24th and December 25th, only a day prior to the onset of blizzard conditions.

For example, HPC medium range forecasts indicated the possibility of a heavy snow event as early as 6 days prior to the event and then continued to advertise the potential for a major storm for the next several days. However, as the storm potential drew closer on the 22nd through the 24th of December, snowfall forecasts downplayed the storm in the New York City area. It was not until Christmas morning, December 25th, when NWS forecasters from HPC and local NWS forecast offices provided a more certain forecast of a foot of more of snow for the area surrounding New York City, with a blizzard warning issued on the afternoon of Christmas day, 14 hours before the onset of the storm.

The lack of model convergence leading up to this storm represents a marked departure from recent storm events, especially those which occurred during the winter of 2009/2010, where model forecasts provided consistent forecasts of major storm events throughout the United States 5, 7 and even up to 8 days in advance. These accurate and consistent run-to-run forecast packages allow for more confident forecasts of the likelihood of heavy snow, and provides decision makers more lead time to make the important decisions as they ramp up the activities needed to prepare for these storms. In this case, the forecasts did not provide a solid basis for the confidence needed to start preparing for the storm potential until 24 to 36 hours before the event.

The model uncertainty also reduced the lead time for decision makers in the aviation community. However, the convergence of model forecasts on the 25th of December allowed for sufficient, albeit sub-optimal time to cancel flights and provide advance warning of impending serious airline interruptions and possible airport shutdowns. While an ad hoc NWS conference call made on 25 December was crucial to decisions that impacted airport operations, there had been notice of the possibility of a major East Coast winter storm as early as 23 December. At this time, the airline industry began to factor in and prepare for the potentially severe weather conditions that could impact the heavy travel period after Christmas. However, ideally, less model uncertainty could have allowed decision makers to implement preventative actions sooner and with more precision.

While this report does not provide specific reasons for the performance characteristics of all the models, we do note that this case was marked by the complex phasing of different short-wave upper-level troughs upstream of the cyclogenetic event. These phasing characteristics are a marker for La Nina patterns which existed for the Winter 2010/2011, which are known to be particularly difficult to forecast with certainty in the medium range.

With the forecast uncertainty exhibited by this case, quality control issues also may have had a significant contribution to the erratic forecasts. Issues such as Vertical Azimuth Display (VAD) winds, AIREP and ACARS wind errors and faulty ship observations may have all contributed to forecast inaccuracies. Additional model experiments would be required to accurately assess the impact of these issues on the forecasts.

The forecast issues associated with this case and the associated lack of confidence in the forecast for a major winter storm limited the decisions made by city officials leading up this storm. This link between the "sudden change" in the forecast and an inadequate response in the official report issued by New York City suggest that 1) much more needs to be done to improve the deterministic and ensemble forecasts in the medium to short range; 2) that confidence levels need to be improved in the forecasts, especially for the parameters that are key for decision makers to act (ie., snowfall amounts, rates of snowfall, wind, temperatures, duration), and 3) that research and operational forecasts work closely with decision makers to get a better understanding of thresholds for decisions to better extract information from a forecast that is relevant to those who prepare for the oncoming storm.

Introduction

A major snowstorm on 26-27 December 2010 was accompanied by heavy snow and very high winds, producing blizzard conditions in portions of the heavily populated Northeast United States. In particular, the metropolitan New York City area bore the brunt of the storm with around 20 to over 30 inches of snow accompanied by winds that gusted from 40 to over 60 miles per hour for nearly 12 hours during the height of the snowstorm. These conditions crippled transportation in the days following the Christmas holiday with a near complete shutdown of air, rail and road transportation systems from New Jersey across New York City and into New England. The storm left millions of people stranded or stuck at home during a time of heavy holiday travel, with thousands of abandoned vehicles, thousands of cancelled flights, and crippled commuter trains. With roads littered with abandoned vehicles, snow plow operators were prevented from clearing many roads and emergency workers in New York City and elsewhere were unable to reach people facing life or death situations, resulting in several deaths. Drifting snow buried cars (Fig. 1) and made snow removal difficult if not nearly impossible.

This storm will likely go down in the history books as one of the most severe storms of record for the New York City region. In New York City, many streets remained unplowed for several days after the storm, creating a public furor directed toward New York City Mayor Michael Bloomberg and his administration, as well as the Governor of New Jersey, Chris Christie.

Figure 1. Cars buried in snow along a Brooklyn Street. December 27, 2010.

A report and summary of recommendations made for Mayor Bloomberg of New York City, entitled "Preliminary Review of the city's response to the December 2010 Blizzard", described a couple of "*natural factors*" that exacerbated the city's ability to effectively meet the challenges presented by the storm. These included "*weather forecasts predicted low accumulations up until 18 hours prior to the storm*" and that snow "fell at an unusually fast rate of over 2" per hour or more". The implications of these findings were that a changing weather forecast and subsequent heavy snowfall rates contributed to the inadequate response by the city.

The report also found six problem areas that contributed to the city's poor response to the storm that left many streets unplowed and impassable, including the decision by New York City not to declare a snow emergency. This decision may also have been related to the fact that two recent 20-inch snowfalls on 25-26 February 2010 and on 10-11 February 2006 had been reasonably well-handled by the city's snow removal efforts, even through snow emergencies had not been declared for those situations. However, these other two storms did not have the high winds and heavy moisture-laden snow on roads that characterized the December 2010 storm. These factors likely contributed to the difficulty of snow removal on a major holiday when many cars remained on the streets.

The snowstorm was a challenging storm to predict with significant lead time. While some models indicated the possibility of an East Coast storm as much as 6 to 7 days in advance, extended range forecasts by the NWS Hydrometeorological Prediction Center (HPC) highlighted the potential for a major storm 7, 6, 5, 4, and 3 days in advance. These forecasts were issued expressing a large degree of uncertainty about if and when there could be a significant impact on the major metropolitan areas from Washington D.C. to Boston, MA. A consensus on the locations of the heaviest snow area and ultimate impact of the storm did not emerge until about 36 hours prior to the onset and rapid deterioration of conditions associated with the storm. The lack of certainty in the forecasts in the 5 to 2-days prior to the storm, or "medium range", was related to the inconsistency of the forecast storm track and associated precipitation, and prevented forecasters from issuing a clear indication of the potential magnitude of the storm for the areas surrounding New York City until Christmas Day, only one day before the storm moved into the New York City metropolitan area.

The purpose of this report is threefold: 1), to document and assess the forecast process in place during the storm, both from a modeling and forecaster perspective, with a comprehensive examination of what modeling tools were available to forecasters and when and whether they captured some crucial distinctions that made this storm particularly severe; 2), to determine if the forecasts were communicated accurately between the National Centers and local National Weather Service (NWS) forecast offices; 3), was information adequately communicated to decision makers, including emergency managers, the media, and the public. Finally, the report will summarize what went right and what went wrong, and make recommendations for improvements in models, operations and research and development that can be applied to improving the predictions and ensuring that the right information is being conveyed to decision makers before, during and after the storm event.

The report is divided into three parts. The first part describes an overview of the storm and a comprehensive description of the model information that was available to forecasters, focusing on particular times in which information either aided or added uncertainty to the forecast. In particular, descriptions of both ensemble and deterministic forecasts are evaluated to assess how HPC based their forecasts leading up to the storm. The second section focuses on the performance of the local forecast offices in the Eastern region, which issued the actual advisories and warnings for this event. The third section describes the role of Decision Support Services (DSS), a crucial link between how information from the Weather Service is communicated to emergency managers and the public.

A key focus of the report will be conclusions and recommendations to assess if the weather forecasts adequately addressed the complexity and uncertainty in the model forecasts, whether those forecasts had been communicated to decision makers and what improvements could have resulted in a better outcome with decision makers making the right call for the expected impacts that ultimately occurred.

Part 1: Storm Overview.

This storm was associated with a rapidly deepening cyclone in which the central pressure fell about 30 mb in 24 hours, much of it during a 12-hour period during the afternoon and evening of 26 December. As the central pressure dramatically fell during the afternoon and evening of 26 December, winds increased rapidly from New Jersey across Long Island into eastern New England, producing blizzard conditions. Whiteout conditions were commonly reported during the evening and overnight from New Jersey to Massachusetts with reports of thundersnow in Manhattan and northeastern New Jersey.

The heaviest snows fell in bands that were concentrated over eastern New Jersey into eastern New York. The snowfall distribution was not particularly uniform (Fig. 2). Areas of central Connecticut and Massachusetts received less snow than predicted while the Boston metropolitan area also reported high winds and heavy snow.

Precipitation mainly fell in the form of rain across southeastern Massachusetts where the center of the low came very close to Nantucket on the morning of the 27th . As the center approached Nantucket, its pressure fell to a remarkably low value around 962 mb. Across southeastern Massachusetts, winds gusted to between 60 to 80 mi h^{-1}. and flooding inundated flood-prone areas such as Scituate, MA.

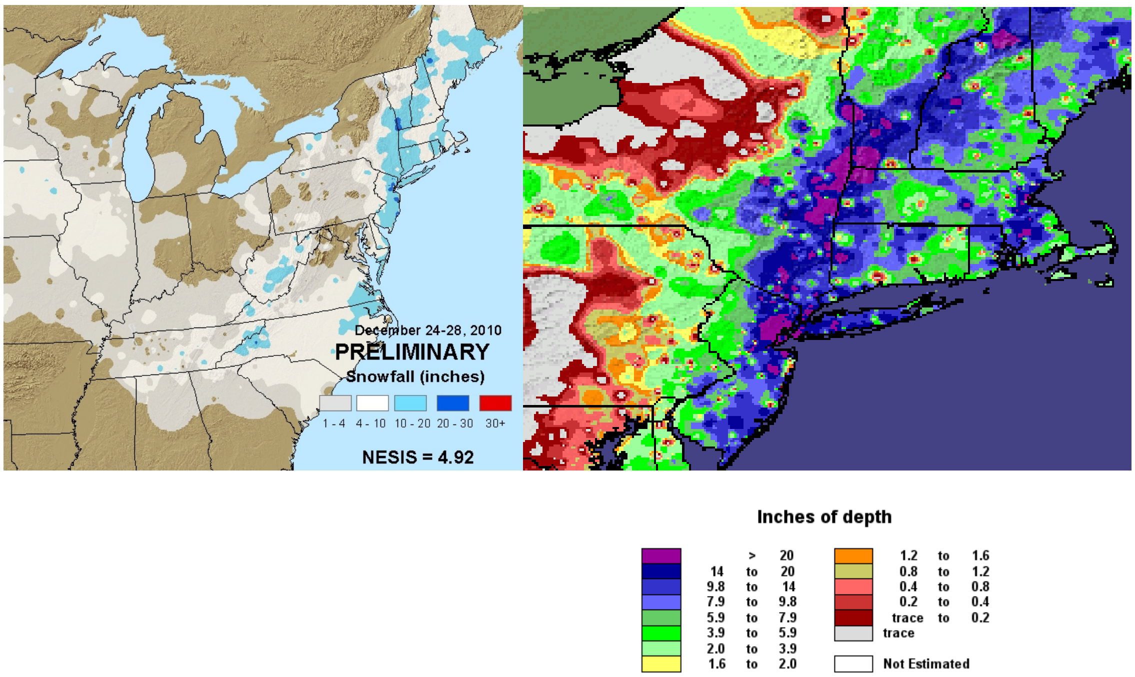

Fig. 2. Storm snowfall for 24-28 December 2010 (left) National Climatic Data Center, (right) from National Operational Hydrologic Remote Sensing Center (NOHRSC)

Prior to affecting the Northeast United States, the developing storm also produced moderate to heavy snow across parts of the Southeast United States and then northeastward across eastern North Carolina and the coastal areas of Virginia, Maryland and Delaware before slamming into New Jersey, southeastern New York and New England. More than 14 inches of snow fell in Norfolk, VA, the 3rd heaviest fall on record. Blizzard warnings were issued by the National Weather Service from the Delaware coast up along the entire Northeast coast. Remarkably, even with the track of the developing low off the East Coast, Washington D.C. escaped the heavy snowfall with only an inch or less falling within the metropolitan area though eastern and southeastern suburbs received more substantial amounts.

Heaviest snows fell near New York City, especially across northeastern New Jersey, where amounts of 24 in to 30 in (60 to 75 cm) and higher were common (Fig. 2). In addition, winds blew upwards of 30 to 45 miles per hour with wind gusts commonly exceeding 50 to 60 miles per hours. Snow continued to blow around well after the storm ended, hindering the cleanup.

A sequence of surface weather and 500 mb charts show the evolution of the storm (Figs. 3 and 4). This storm developed after an amplifying shortwave downstream of a high amplitude ridge over the western United States merged with a modest shortwave moving eastward toward the Gulf of Mexico. One shortwave crossed the southern United States and moved eastward toward the Gulf of Mexico and was associated with a relatively weak surface cyclone on 25 December. However, the trough east of the high amplitude ridge deepened significantly on the 25^{th} and 26^{th} of December and merged with the relatively weak trough moving east over the Gulf. Once the merger occurred late on the 25^{th} into the 26^{th}, the cyclone deepened explosively as it moved northeastward just off the East Coast. Storms which are associated with this type of trough merger are known to be significant forecast challenges.

The initial surface low developed along the Texas coast at 0000 UTC 25 December. Over the following 24 to 36 hours, the trough over Texas merged with a deepening trough over Oklahoma and Missouri at 1200 UTC 25 December and amplified. The surface low responded by intensifying rapidly as it moved northeastward from the northeast Gulf of Mexico at 0000 UTC 26 December to south of Cape Hatteras, NC at 1200 UTC 26 December to south of eastern Long Island at 0000 UTC 27 December.

While the movement of this low across the Gulf Coast on 25 December was accompanied by rain along the immediate Gulf Coast, a ribbon of snow developed to the north of the low over Tennessee into northern Mississippi, Alabama and Georgia. By Christmas evening, snow had spread northeastward across western and central North Carolina into southeastern Virginia.

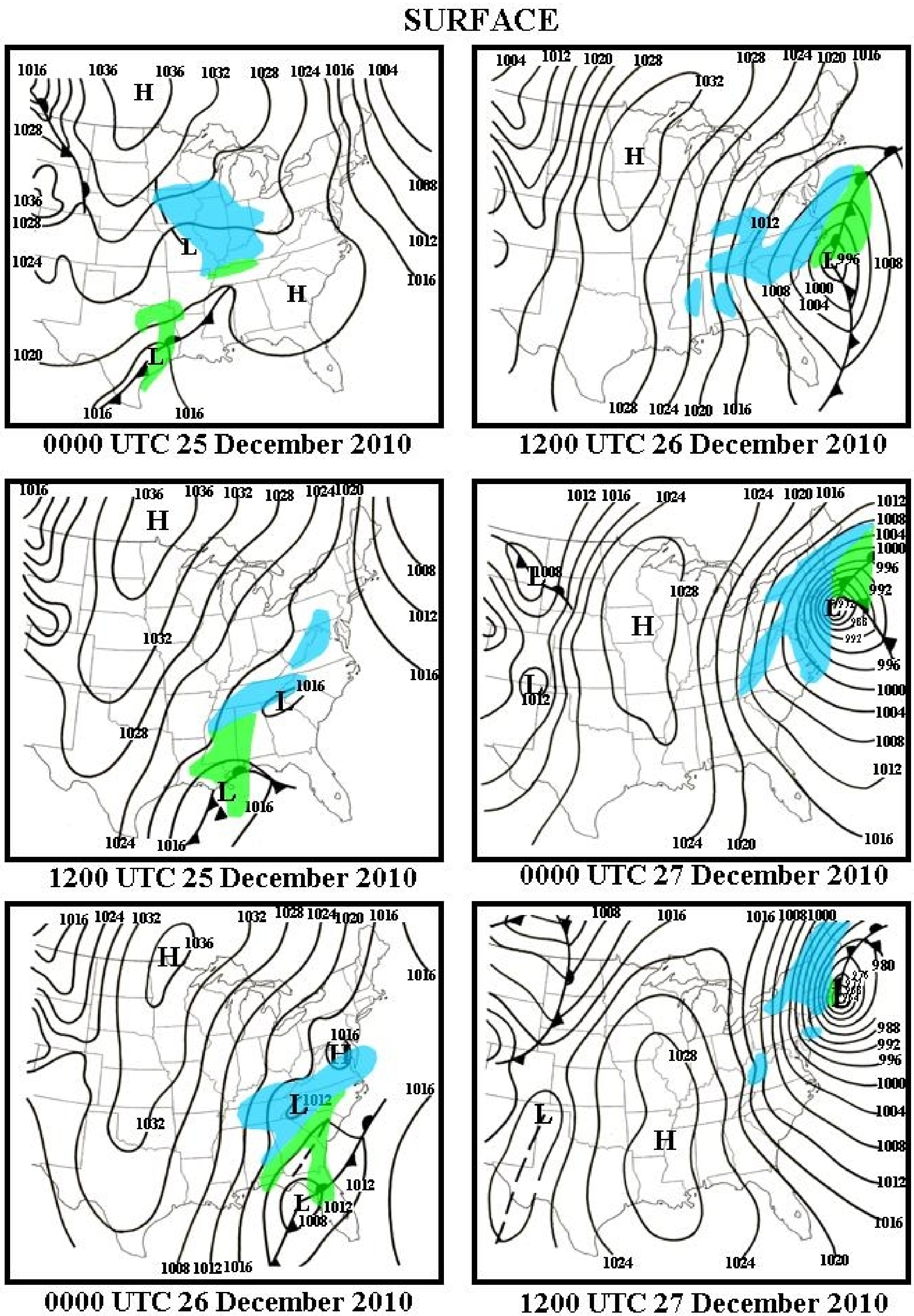

Figure 3. Twelve-hourly surface weather charts for 0000 UTC 25 December to 1200 UTC 27 December. Green shading represents rain; blue shading represents snow.

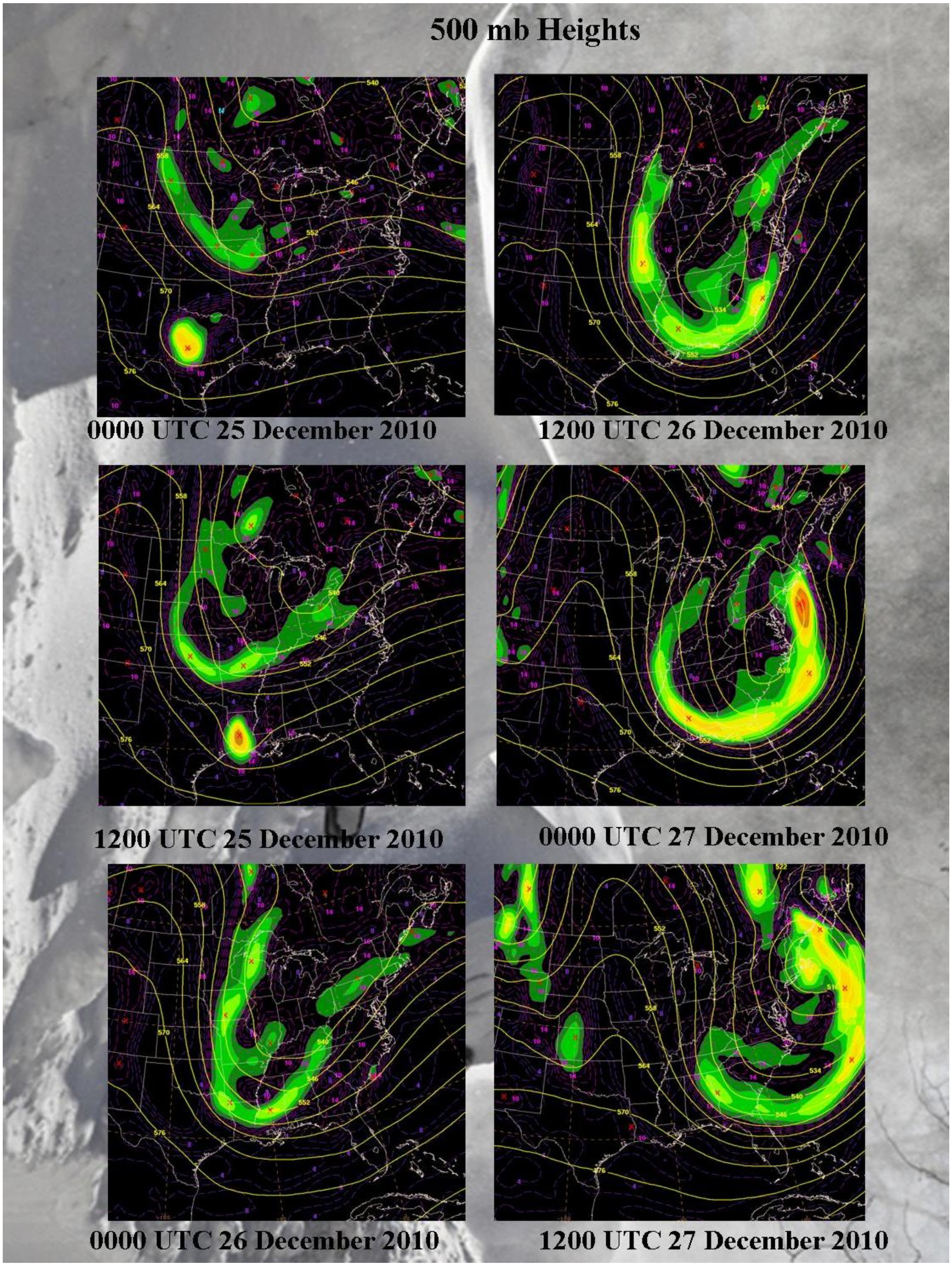

Fig.4. 500 mb charts for 0000 UTC 25 December to 1200 UTC 27 December 2010.

Overnight, the surface low crossed the northern Florida peninsula and emerged into the Atlantic Ocean off the Southeast coast. By morning, snow was occurring from eastern Georgia and northwestern South Carolina northeastward along the southeastern coast of Virginia and across the DelMarVa peninsula, where snowfall totals exceeding one foot (30 cm) occurred, including the Norfolk metropolitan area.

During the day of 26 December, the surface low deepened explosively off the Middle Atlantic coast and moved east of the New Jersey coast by 0000 UTC 27 December, where the forward motion of the low had slowed. The surface low deepened 24 mb in 12 hours from 1200 UTC 26 December to 0000 UTC 27 December. Snow had spread northward up along the Atlantic coast, mostly sparing Washington D.C. and Baltimore, but moved into the Philadelphia, New York and Boston metropolitan areas by evening. The heavy snow was accompanied by increasing north to northeasterly winds that continued thru the evening into the overnight hours, causing low visibilities, blinding whiteouts and rapid snowfall accumulations.

Crippling snowfall and high winds had continued overnight and into the morning of 27 December. The snow continued but tapered off by morning across New York City and Philadelphia, but continued in Boston into the late morning hours. The surface low had moved slowly northeastward overnight and was located near Nantucket Island by 1200 UTC 27 December, with a central pressure estimated at 962 mb. With such a deep low over eastern New England, winds continued to blow and drift the snow even after ending on 27 December.

Climate factors:

The storm occurred during a pronounced negative phase of the ENSO, or La Nina, which often leads storms to track into the Ohio Valley and does not usually favor major snowstorms in the Northeast. However, this storm also developed during a period in which the North Atlantic Oscillation was in its very negative phase, which is well known to lock in colder air across the eastern United States that is needed to ensure that precipitation can fall as snow rather than rain as the storm tracks more eastward up along the coast. Some speculation suggests that the North Atlantic Oscillation (NAO) signal may have overwhelmed the ENSO signal not only for the 26-27 December period but also for the winter months December 2010 through January 2011, which remained cold and snowy for much of the eastern United States.

Part 2: Discussion of the Model Forecasts

The models being evaluated in this report represent a wide range of forecast systems in use within the National Weather Service. In particular, they form the basis of the forecast process used at the HPC, where forecasters generate medium range forecasts, quantitative precipitation forecasts, and winter weather predictions, such as heavy snow forecasts. There are two classes of numerical model information available, including deterministic forecasts and ensemble forecasts, both of which will be described in this section.

The main focus of this section is to examine these suites of model forecasts and to illustrate the significant model trends that first indicated the possibility of a major East Coast storm up to a week prior to the storm. In addition, subsequent forecasts which increased the uncertainty about the heavy snow event, especially on 22-23 December, are also described. On 24 December, large model changes not only increased the uncertainty, as to whether or not a major snowstorm would occur, as some models indicated a greater likelihood of heavier snow, while others minimized that likelihood with the possibility that the storm might head harmlessly out to sea. Finally, the models converged on a solution on 25 December that targeted New York City as the location of a likely blizzard.

The operational ensemble systems include the GEFS, NAEFS, Canadian and ECMWF models. The deterministic models include the current operational GFS (Global Forecast System), NAM (North American Model), European Centre for Medium Range Forecasts (ECMWF), Canadian and UKMET models. The performance of the more experimental versions of the numerical model suite, such as the WRF, will not be addressed in this study.

The main variables to be examined include variations in storm track and intensity, precipitation location and amounts, location of the western edge of the precipitation and possible impacts due to changes in track and intensity.

Longer range forecasts are considered those made approximately 6 to 8 days prior to the event. Medium range forecasts are considered those made 3 to 5 days while short-range forecasts are those made 1 to 2 days ahead.

Longer Range Forecasts (6 to 8 days)

Ensemble forecasts

A sequence of spaghetti charts showing the 540-decameter height line on the 500 mb chart during the 8 to 6-day period prior to the 1200 UTC 26 December time when the strong surface low was developing southeast of Cape Hatteras, NC are shown in Figs. 5a, b and c. The spaghetti charts are comprised of members of the GEFS, European and Canadian members, as well as the GEFS, European and NAEFS ensemble means and the operational GFS and European models at 0000 UTC for 18 to 20 December.

Eight days prior to the storm, only a few members were as far south and none west of the observed 500 mb heights as all forecasts indicated the likelihood that the East Coast trough was much broader than observed and farther east, indicating virtually no likelihood of a significant storm moving up along the Atlantic coast. On days 7 and 6, there are more members that come close to the actual pattern, but the majority of ensemble model members continue to point to the higher probability of a storm track to be well east of the East Coast and probabilistic forecasts would have very low odds of a significant storm.

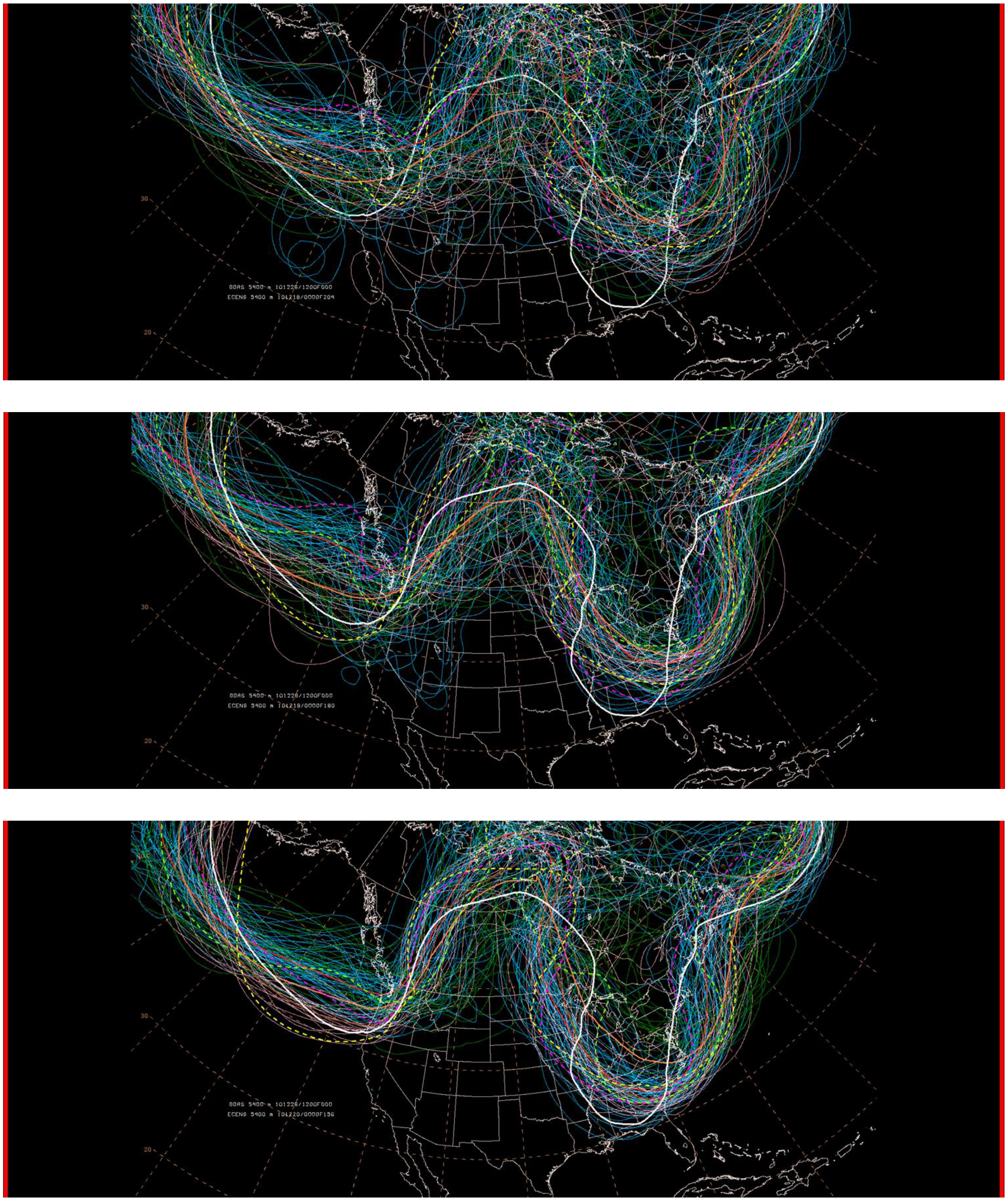

Fig. 5a-c. Ensemble forecasts of the 540 dm height field valid at 1200 UTC 26 December. (Top) 204h forecast; (center) 180h forecast; (bottom) 156h forecast. White line is verifying analysis. Courtesy of David Novak.

NCEP GEFS forecasts of mean sea-level pressure and anomalies from 18-20 December valid at 1800 UTC 26 December 2010 are shown in Fig 6 (from Grumm). These ensemble mean data also showed a cyclone located well off the East Coast, likely too far east to produce significant impact to the coastal regions outside of easternmost New England. This storm was also predicted to move fast relatively to subsequent forecasts and implied a storm over the Tennessee Valley on Christmas Eve than along the Carolina coast by Christmas morning.

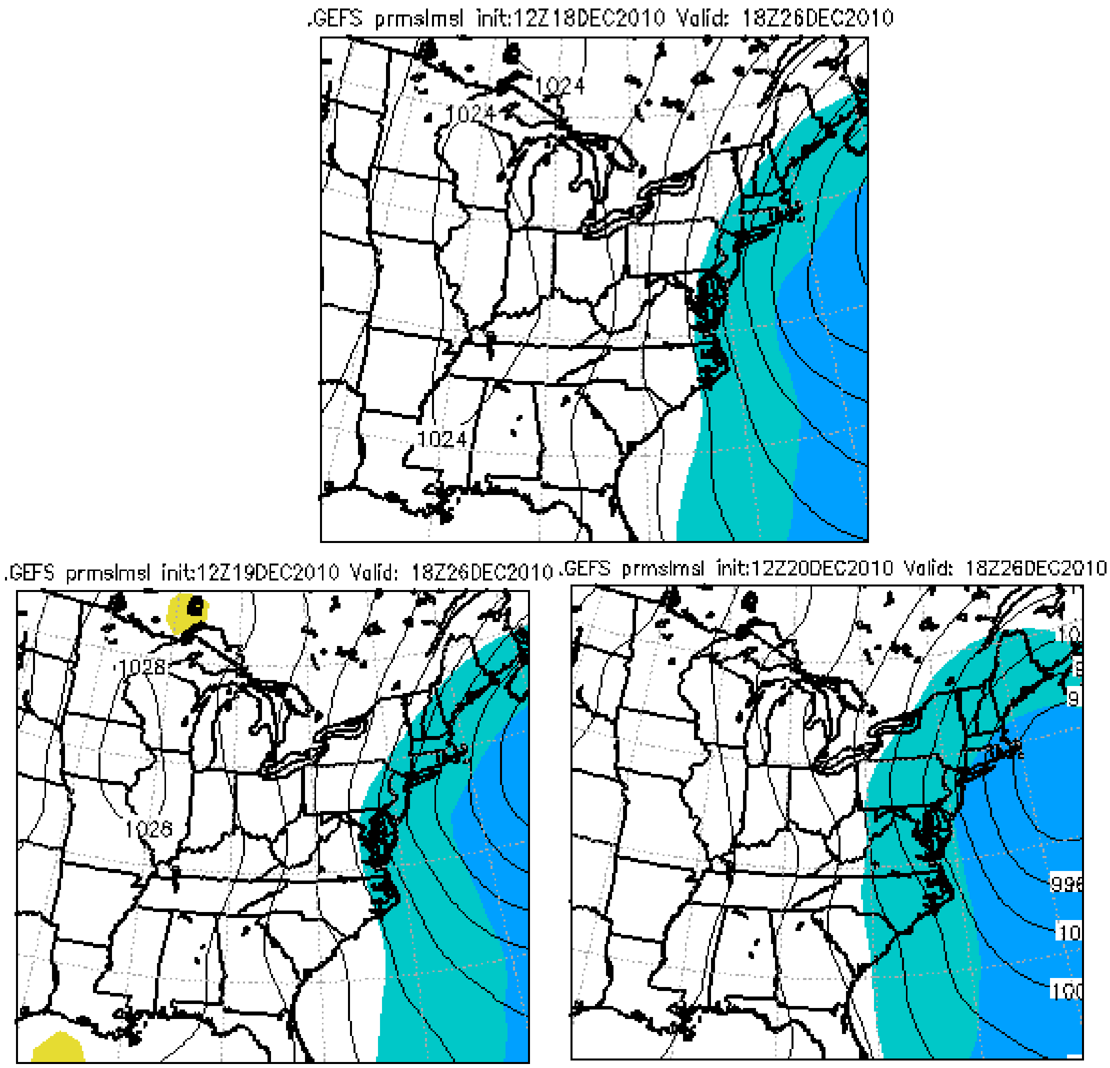

Fig. 6. GEFS mean sea-level pressure forecast valid at 1800 UTV 26 Dec 2010. (top) 204 hr forecast, (bottom left) 180 hr forecast; (bottom right), 156 hr forecast.

A comparison of the 156-hour and 132-hour GEFS, European and Canadian ensemble means for the sea-level pressure field verifying at 0000 27 December 2010 is shown in Fig. 7. Of the three ensemble systems, the ECMWF ensemble means appear to show a possible significant low pressure system closer to the Middle Atlantic and New England coasts than either the GEFS or Canadian means. This was especially true at days 5 to 6 (Fig 7b), when the ECMWF ensemble mean showed a significant low off the Middle Atlantic coast.

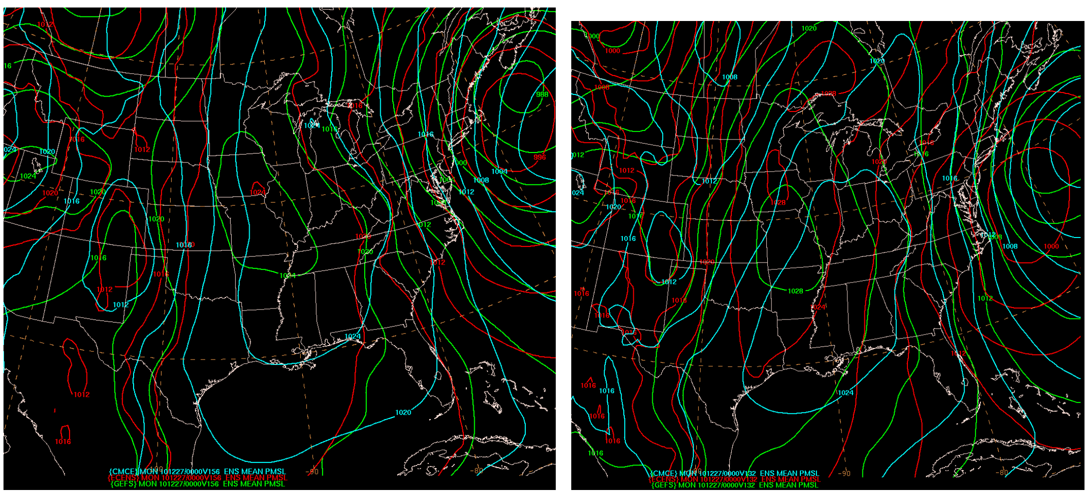

Fig. 7. Comparison of the Canadian (blue), ECMWF (red) and GEFS (green) mean pressure forecasts valid at 0000 UTC 27 December 2010. (left) 156-hr forecast; (right) 132-hour forecast.

These forecasts provided by the ECMWF led the medium range forecasters at HPC to predict that a significant storm was possible just off the Long Island/southeastern New England coast 6 days in advance (Fig. 8; compare with the analyzed 1200 UTC 27 December surface map in Figure 3).

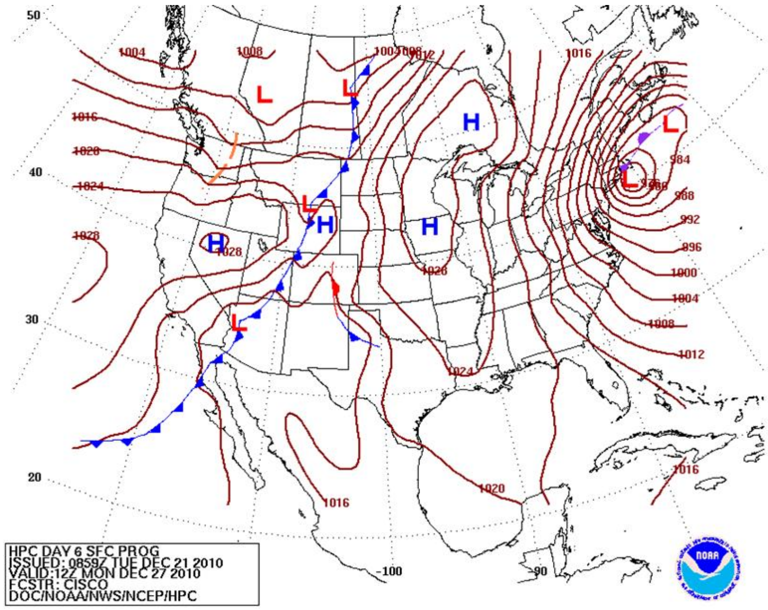

Fig. 8. HPC 6-day forecast verifying 1200 UTC 27 December 2010.

Deterministic forecasts

A few operational deterministic forecast models were predicting a significant cyclone off the New England coast for Christmas evening (December 25) as early as 7 days in advance (Fig. 9 ; the ECMWF is in red) - these forecasts were initialized at 1200 UTC December 18. An earlier version of the GFS predicted an intense cyclone east of

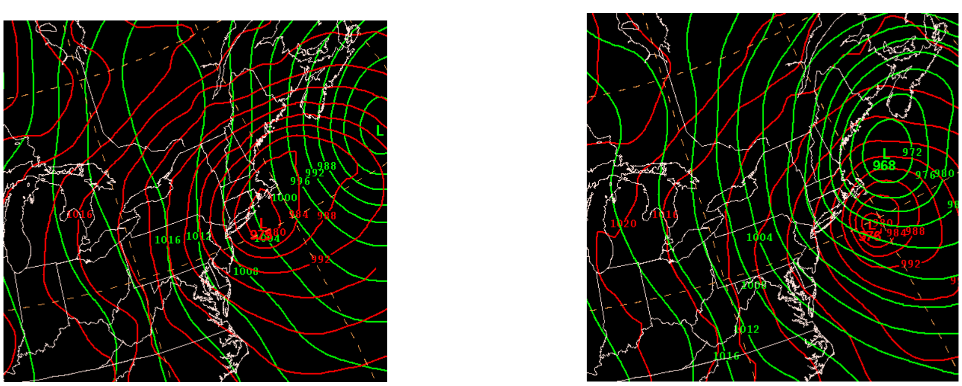

Fig 9. Comparison of the operational 168-h forecasts (left) and 156-h forecasts (right) from the GFS (green) and the ECMWF (in red) verifying at 0000 UTC 26 December 2010.

New England even 8 days in advance. On days 5 to 6 (the 12/19/00z through 12/21/00z model runs), both the operational GFS and European both had some indication of a possible storm in the Northeast although rather than affecting parts of the Northeast on Christmas Day, the models indicated that the storm would evolve at a slower pace and might affect the region on the day after Christmas. At this point, the forecasts did not have much run to run consistency, which is not surprising so far out in advance.

Medium range Forecasts (days 3 to 5)

Ensemble Forecasts

While the longer range forecasts had pointed to the possibility of a significant storm possible from the Mid-Atlantic to New England States, the medium range forecasts initialized from 5 to 3 days prior to the storm did not increase confidence that a distinct set of solutions would point to a preferred and more probable storm track and intensity for this system. While there was an envelope of solutions that pointed to the likelihood that a cyclone would develop along or off the Atlantic coast on 26 December, there was a large spread of solutions and thus a high degree of uncertainty associated with the potential cyclone.

Figure 10 shows the forecasts valid at 1800 UTC 26 December UTC from a set of GEFS forecasts initialized 5 to 3 days prior to that time. Though many of these ensemble mean forecasts showed a deep cyclone, most were well offshore. However, the shorter range forecasts (Fig. 11) showed a sharp westward shift to the cyclone track. Though not shown, the larger anomalies and generally deeper cyclone were due in part to smaller spread between members

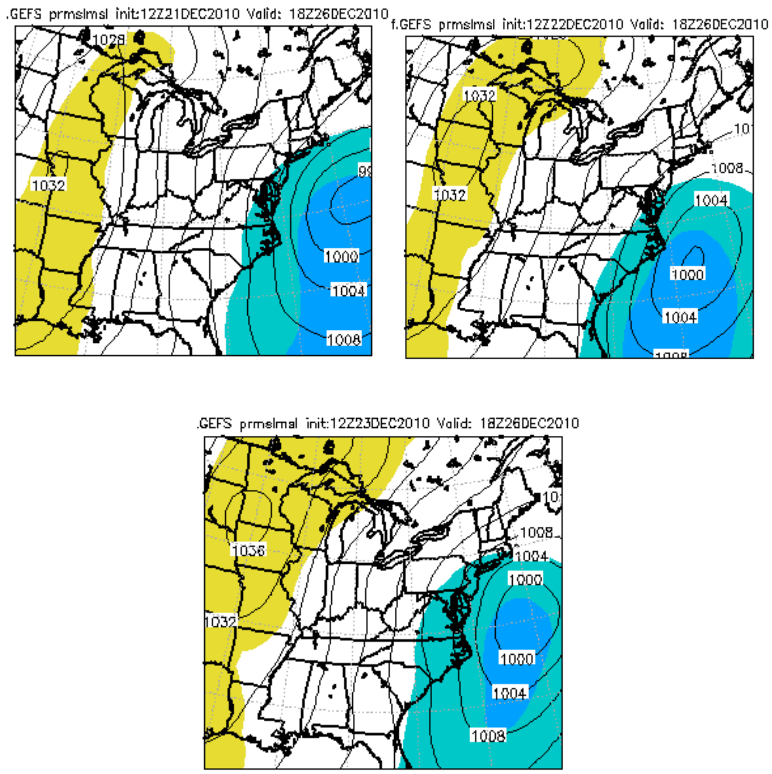

Fig. 10. GEFS mean sea-level pressure forecast valid at 1800 UTC 26 Dec 2010.(top left) 132 hr forecast, (top right) 108 hr forecast; (bottom),84 hr forecast.

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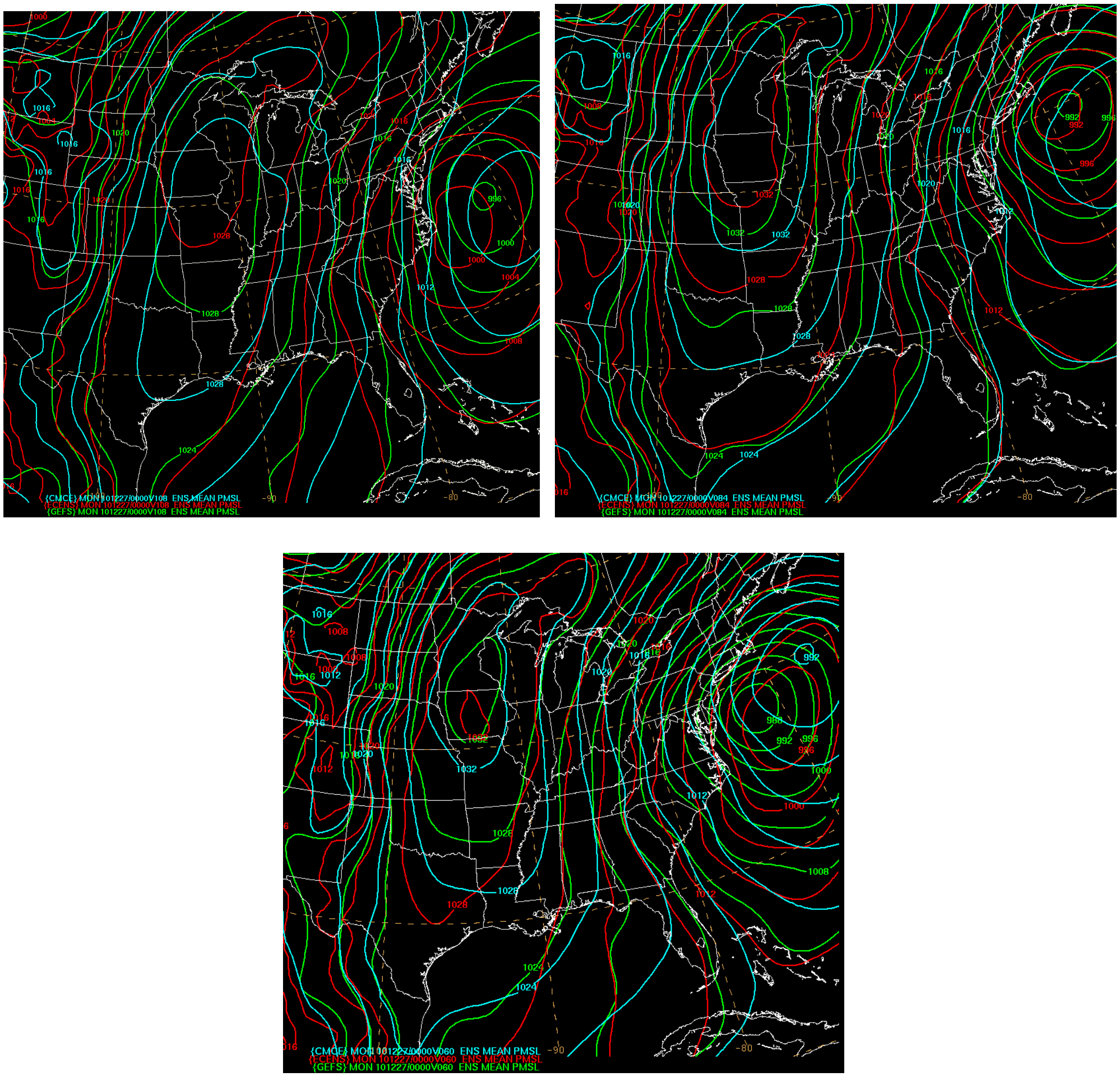


Fig. 11. Comparison of the Canadian (blue), ECMWF (red) and GEFS (green) mean pressure forecasts valid at 0000 UTC 27 December 2010. (top left) 108-hr forecast; (top right) 84-hour forecast and (bottom) 60-h forecast.

Figure 11 is a continuation of the graphics in Fig. 7 showing a comparison of the 5-day, 4-day and 3-day GEFS, ECMWF and Canadian ensemble means for the sea-level pressure field verifying at 0000 27 December 2010. The 108-hour forecast (Fig. 11a) shows that the European ensemble means are indicating a possible storm closer to the coast than either the GEFS or Canadian Ensemble means. At 84-hours prior to the storm (Fig. 11b), both the ECMWF and GEFS means maintain lows just off the southern New

England coasts, likely too far east to bring heavy snowfall to New York City, but still a significant threat to eastern New England. At 60 hours prior to the storm (Fig. 11c), which is the forecast issued at 1200 UTC 24 December, the GEFS mean shows the cyclone very close to where it actually verified, while the ECMWF mean and especially the Canadian means keep the cyclone farther east. These and other ensemble forecasts that showed a significant chance of an East Coast storm led medium range forecasters at HPC to issue graphical forecasts as early as day 6 showing a significant coastal storm (Fig. 8) and sustain that prediction 5, 4 ,3 and 2 days prior to the storm development (Fig. 12). Yet, given the differences between model systems, many forecasters remained uncertain even as the upper-level features started influencing the surface circulation and low pressure system off the East Coast on December 25th.

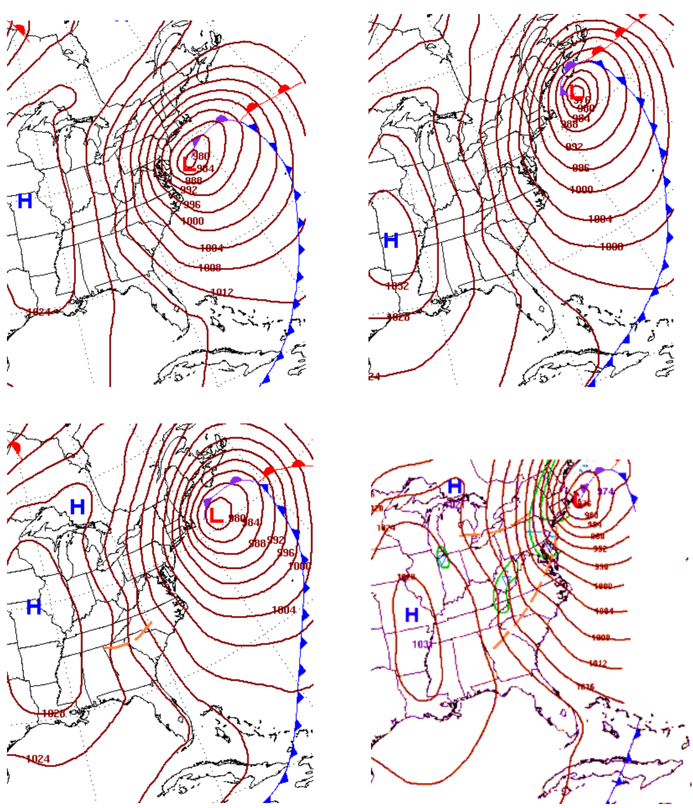
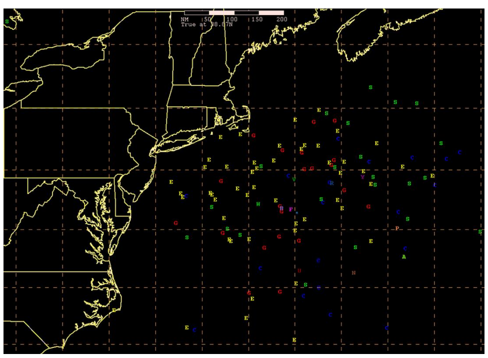


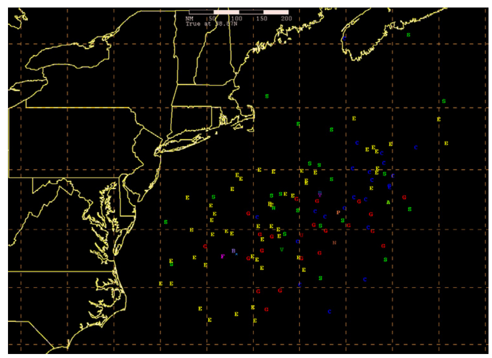
Fig. 12. HPC 5-day (top left), 4-day (top right) , 3-day (bottom left), and 2-day forecast (bottom right) verifying 1200 UTC 27 December 2010.

A multi-model and ensemble forecast (Fig. 13) shows low pressure centers not only from the GEFS system (red), but also from the European system (yellow), the Canadian model members (blue), the SREF members (green) and various operational models. Even though these models occur at the near end of the medium range forecast spectrum and enter in the realm considered short range forecasting, it is clear that a large spread remained among all members from 84 hours to 60 hours prior to 0000 UTC 27 December (initialized from 1200 UTC 23 December through 1200 UTC 24 December.). These ensemble forecasts show a large amount of spread and considerable uncertainty,

3 ½ days prior: 84-h fcst vt 12/27/00



3 days prior: 72-h fcst vt 12/27/00



Key
G – 20 GEFS
E – 50 ECMWF ENS
C – 20 CMC ENS
S – 21 SREF
A – CMC
B – GEFS BC
F – GFS
N – NAM
P - NOGAPS
R – SREF MEAN
U- UKMET
V – GEFS MEAN
W- ECMWF
Y – SREF BC MEAN

2 ½ days prior: 60-h fcst vt 12/27/00

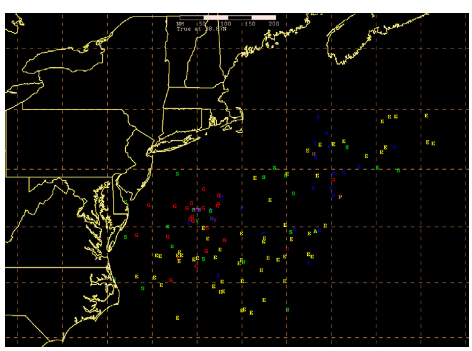


Fig. 13 Ensemble members verifying surface low positions verifying at 0000 UTC 27 December 2010. Green represents GFS – red represents ECMWF

making a deterministic prediction of a significant snowstorm difficult. At best, the forecast of a significant event could be expressed probabilistically, with the low potential of a significant snow (particularly at forecast hour 60) and the likely scenario a non-event.

Deterministic forecasts

A comparison of the operational deterministic forecasts issued 144 to 120 hours out show the operational ECMWF tracking the low along the coast but farther south, while the GFS kept the low farther east but oscillating inconsistently with time (Fig. 14 a, b, c). Despite the inconsistency, the Climate Prediction Center (CPC) issued the possibility of a heavy snow hazard from North Carolina to New England on 21 and 22 December during the period around and following the Christmas holiday (Fig. 15).

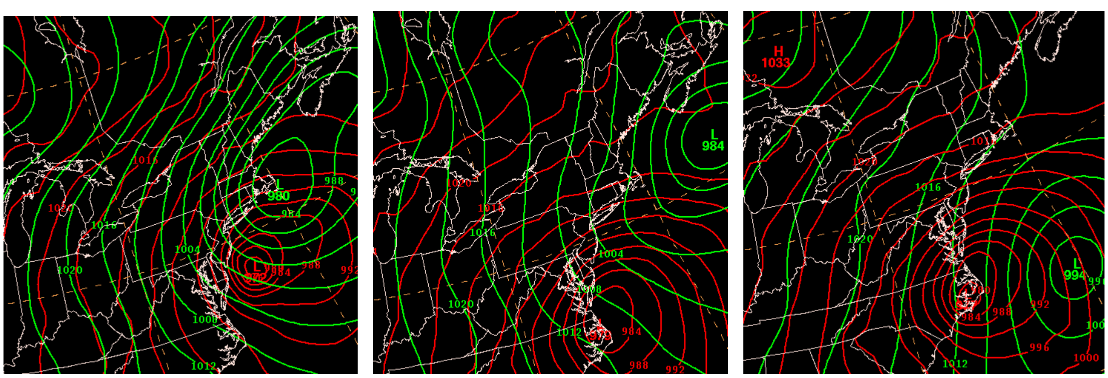


Fig. 14. Comparison of the operational 144-h forecasts (left), 132-h forecasts (middle) and 120-h forecasts (right) from the GFS (green) and the ECMWF (in red) verifying at 0000 UTC 26 December 2010.

While the operational GFS continued to forecast a center too far east of the Northeast United States through the 108-hour forecast, the operational European shifted the strong low from near the New England coast by 0000 UTC 27 December to a position

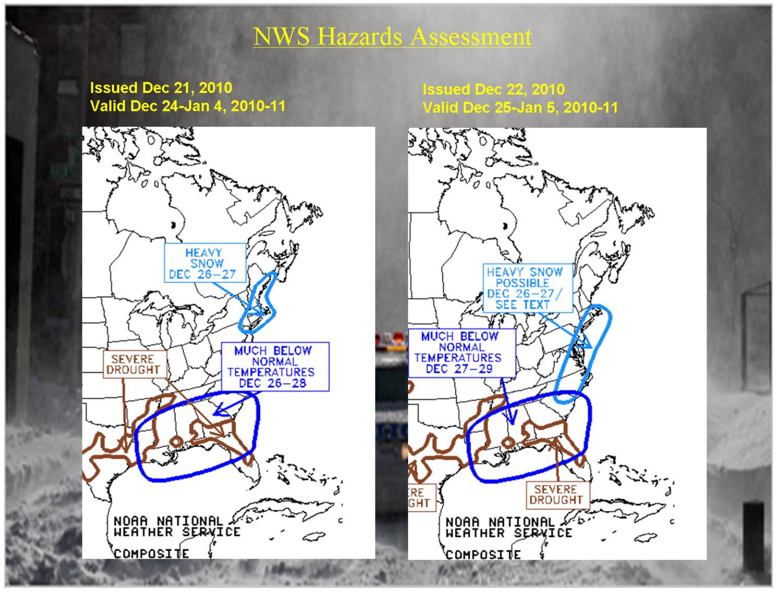


Fig. 15. NWS Hazards assessment from 21 and 22 December 2010.

near Cape Hatteras from the 132-hour to the 108-hour forecast (5 to 4-day forecasts initialized on 21-22 December). These forecasts are actually slower than the actual storm and farther west, which would have impacted the Washington-Baltimore area as well as locations farther north and east. A comparison of the European and GFS forecast tracks initialized at 1200 UTC 22 December versus the analyzed track is shown in Fig. 16.

While the GFS was now forecasting the cyclone to be located too far to the east to have much impact on the Northeast Coast, the operational European was indicating a significant threat of snowfall for a large area of the Northeast through the 4-5-day forecast period.

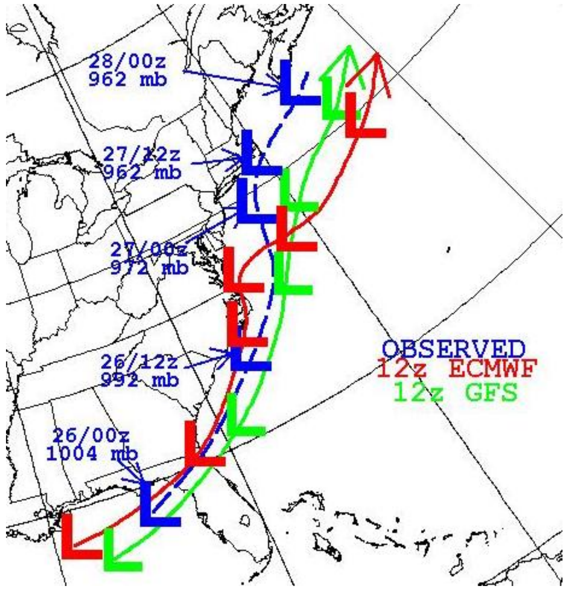


Fig. 16. Comparison of observed cyclone track to the operational 1200 UTC 22 December ECMWF and GFS forecasts.

The 96-hour forecast initialized at 0000 UTC 23 December (Fig. 17b) again shifted the European operational forecast farther northeast, actually close to the verifying position at 0000 UTC 27 December, while the concurrent GFS solution is farther north and east but would bring significant snow to southeastern New England.

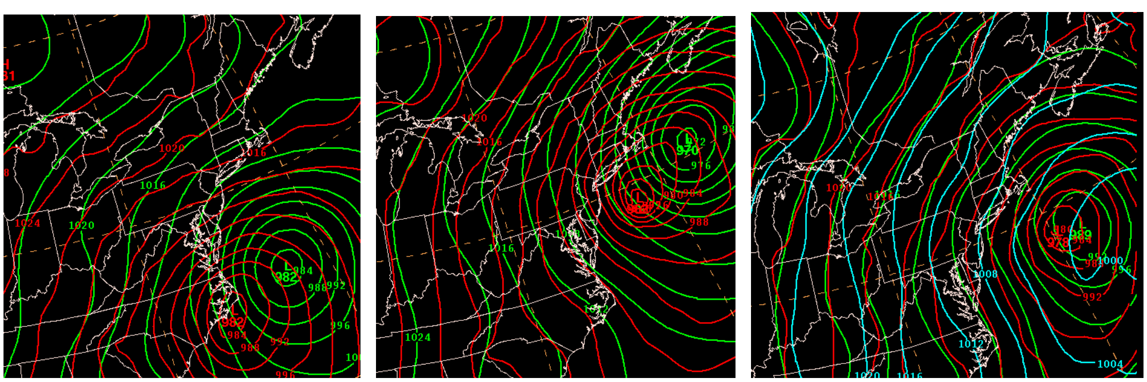


Fig. 17. Comparison of the operational 108-h forecasts (left), 96-h forecasts (middle) and 84-h forecasts (right) from the GFS (red), the ECMWF (in green) and NAM (in blue starting at 84-h) verifying at 0000 UTC 27 December 2010

Three to four days prior to the storm (December 22 to 23 forecast runs), the operational ECMWF and GFS actually come into alignment with the 84-hour forecast valid at 0000 UTC 27 December (Fig. 17c). However, the combined forecasts are both too far east of the verifying low center position and are indicating a threat of heavy snow possible for eastern New England, but not for New York City. A comparison of the European and GFS forecast tracks initialized at 1200 UTC 23 December versus the analyzed track is shown in Fig. 18, showing both tracks too far east of the verifying location.

In general, the 96-hour and 84--hour forecasts show a threat to southern New England but only possibly in New York City. This was true for the forecasts initialized between 12/23/00z and 12z. The 24-h precipitation forecasts from the 1200 UTC runs of the NAM, GFS and ECMWF (Fig. 19) all show the heaviest precipitation threat exists mostly across eastern New England, with the 0000 UTC GFS forecast posing the most widespread amounts, but still minimizing the threat to New York City.

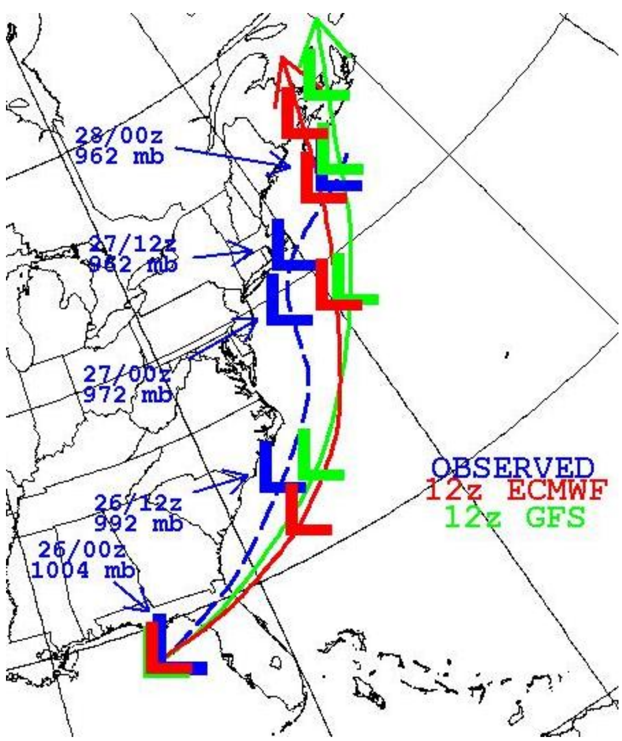


Fig. 18. Comparison of observed cyclone track to the operational 1200 UTC 23 December ECMWF and GFS forecasts.

By 23 December 1200 UTC, the storm system fell within the forecast range of the NCEP NAM (Fig. 20c). The operational forecast from the NAM at 12/23/12z had a solution for a cyclone that showed little if any threat even to southern New England. As a matter of fact, many of the deterministic forecasts issued at 0000 UTC 24 December showed only a marginal threat to anywhere in New England (Fig. 20) since all the tracks were much farther east of the observed track. A key point is that the NAM was 6 to 12 hours slower to converge on the correct solution than the GFS and GEFS ensembles.

84 h forecast of 24 h accumulated precip

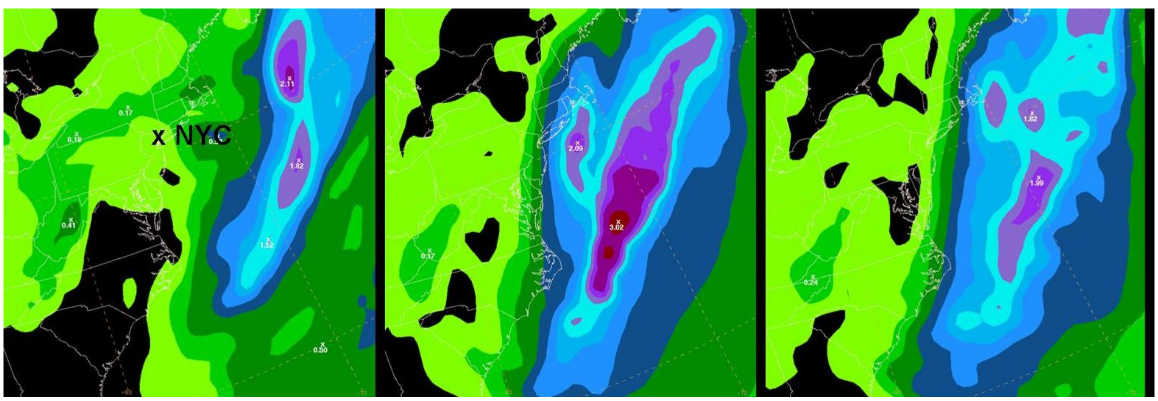


Fig. 19. NAM, GFS and ECMWF 84-h forecasts of 24-hour precip verifying at 1200 UTC 27 December 2010

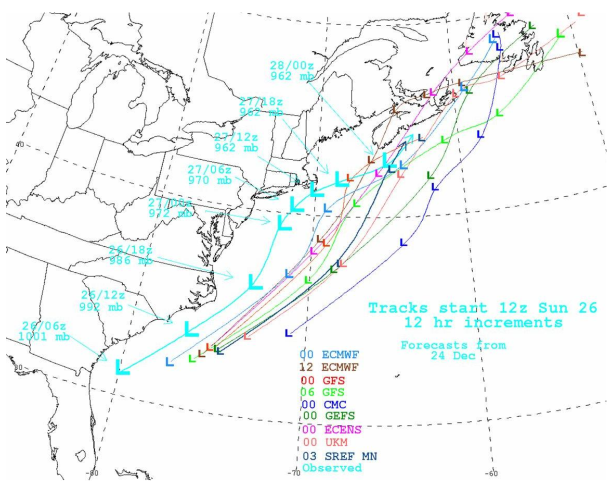


Fig. 20. Forecasts tracks from several different models initialized mostly at 0000 UTC 24 December.

00 UTC 24 Dec Runs

Short range forecasts (1-2 days)

Ensemble Forecasts

Starting with the 1200 UTC 24 December forecasts, the ensemble display of low pressure centers (Fig. 21) shows much more clustering of the surface low at 0000 UTC 27 December cared to earlier forecasts (Fig. 13), representing a much more consistent set of forecasts. Within this cluster is more clustering located just east of the Maryland-Delaware coast, which appears highly influenced by the GEFS members as well as the operational 0000 UTC 25 December GFS, which is discussed in the next section. The close westward edge of the clustering just off the southern New Jersey

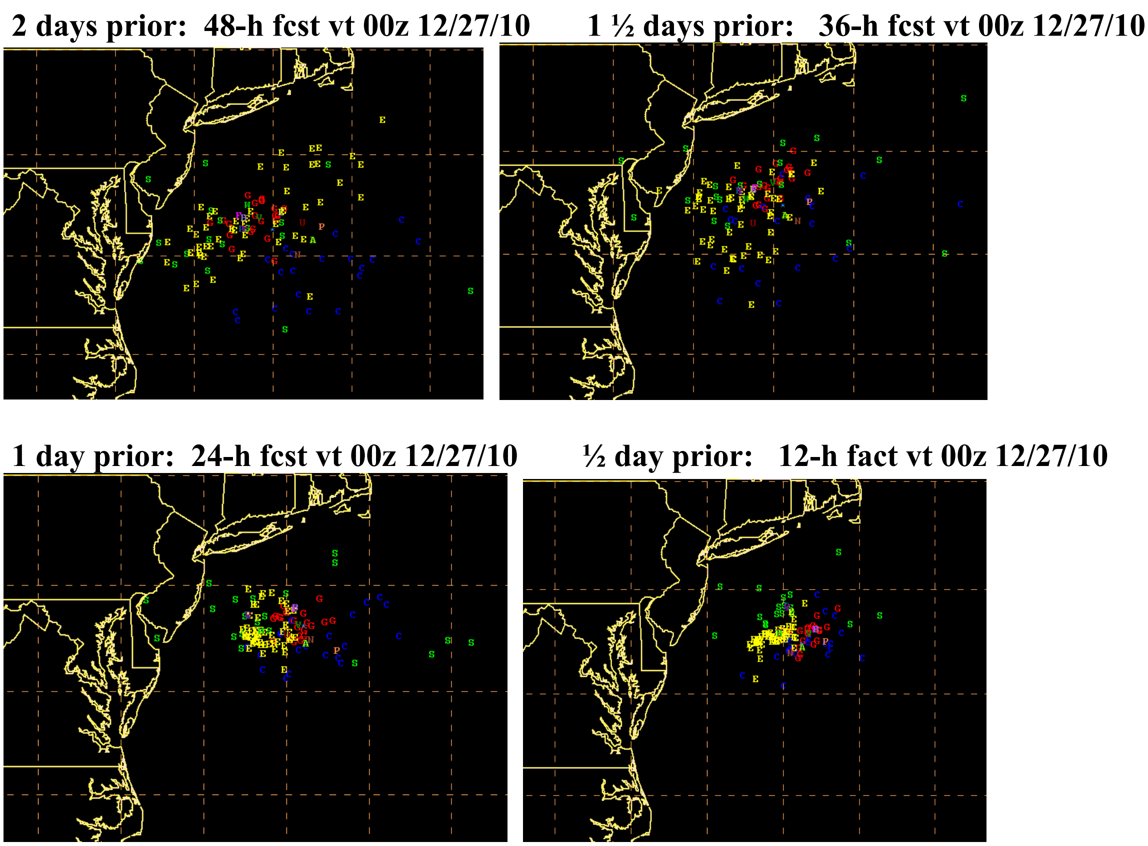


Fig. 21. Ensemble members verifying surface low positions verifying at 0000 UTC 27 December 2010. Green represents GFS – red represents ECMWF

– DelMarva coast continues through the 36-hour cycle (initialized at 1200 UTC 25 December) but those westward members begin to drop out by the 24-hour and 12-hour forecasts, which have the cyclone center farther east south of eastern Long Island.

A 6-hourly sequence of SREF forecasts verifying at 0000 UTC 27 December (Fig. 22) shows that surface low, which had appeared to represent little threat from forecasts initialized through 0900 UTC 24 December, changed character by the 1500 UTC forecast. In the set of forecasts initialized at 1500 UTC and 2100 UTC 24 December, the forecast low is farther westward in each run suggesting a dramatic shift on the potential snow and precipitation shield north and west of the cyclone. However, even these forecasts were too far south and west of the actual cyclone and helped steer forecasters in the Washington D.C. area to overestimate the likelihood of significant snow.

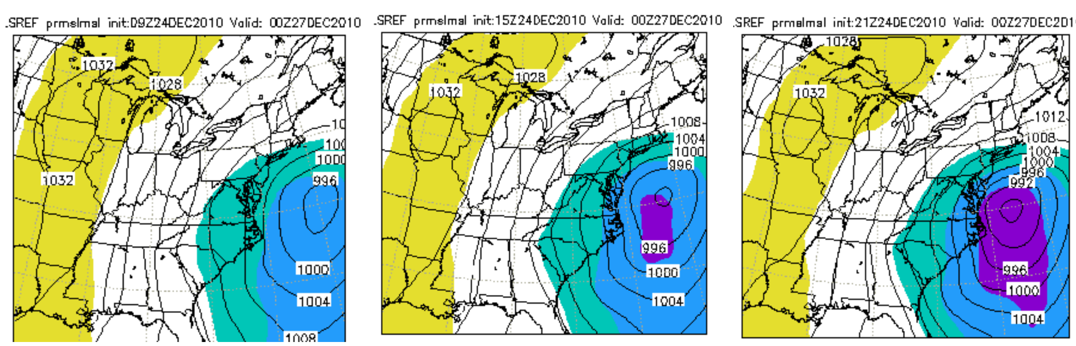


Fig. 22. SREF mean sea-level pressure forecasts valid at 0000 UTC 27 December 2010.
(left) init at 0900 UTC 24 Dec; (middle) init at 1500 UTC 24 Dec; (right) init at 2100 UTC 24 Dec.

A summary of the SREF/GEFS forecasts for the period 1, 2 and 3 days prior to the snowstorms, and compared to the HPC forecast low tracks are shown in Fig. 23. Mean precipitation amounts predicted by the SREFS on 25 December (Fig. 24) indicated more potential for snow in Washington D.C. than actually occurred.

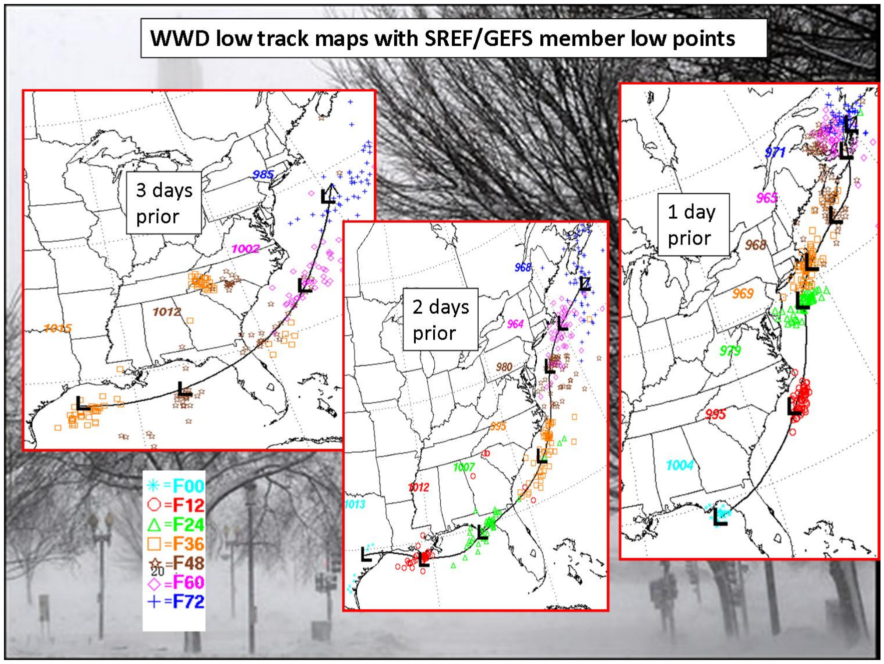


Fig. 23. Daily surface low tracks produced by the winter weather desk at HPC on Dec. 24, 25 and 26th, 2010, with locations of SREFS/GEFS forecast low positions.

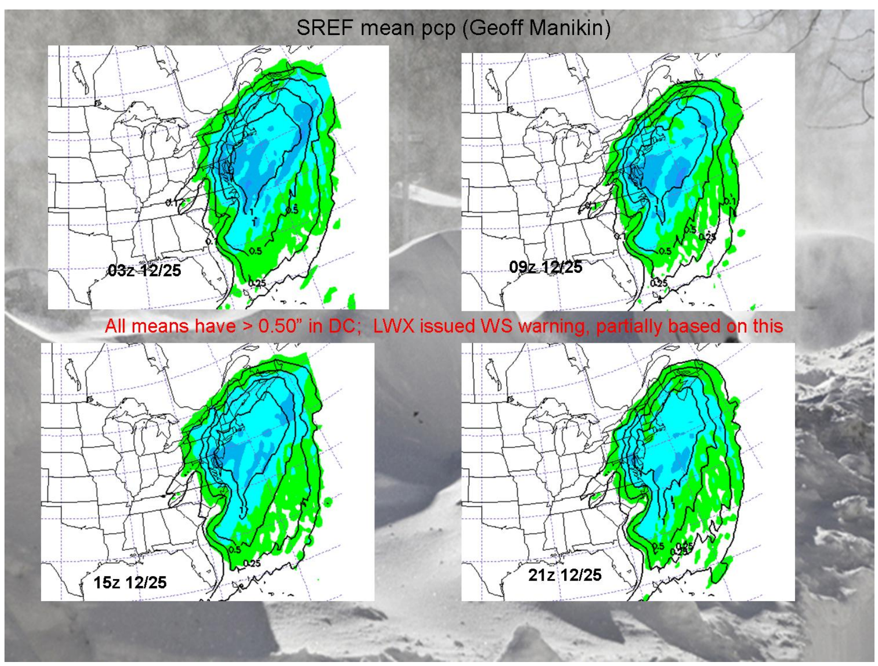


Fig. 24. Mean SREFS storm total precipitation for forecasts issued at various times on Dec. 25 2010.

Deterministic Forecasts

The 72-hour forecasts issued by the ECMWF and GFS at 12/24/00z at 0000 UTC 27 December were farther west than the previous main forecast cycle (Fig. 25a), with solutions allowing at least some snow to fall in both southern New England and New York City. The NAM forecast issued at the same time still pointed to a solution too far east to have much impact even in eastern New England.

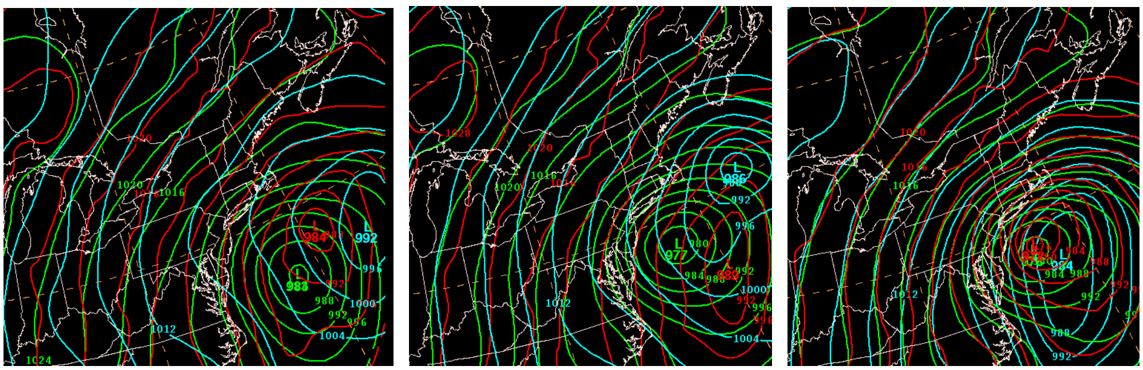


Fig. 25. Comparison of the operational 72-h forecasts (left), 60-h forecasts (middle) and 48-h forecasts (right) from the GFS (red), the ECMWF (in green) and NAM (in blue) verifying at 0000 UTC 27 December 2010

This is the period which starts off with the model forecasts initialized at 1200 UTC 24 December and 0000 UTC 25 December. This is also a time period when many of the forecasts began to converge toward the potential for a cyclone closer to the coast and for heavy snow in many of the major cities along the East Coast.

The 24 December 2010 forecasts

Even as the period approaching the upcoming event was growing shorter, the deterministic model forecasts issued on 24 December exhibited some profound changes that worked against a consensus forecast for New York City.

With the 60-hour forecast issued by the 1200 UTC 24 December GFS (Fig. 25b), the operational GFS created a lot of excitement by moving the cyclone center considerably farther westward than earlier runs, bringing the possibility of heavy snow not only to southern New England and New York City, but also farther south and west to the Washington-Baltimore area. A comparison of the European and GFS forecast tracks initialized at 1200 UTC 24 December versus the analyzed track is shown in Fig. 26, clearly showing the GFS following a path that actually verified much closer to the actual cyclone track, especially as other models continue to show the cyclone tracking much farther east (Fig. 26).

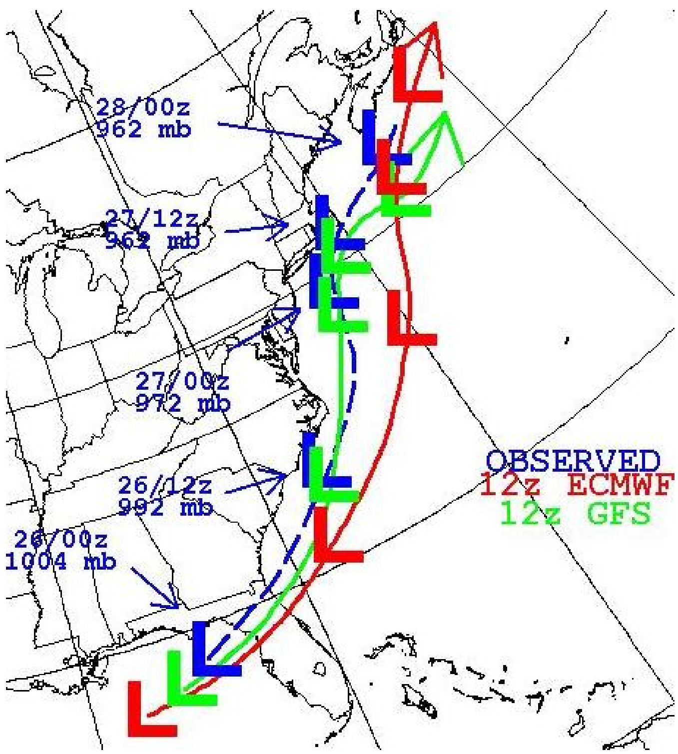


Fig. 26 Comparison of observed cyclone track to the operational 1200 UTC 24 December ECMWF and GFS forecasts.

At this time, the operational ECMWF run goes the other way, predicting a weaker cyclone now that goes too far east to produce any snow of significance anywhere along the Northeast Coast. In addition, the operational NAM initialized at 1200 UTC 24 December is also too far east. A summary of many of the model forecasts issued at 1200 UTC 24 December are shown in Fig. 27 showing that the GFS operational run at this time was much farther west than many other operational runs. The GFS correctly began converging on the correct track of the cyclone.

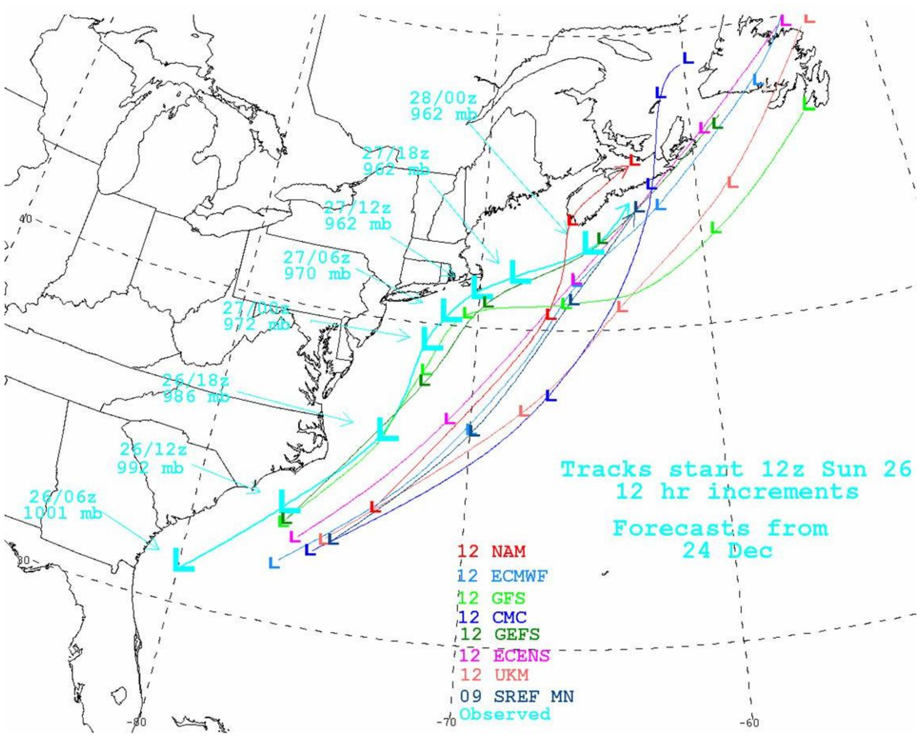
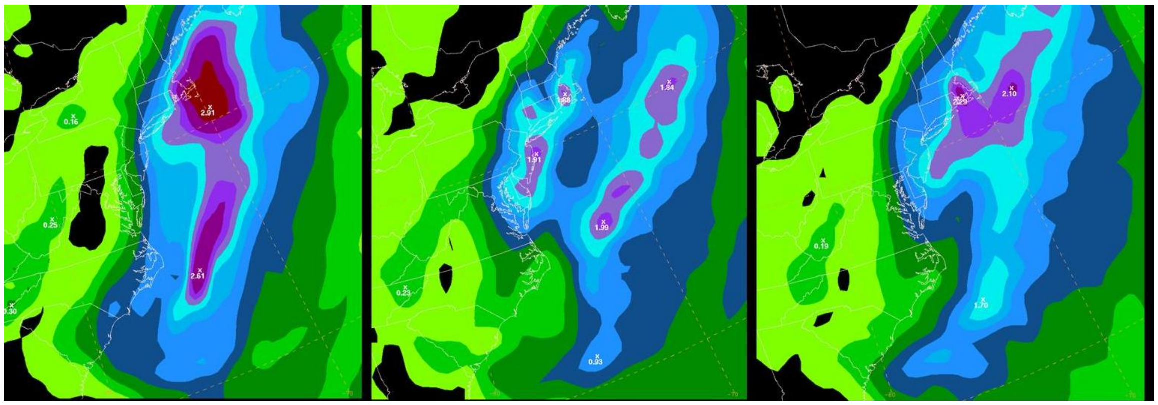


Fig. 27. Forecasts tracks from several different models initialized mostly at 1200 UTC 24 December.

The precipitation forecasts from these runs showing the NAM, GFS and ECMWF predictions from the 1200 UTC 24 December run are shown in Fig. 28, showing a clear threat of heavy snow for New York City but the GFS is overpredicting snow for Washington-Baltimore.

12 UTC 24 Dec Runs

72 h forecast of 24 h accumulated precip



NAM **GFS** **ECMWF**

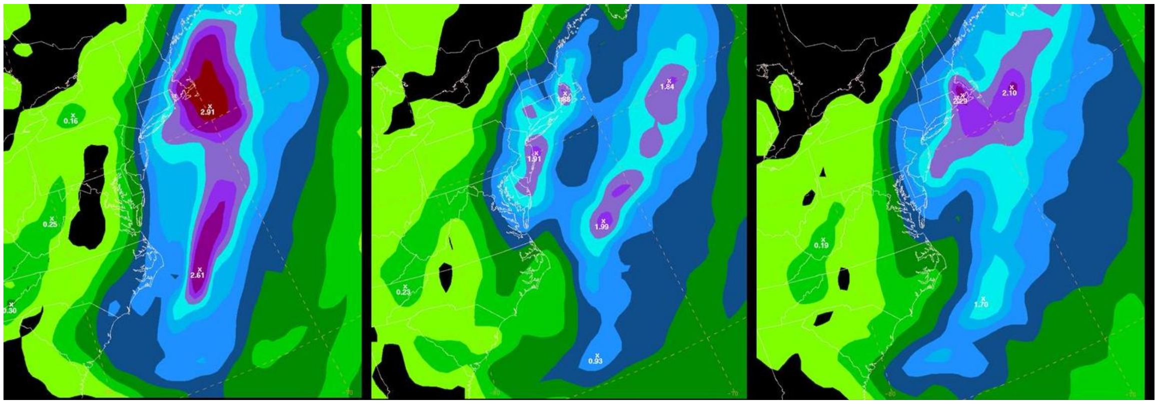
Fig. 28. NAM, GFS and ECMWF 72-h forecasts of 24-hour precip verifying at 1200 UTC 27 December 2010**.**

With the 54-hour thru 42-hour forecasts verifying at 0000 UTC 27 December, the operational GFS continues to forecast heavy snow far enough west to create significant snowfall into the Washington-Baltimore area. The 48-hour ECMWF forecast (Fig. 25c) initialized at 0000 UTC 25 December actually has a more westward solution again threatening much of southern New England and New York City. The 54-hour to 42-hour NAM forecasts are still too far east to bring heavy snow into New York City but does generate heavy snows into eastern New England.

A comparison of the total 48-hour precipitation forecasts from the 1200 UTC 25 December NAM, GFS and European models (Fig. 29) show that the GFS at this time correctly predicted heavy snowfall in New York City while overpredicting precipitation in Washington, D.C. Meanwhile, the NAM and European bring significant snow into New York City but leaves the heaviest snowfall east of the city over Long Island.

00 UTC 25 Dec Runs

60 h forecast of 24 h accumulated precip



NAM **GFS** **ECMWF**

Fig. 29. NAM, GFS and ECMWF 60-h forecasts of 24-hour precip verifying at 1200 UTC 27 December 2010**.**

Forecasts initialized 48 to 36 hours before the event (25/ 0000 UTC and 25/1200 UTC) from the three deterministic models, including the NAM, GFS and ECMWF (Fig 30) provide a realistic and consistent forecast of heavy coastal snows from eastern Virginia through New Jersey across New York City across New England, while missing the Washington-Baltimore area. These are also the times that most operational models come into alignment.

The 1800 UTC 25 December 2010 NAM and GFS forecasts (Fig. 31) both correctly placed local precipitation maxima near New York City. The 0000 UTC 26 December GFS and NAM forecast runs both kept heaviest precipitation east of the Washington D.C. area. However, the 03z SREF forecast continued to produce significant precipitation amounts in the Washington area although the 09z run moved it slightly eastward.

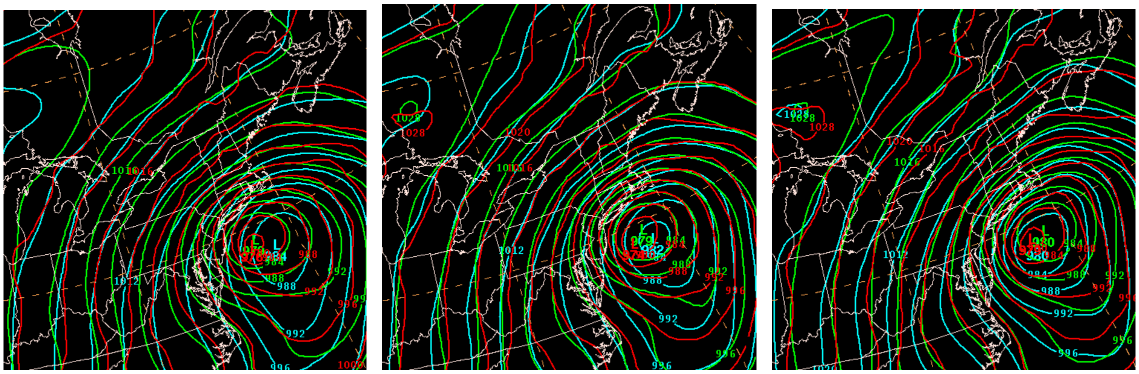


Fig. 30. Comparison of the operational 36-h forecasts (left), 24-h forecasts (middle) and 12-h forecasts (right) from the GFS (red), the ECMWF (in green) and NAM (in blue) verifying at 0000 UTC 27 December 2010

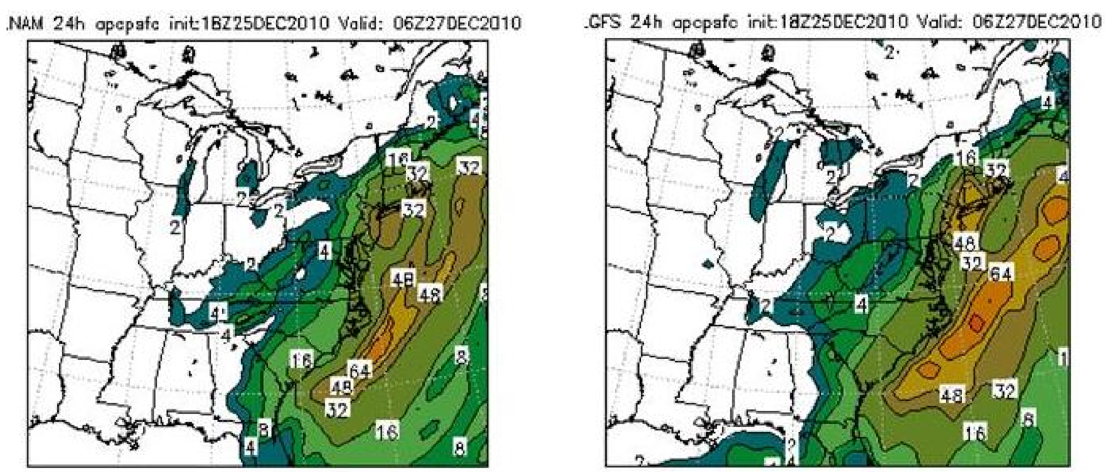


Fig. 31. Operational 24-hour precipitation forecasts from 1800 UTC 25 December 2010 NAM (left) and GFS (right).

Summary of the Ensemble and deterministic forecasts for the December 2010 Blizzard:

The ensemble forecasts indicated the possibility of a significant East Coast storm as early as 8 days in advance. While there was a clear consensus approximately a week in advance that a storm was possible off the East Coast, the majority of ensemble members, and the ensemble means, suggested that the storm would stay well to the east so that significant precipitation might brush portions of New England. There was enough uncertainty that medium range forecasters suggested the possibility of a high impact event as early as 6 days in advance.

Three to five days in advance of the storm, the total suite of model guidance did not appear to increase confidence that a particular solution might have more impact to the Northeast with heavy snow and high winds. The ensemble forecasts continued to show a very large range of solutions with only a small percentage of solutions showing a storm location that matched with reality. The important consideration here is that even though the mean solution kept the storm far enough east that perhaps only New England was threatened, there were a small number of solutions that did threaten New York City with the potential for heavy snow.

With the advent of the three to two days forecasts issued on 23-24 December, there were some significant shifts. While the European ensembles trended eastward away from a significant snow threat, the GFS/SREF ensembles appeared to trend westward during the day of 24 December. So, while the European forecasts seemed to ease the threat of significant snow, the GEFS/SREFS both seemed to indicate an increased threat of heavy snow, not only for New York City, but even as far south and west as Washington, D.C. While little snow fell in the nation's capital, these forecasts correctly suggested the threat to New York City.

For the ensemble forecasts, particularly the GEFS and SREFS solutions began converging by 1200 UTC 24 December (the SREFS began at 1500 UTC). It was only until 25 December that the deterministic forecasts (see next section) converged closer on a solution that gave New York City, New Jersey and New England the brunt of the snowstorm while minimizing the threat to Washington D.C.

The operational forecasts indicated the possibility of a significant East Coast snowstorms as early as 7 days in advance, with the 168-hour forecast by the GFS and the 156-hour forecast by the ECMWF both indicating the potential for heavy snow in the heavily populated Northeast.

Over the next several days, the models waffled back and forth, with the operational European model trending more toward a heavy snow solution for the East Coast although it put the area of heavy snows northwest of a position near Norfolk, Virginia. Meanwhile, the GFS trended more towards an eastward solution, indicating less of a threat for the Middle Atlantic states, and more of a threat for eastern New England.

By 0000 UTC 24 December, a consensus of solutions appeared which seemed to spare New York City the heaviest snows as nearly all deterministic solutions trended eastward off the East Coast. However, by 1200 UTC 24 December, the operational GFS correctly trended much farther westward, indicating the potential for heavy snowfall not only in New York City but as far south and west as the Washington D.C.-Baltimore, MD area. However, the operational ECMWF continued to trend farther east, as did the NAM, keeping the heaviest snows either over New England or off the coast. Finally, by 0000 UTC 25 December, another consensus solution began to appear, suggesting that the models were finally converging on a track consistent with the GFS forecast from 24 December that indicated that the New York City-Boston corridor was in line with the potential for the heaviest snow with very strong winds associated with a rapidly deepening surface low. This consensus for a major snow event for New York City and surrounding areas emerged 36 to 48 hours before the onset of the heaviest snows.

HPC winter weather desk forecasts.

Day-3, Day-2 and Day-1 categorical snowfall forecasts of 24-hour snow amounts exceeding 4 inch, 8 inch and 12 inches are routinely issued by the winter weather desk at HPC.

While the GFS, GEFS and SREFS members were trending toward a more westward track as early as 1200 UTC 24 December, the day 3 4-inch snowfall forecast issued by HPC after the 1200 UTC 24 December morning forecasts were issued only showed a threat of significant snow across the eastern New England coast and no indication of a potential for snowfall exceeding 12 inches (Fig. 32).

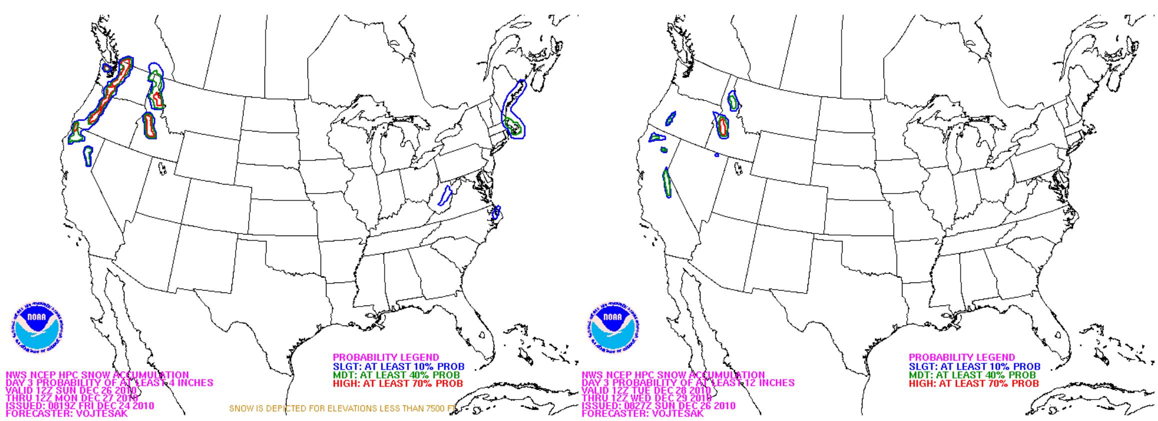


Fig. 32. Probabilistic forecasts of at least 4 and 12 inches of snow for the period 1200 UTC 26 December to 1200 UTC 27 December.

Even by the next 12-hour forecast cycle that used the suite of models initialized through 0000 UTC 25 December, the HPC forecasters still did not expect the heaviest snow to fall west of extreme eastern New England (Fig. 33).

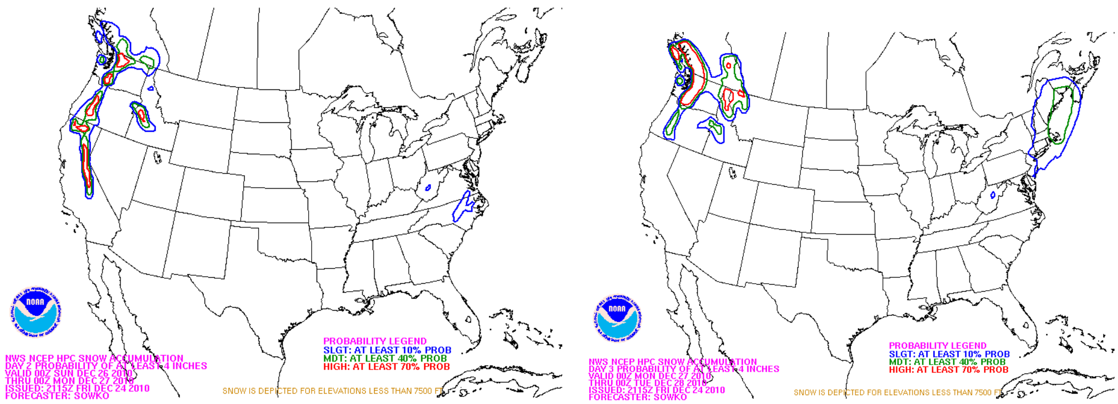


Fig. 33. Probabilistic forecasts produced following the issuance of 0000 UTC 25 December model forecasts of at least 4 inches of snow for two 24-hour periods; 0000 UTC 26 December to 0000 UTC 27 December and 0000 UTC 27 to 28 December 2010.

HPC forecasts issued on Christmas morning, following the 1200 UTC 25 December runs were accessed are shown in Fig. 34. These are the first HPC winter weather products that indicated that New York City would likely get more than 4 inches of snow, and possibly greater than 12 inches of snow, but less than 10 percent.

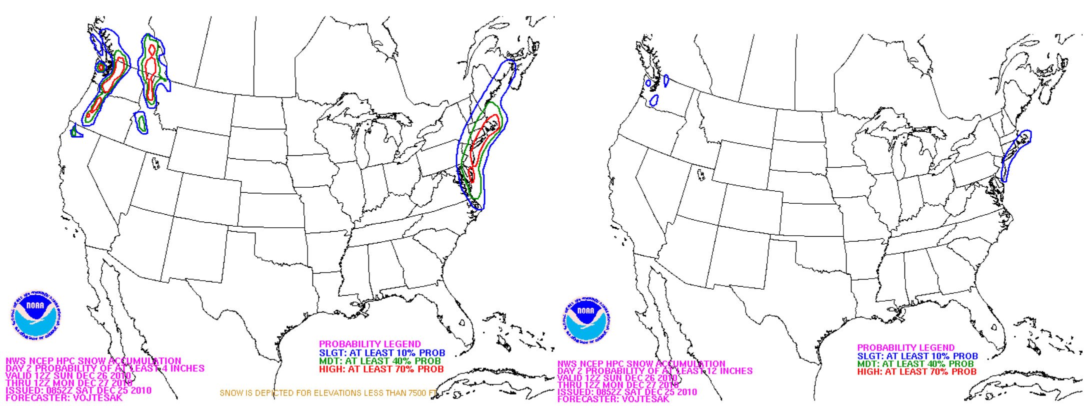


Fig. 34. Probabilistic forecasts produced following the issuance of 1200 UTC 25 December model guidance of at least 4 inches and 12 inches of snow for the period 1200 UTC 26 December to 1200 UTC 27 December.

The HPC forecasts issued after the 0000 UTC 26 December guidance package was received are shown in Fig. 35. Since the snow falls over two consecutive 24-hour periods, one can infer that New York City has a high likelihood of heavy snow from these forecast probabilities of greater than 4 inches and 12 inches of snow.

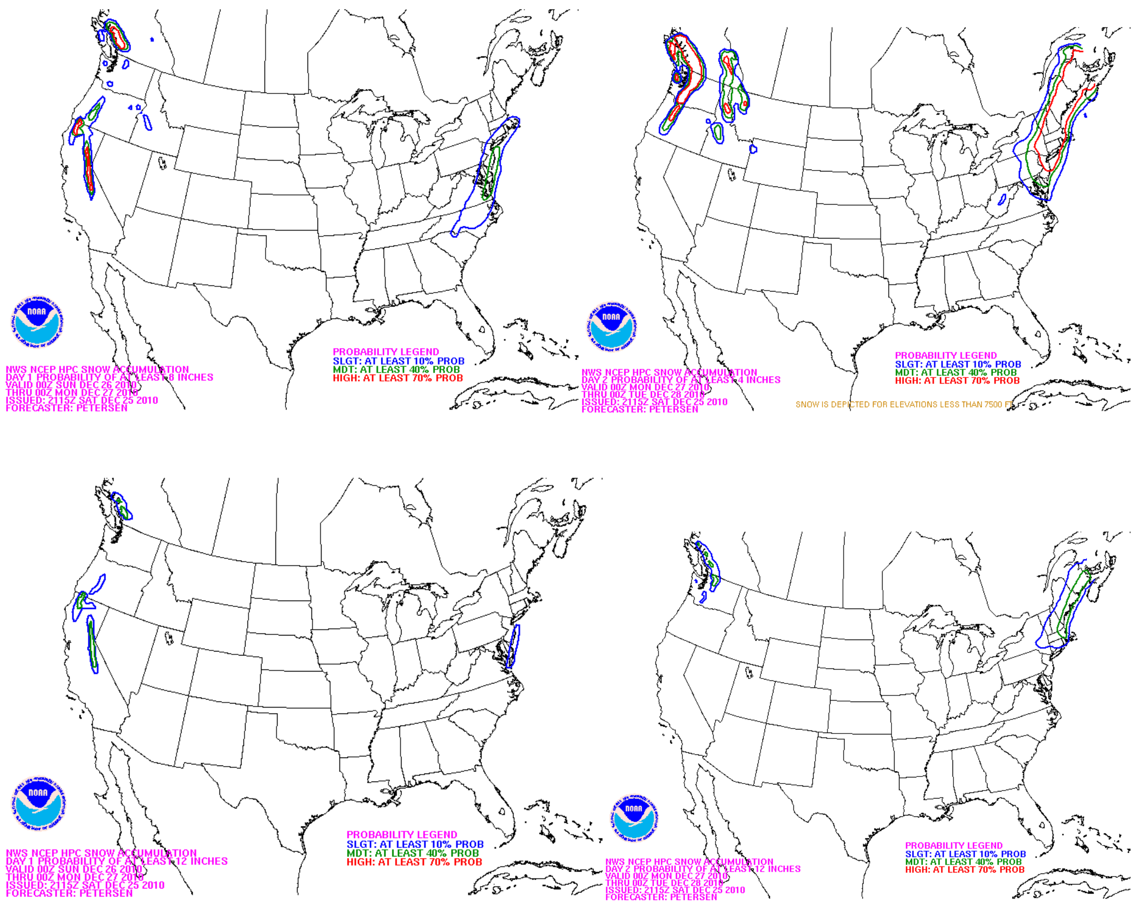


Fig. 35. Probabilistic forecasts produced following the issuance of 0000 UTC 26 December model forecasts of at least 12 inches of snow for two 24-hour periods; 0000 UTC 26 December to 0000 UTC 27 December and 0000 UTC 27 to 28 December 2010.

Finally, the HPC forecasts issued after the 1200 UTC 26 December guidance package was received are shown in Fig. 36.

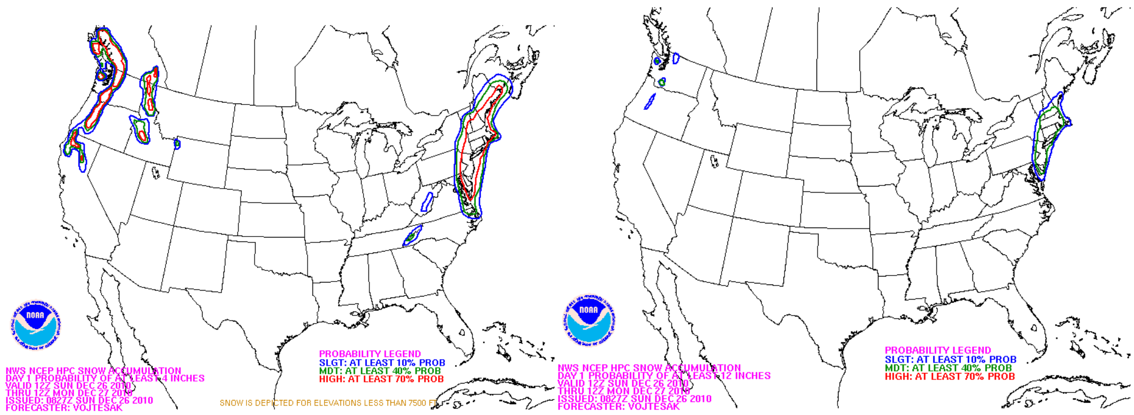


Fig. 36. Probabilistic forecasts produced following the issuance of 1200 UTC 26 December model guidance of at least 4 inches and 12 inches of snow for the period 0000 UTC 26 December to 0000 UTC 27 December.

Therefore, HPC forecasters did not believe the trends in the GFS, GEFS or SREFS forecasts until Christmas morning, only 36 hours prior to the onset of the heaviest snow.

Possible observational errors and Quality Control Issues

There were a number of data quality control (QC) and usage problems that may have contributed to erratic forecasts (tracks, precip, etc.) for the December snowstorm. It can not be determined definitively if certain QC issues made a difference in model forecasts, without additional model experiments designed around withholding problem observations. However, since a number of ensemble forecasts showed large variance, it is expected that QC errors could have significant impact on model skill. Furthermore, some spurious large analysis changes from the model background (BG also referred to as the guess) due to QC problems may have had a bigger impact on forecasts than the generally smaller and more random ensemble analysis perturbations. Currently, ensemble perturbations do not directly include data QC uncertainty effects as that would be very costly in computer time.

The biggest data QC problem for this period appears to be that in a number of off-time (06Z and 18Z) analyses, the Vertical Azimuth Display (VAD) radar winds caused relatively large impact by slowing analysis winds on the order of 20 knots over the CONUS. These VAD data supply a potentially very useful, high density network of wind profiles every half hour, but these data have serious problems including low speed biases and bird migration impact in the spring and fall. For example, Fig. 37 shows the GFS analysis minus guess had 25 knot wind changes at 750 hPa for 06Z, 21 December 2010 in the west Texas area. These large wind changes are believed to be due to VAD winds with spurious slow winds that passed QC, and suggest that the VAD QC needs to be more aggressive. Tests at NCEP will be started soon using new VAD winds derived from level II radar winds after QC.

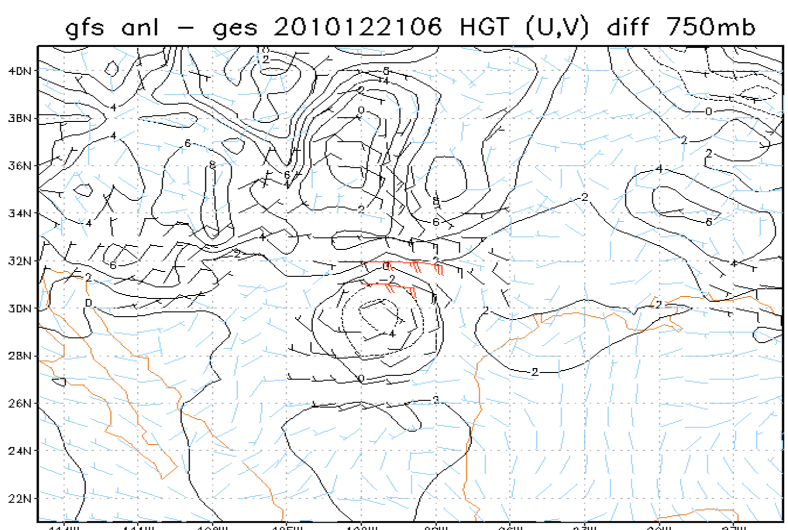


Fig. 37. GFS analysis minus guess heights and winds in knots, 750 hPa 06Z 21 December 2010

The VAD QC and other QC codes running prior to the GSI analysis have a common problem of using a low resolution BG without time interpolation and error using a standard atmosphere to estimate pressures from winds reporting in altitude only, all of which are inferior to the interpolation of the BG in the GSI. Some wind data with small increments to the BG in the GSI had large increments to the BG in pre-GSI QC codes and were improperly rejected. Some areas showed large changes in the BG wind with time, which indicates that a 4DVAR analysis may be useful during this period.

There were also some QC problems with some AIREP reports at wrong locations that passed QC due to an old waypoint dictionary at the NWSTG that was replaced on 22 February 2011. Some minor QC problems with ACARS reports at wrong locations that also passed QC would have been rejected by the NRL aircraft QC code scheduled for operation in Q2 of 2011. Some ships and buoys with large slow speed biases right along the east coast passed QC too often and caused some slowing of analysis winds which may have impacted forecasts. The worst example was ship NWS0029 that had all calm winds after December 20th, and many of these passed QC. The NCEP reject-list system is planned to be improved to find such problems sooner.

In addition, there is the long standing problem where the GFS analysis is about .5 to .75 degrees warmer than radiosonde temperatures around jet-stream level due to large numbers of aircraft data with warmer biases as pointed out by Ballish and Kumar (BAMS, Nov. 2008). This problem would be improved by both aircraft temperature bias correction as well as improved radiation correction (RACOR) with the US Sippican Mark II sondes. Recent work by NESDIS's Anthony Reale and Bomin Sun (AMS annual meeting, Jan. 2011) suggest that these sondes are a few tenths of a degree too cold from about 400 to 100 hPa by comparison with GPSRO data. New software being implemented at US upper air sites has an improved RADCOR that should lessen this problem. So far, we do not know the impact of these temperature problems on forecasts.

Tests have been done using speed dependent QC and ECMWF like filtering rules with satellite winds that did show some positive impact on forecast skill. Such tests could be run for this time period and may be helpful in cases where an important area in the analysis is in the Pacific.

Impact of model forecasts on the Aviation community

The total cost of domestic air traffic delays to the United States economy was as much as $41 billion for 2007 (reference). The majority of these delays are directly attributable to weather. Following several lengthy and well publicized tarmac delays that kept passengers "trapped" onboard aircraft for several hours, Congress explored a Passenger's Bill of Rights as early as 2005. Although legislation was discussed but never enacted, Congressional and DOT outrage peaked following the flight of Express Jet 2816 on 8 August 2009, which kept passengers sitting on-board the aircraft for nearly six hours following a weather diversion to Rochester, MN. This led Congressional passage of the Three-Hour Tarmac Rule which went into place on 29 April 2010. The Three-Hour rule has been described as a National Airspace System (NAS) industry “game-changer,” as airlines now face a fine of up to $27,500 per passenger for tarmac delays exceeding three hours. As a result, flight cancelations rather than lengthy tarmac delays are now more common than prior to the new law. For example, in the six months following the April 2010 legislation, only 12 domestic flights experienced tarmac delays exceeding three hours, compared to 546 during the same six month period the previous year (RITA, USDOT). The airline industry is changing their approach to managing aircraft and passengers due to weather delays, and becoming more proactive by canceling flights to insure against long tarmac delays and costly penalties.

Turning attention to the blizzard of 26 December 2010, the Aviation Weather Center (AWC) began coordination with NWS aviation meteorologists (e.g., RAMS, OCWWS/ASB, Matt Lorentson) and the FAA National Air Traffic Control System Command Center (ATCSCC) on 23 December 2010 when the first AWC Impact Dashboard was issued, describing the *potential* for a substantial snow and wind event along the East Coast depending on the track of a coastal low expected to develop rapidly over the Holiday weekend. The discussion included an 81-hour SREF spaghetti chart of surface low centers valid at 18 UTC 26 December 2010 to illustrate the uncertainty in position of the low center (Fig. 38). At the time, most SREF members kept the low relatively far offshore. The AWC updated the dashboard on the 24th, and coordinated a conference call midday on the 25th as the models and ensembles showed an increasing probability of a significant winter event. This call was led by Bob Maxson, Director of the AWC, and included the Director of the NWS Eastern Region, all the WFOs along the mid-Atlantic region to Portland, ME, and Matt Lorentson (stationed at the ATCSCC). At that time, the 09 UTC 25 December SREF 33-hour forecast ensemble mean and spaghetti chart of sea level pressure and low centers showed the surface low center much closer to the coast with the SREF membership in much closer agreement than two days earlier (valid 18 UTC 26 December; Fig 39). Snowfall plumes from that run of the SREF still showed considerable uncertainty in snowfall amounts, but a SREF mean around 12" and the primary cluster around 17" at JFK (Fig. 40)

The aviation industry was proactive in flight cancellations in anticipation of the major winter storm on 26-27 December 2010. The New York City area was responsible for the brunt of the aviation impact, with thousands of flights canceled at the city's three commercial airports: JFK, LaGuardia, and Newark Liberty on 26 and 27 December. Four of the nation's largest airlines operate hubs at one of the three NYC airports (American, Continental, Delta, and JetBlue), while US Airways operates hubs at Philadelphia and Charlotte, which also experienced winter weather as a result of this storm. The impact to aircraft operations at the three NYC airports reduced capacity around 65% on 26 December and 99% on 27 December as compared to the previous year (Fig 41). The NYC airports were closed for approximately 24 hours and began to slowly restore service during the late afternoon and evening of the 27^{th}. Farther to the west, O'Hare International Airport and Midway Airport in Chicago also experienced weather issues on 26 December, with more than 200 flights canceled due to lake effect snow, difficulty in deicing planes, and the East Coast blizzard.

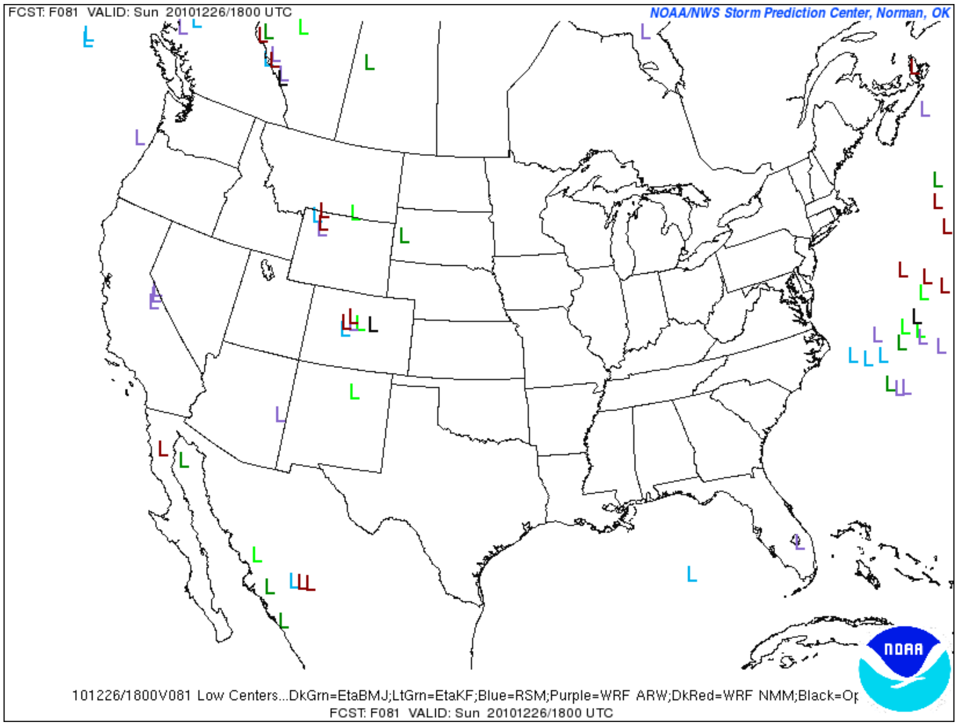


Fig. 38 SREF 81-hour SLP low center spaghetti forecast valid 18 UTC 26 December 2010.

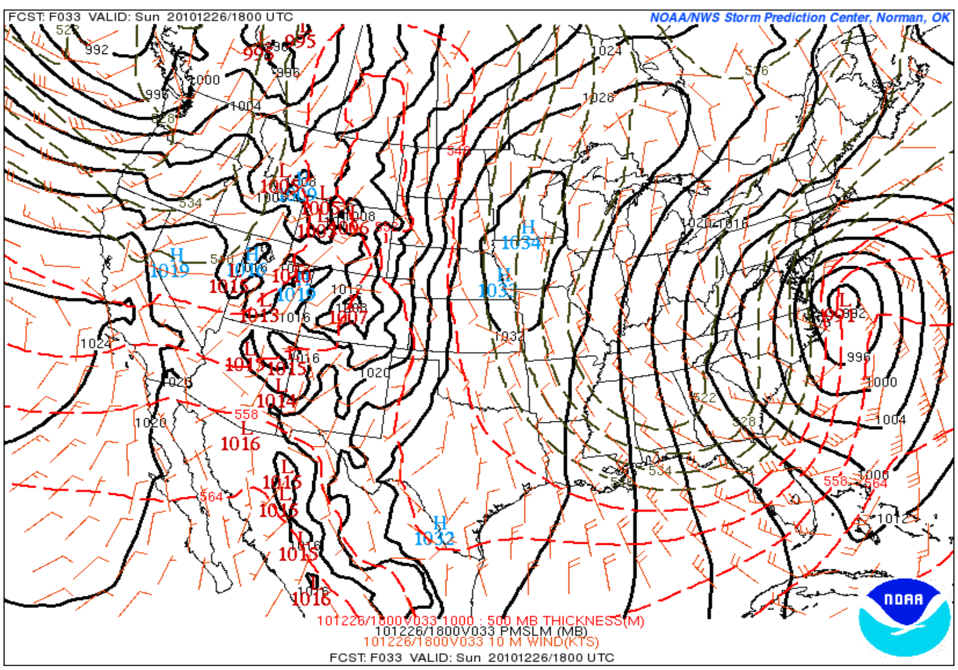


Fig 39a. SREF mean 33-hour SLP forecast valid 18 UTC 26 December 2010.

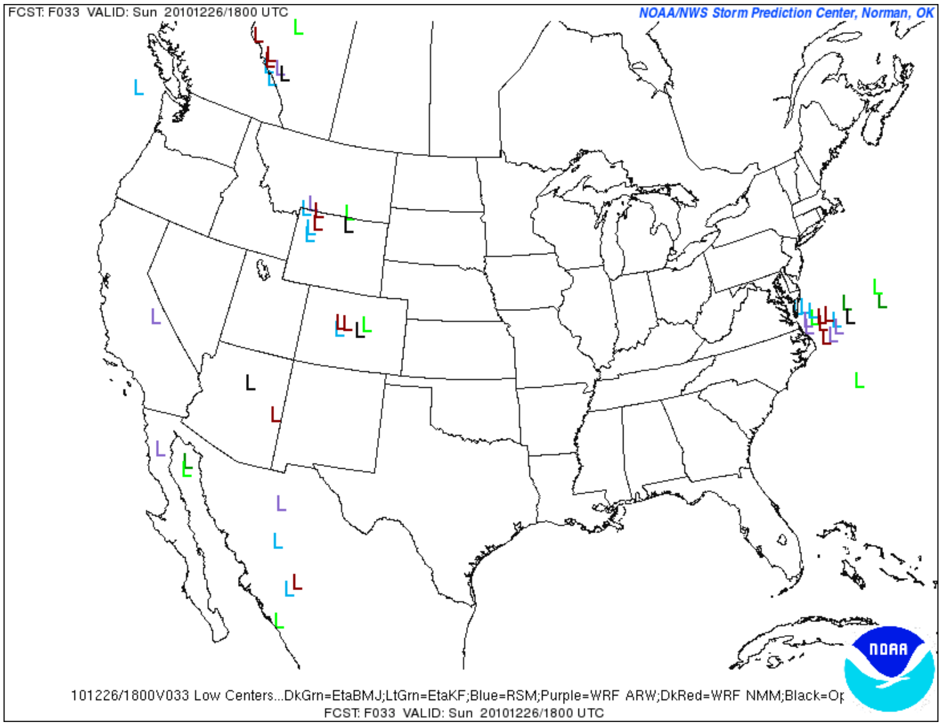


Fig 39b. SREF 33-hour SLP low center spaghetti chart valid 18 UTC 26 December 2010.

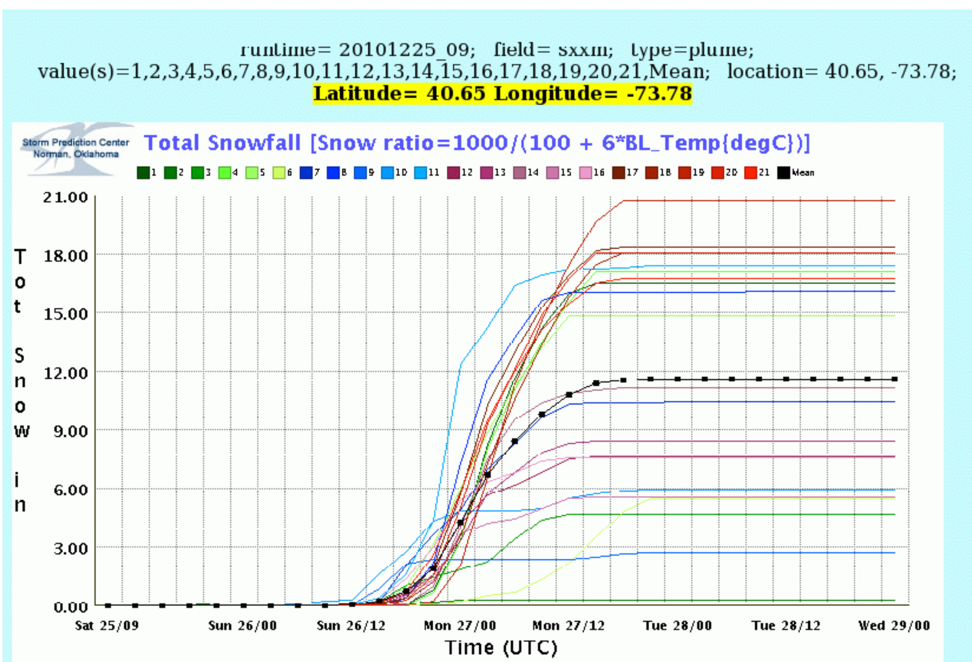


Fig 40. SREF snowfall plumes at JFK (mean ~12"; range ~1" to ~21"). Main cluster around 17" and secondary loose cluster between 5" to 10".

New York Blizzard

26 December 2010

Impact to operations compared to the same day a week prior.

Airport	Date	Traffic Reduction	Airport	Date	Traffic Reduction
EWR	12/19 vs.12/26	62%	EWR	12/20 vs.12/27	99%
LGA	12/19 vs.12/26	69%	LGA	12/20 vs.12/27	99%
JFK	12/19 vs.12/26	57%	JFK	12/20 vs.12/27	95%

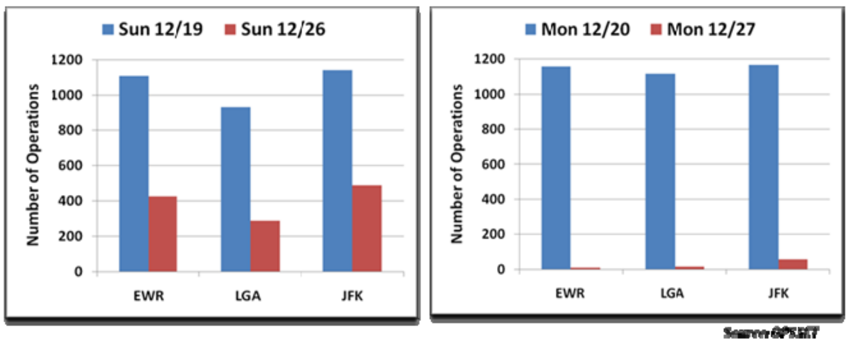


Figure 41. The reduction in operations the day of the blizzard (Sunday 26 December) and the day following (Monday 27 December) and compares it to the number of operations the week prior.