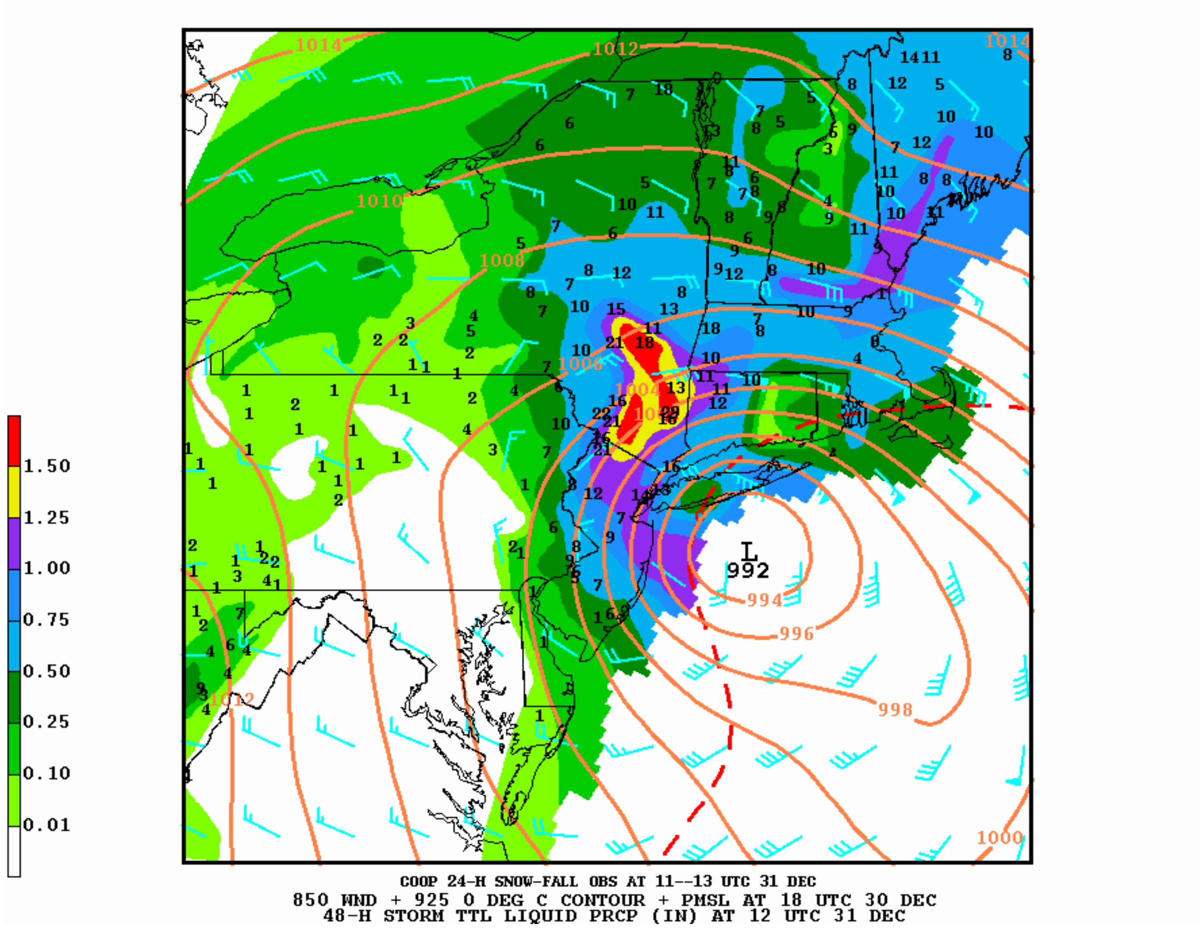
An Assessment of NCEP/Eta Model Performance for the December 30, 2000 Snowstorm



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COVER FIGURE. 850-mb winds (knots, cyan); 925-mb 0E C isotherm (red, dashed); MSL pressure (orange, solid, 2-mb interval); 48-h storm total liquid precipitation ending 12 UTC 31 December (inches, shaded--see color bar); and cooperative observer 24-h snowfall amounts at 11--13 UTC 31 December (inches, black). All fields except precipitation amounts from the FNL at 18 UTC 30 December 2000. Courtesy Keith Brill, Stephen Jascourt, NCEP.

1. Background

NWS forecasts for the December 30, 2000 snowstorm in the Northeast US played a significant role in successful emergency preparation in many locations. Longer-range numerical model guidance provided early indications of the potential for the major East Coast snowstorm 4-5 days in advance. Short range models, with predictions of snowfall in excess of one foot, provided an excellent basis for operational forecasts covering the northern New Jersey and New York City areas. However, in other areas, there were significant errors in operational Eta model forecasts especially along the middle Atlantic states – resulting in over-forecasts of snow for the Washington, DC and Baltimore regions and parts of eastern Pennsylvania. Errors were observed in model forecast of cyclone track, intensity and quantitative precipitation (QPF). Additionally, vacillations were also seen in forecasts from one operational run to the next in the days preceding December 30 and this increased forecaster uncertainty.

In an effort to improve numerical forecast guidance produced at NCEP, NWS directed a science review of Eta model performance for the December 30 storm. On 10 and 11 January 2001, a working group consisting of NWS and private forecasters, university scientists and NCEP modelers met to analyze the forecasts made for this storm and identify possible sources of error in order to help improve the forecast process for future coastal storms. The following tasks were identified for the working group to address:

- Assess the operational Eta model guidance used for the December 30, 2000 between 27th - 30th of December.
- Produce a report of findings and recommendations which identifies:

  – Areas where model performed well
  – Significant errors in forecast intensity, movement and QPF
  – Causes of model errors
  – Improvements needed
  – Unresolved issues/questions

This report summarizes the findings of the working group and makes recommendations to improve the model forecasts. The report focuses primarily on operational Eta model forecasts from 1200 UTC 29 December 2000, the most critical time period for issuing Winter Storm Warnings. To speed the assessment, the investigations were to focus on already available model runs, both operational and experimental, thereby minimizing the delays and complications of performing additional model reruns.

Acknowledgments: Jack Hayes, NWS/OST and Geoff Dimego, NCEP/EMC graciously provided direction and advice for the working group. Eileen Maturi, NESDIS and Andy Harris, UK Met office, provided guidance on the creation of sea surface temperatures from satellite and various satellite images needed for a thorough analysis.

2. Storm Overview

The Atlantic coastal storm of 30 December 2000 developed during a period when cold weather dominated the eastern United States. The overall weather pattern featured an upper tropospheric ridge along the Pacific Coast of the continental United States with a broad trough east of the Rockies extending to the Atlantic coast. Before the coastal cyclone developed, an upper-level disturbance entered the US as an "Alberta Clipper" system moving south-eastward across the upper Great Plains, producing heavy snows in Minnesota on the 28th. By 1200 UTC 29 December the upper-level "clipper" shortwave had evolved into a low center located over a weak surface cyclone over Illinois (Fig 1a). Meanwhile, a weak system traversing the Gulf coast quickly moved away from the southeast US.

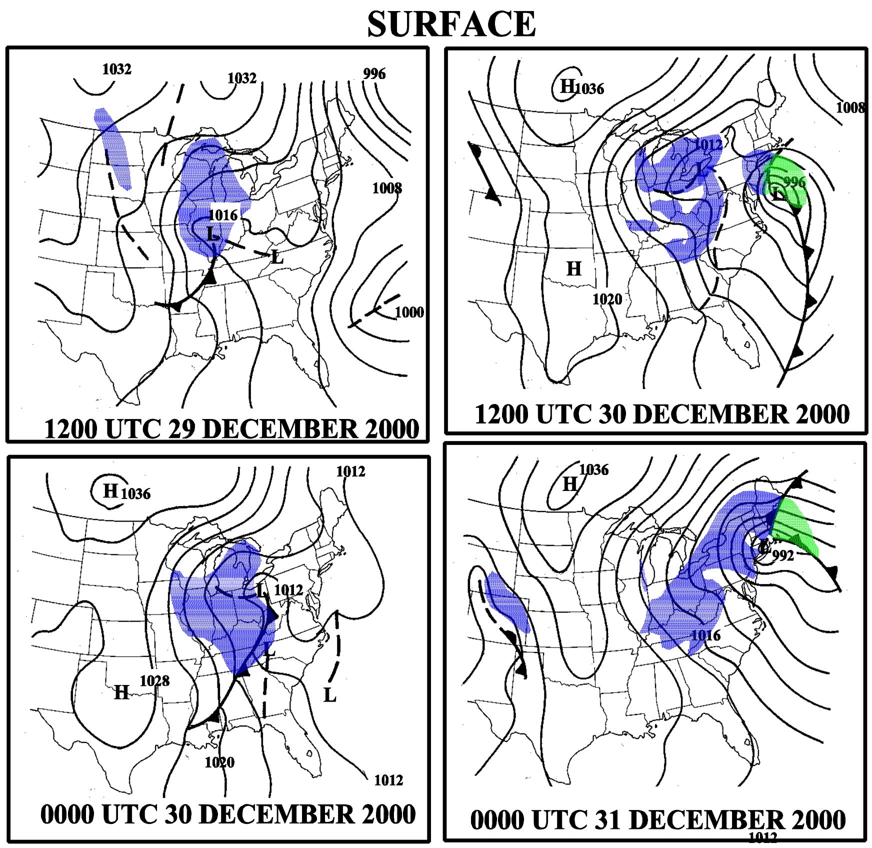

Figure 1. Manual analysis of sea-level pressure (mb) with areas of observed precipitation shaded for (a) 12 UTC 29, (b) 00 UTC 30, (c) 12 UTC 30, (d) 00 UTC 31, December 2000

By 0000 UTC 30 December, a secondary cyclone reformed along the east coast in the vicinity of an off-shore trough (Fig. 1b). Fig. 2 shows a 300-mb jet had redeveloped southeast of the closed-off low center located over Indiana, producing upper level divergence over eastern North Carolina and Virginia. Southerly 850-mb winds along the coast mark the beginning of a low-level transport of ocean warmed and moistened air into the incipient cyclonic circulation.

By 0600 UTC, lightning was observed with the convection well off the eastern shore of Maryland as a new surface cyclone began to form in that area. By 1200 UTC, a rapidly deepening and moving surface low-pressure area was located east of the Delaware and Maryland (Fig 1c), accompanied by nearly 50 knot east-southeasterly winds directed from off-shore toward northern New Jersey and southern New York, producing heavy snow near Philadelphia. By 1800 UTC, the storm was reaching maturity (992 mb, see cover figure), with heavy snow falling from northeastern Pennsylvania and northern New Jersey northward into southern New York state. After 1800 UTC, the storm deepened only slightly while continuing to spread moderate to heavy snow over northern Massachusetts, southeastern New Hampshire, and eastern Maine (Fig. 1d).

A good analysis of precipitation for this event required substantial quality control of the observations, multi-sensor (Stage IV) analyses and River Forecast Center (RFC) mosaic products. The manual, 48-hr total precipitation analysis shown on the cover of this document provided a fair representation of storm total precipitation (inches) over most of the northeastern US affected by the storm. The numbers overlain are 24-hr snowfall amounts (inches) from about 1200 UTC 31 December and highlight both the lack of precipitation in the Washington, DC and Baltimore areas and the sharp western edge of the precipitation area in eastern Pennsylvania. Heavy snow amounts extended northward from northern New Jersey and New York City up the Hudson River valley.

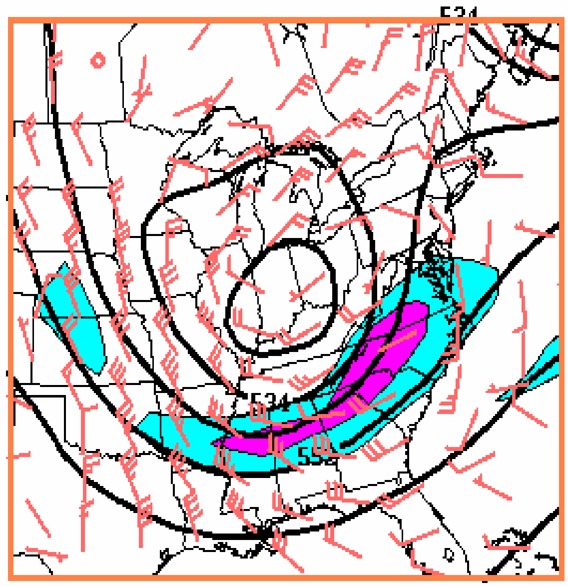

Figure 2. 300-mb jet streak shaded to denote 110 to 130 knots and greater than 130 knots (cyan and magenta);500-mb height contours(dm, heavy black); and 850-mb wind barbs (knots, light red). All fields are from the NCEP final global analysis (FNL) at 00 UTC 30 December, 2000

3. Eta Model Assessment

The Eta Model performance review team met on 11-12 January, 2001 to conduct its initial review for the December 30, 2000 snowstorm. Numerous diagnostic plots were created for the team's review and these visualizations were uploaded to an NCEP/EMC web page for further analysis. In the weeks after, additional diagnostics were created and several conference calls and email exchanges were needed to complete the assessment. This section identifies both the positive and negative aspects of the Eta model performance for the snowstorm.

3.1 Positive Model performance

NCEP models correctly forecast many aspects of the storm. The major ones identified by the team are discussed in this section.

Large scale models forecasted a major and paralyzing snowstorm for the Northeast 4-5 days in advance. Large scale weather patterns were forecast well for this case by both the Eta and Global models. On Monday December 25, forecasts alerted the public to the possibility of a major storm late in the week. By Wednesday December 27, many forecasts pinpointed the Friday night and Saturday time period (December 30) for heavy snow.

The Eta model correctly forecast that the northern branch of the jet stream would be the dominant upper-level forcing. The upper level trough moving southeastward across the northern Plains was forecast to strengthen into a closed low as it moved toward the East Coast. Global model runs early in the week suggested possible phasing with a southern stream trough, but by Thursday, December 28, the Eta correctly indicated they would not phase and the northern branch jet stream would be the dominant feature.

The models accurately forecast the timing of the initial cyclogenesis along the mid-Atlantic coast. They all showed the surface low developing Friday evening, then strengthening and moving northward Friday night and Saturday with heavy precipitation. Run-to-run discrepancies of the Eta, as well as differences between the models, occurred in the mesoscale details regarding the exact location of the cyclogenesis and the strength and track of the cyclone. These small-scale differences, however, were to have profound effects on QPF.

Based on Eta (and other model) runs from 12 UTC December 29, forecasters were able to issue timely warnings for heavy snow from Philadelphia northward across central and northern New Jersey, New York City, eastern New York state and western and northern New England. This entire region received over 6 inches of snow, with 1 foot or more across northern New Jersey, New York City, southeastern New York state and parts of western and northern New England.

The Eta model also correctly forecast sufficient warming occurring over

southeastern New England and eastern Long Island which resulted in precipitation changing from snow to rain. This occurred along and southeast of a line from Boston, Providence to eastern Long Island, including southeastern Connecticut, limiting snowfall to 5 inches or less in these areas. The timing of the change-over, however, was missed by several hours.

3.2 <u>Significant errors in the model forecast</u>

The operational Eta model forecast the storm to track too far to the west by 100 km and to be too intense by almost 5 hPa. In the Washington / Baltimore area, this resulted in an erroneous forecast of around 1 inch of liquid precipitation (equivalent to 10-15 inches of snow)

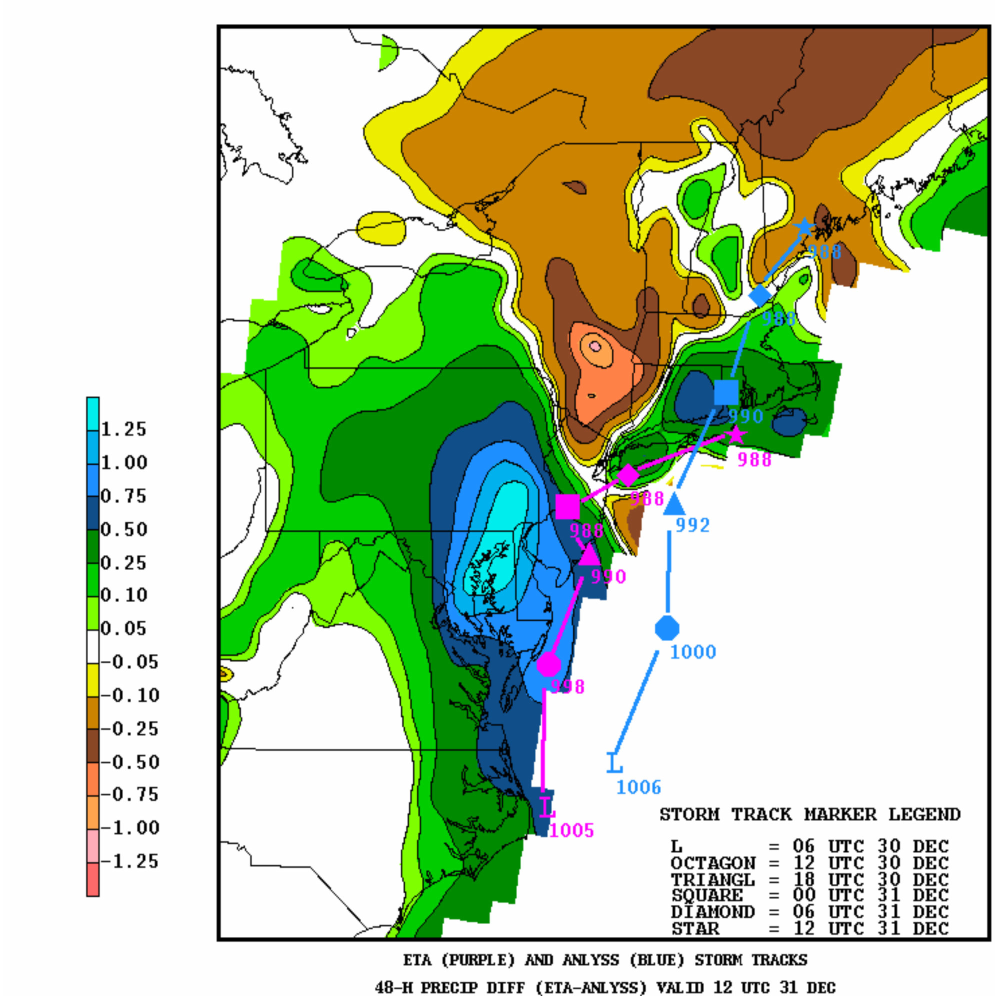

Figure 3. Precipitation differences between 48 hr Eta forecast and analysis shown on cover (inches) valid at 12 UTC 31 December 2000. Observed (blue) and predicted Eta storm track (magenta) beginning at 06 UTC 30 and ending at 12 UTC 31 December 2000 (at 6 hr intervals) also shown

for the 24 h period ending 0000 UTC 31 December 2000. (See Fig. 3).

The Eta model stood alone among the NCEP models in forecasting the storm to be too intense and too far to the west and south. Moreover, the Eta continued to forecast the storm to track further westward with runs subsequent to the 1200 UTC 28 December 2000 cycle. Examples of the Eta model QPF and storm track forecasts are shown in Fig. 4, for model runs initialized 1200 UTC 29 December 2000. When these figures are compared to similar figures from the AVN model (Fig.4) it is readily apparent that the Eta model forecast was predicting a substantial snow fall for residents in portions of the Middle Atlantic States.

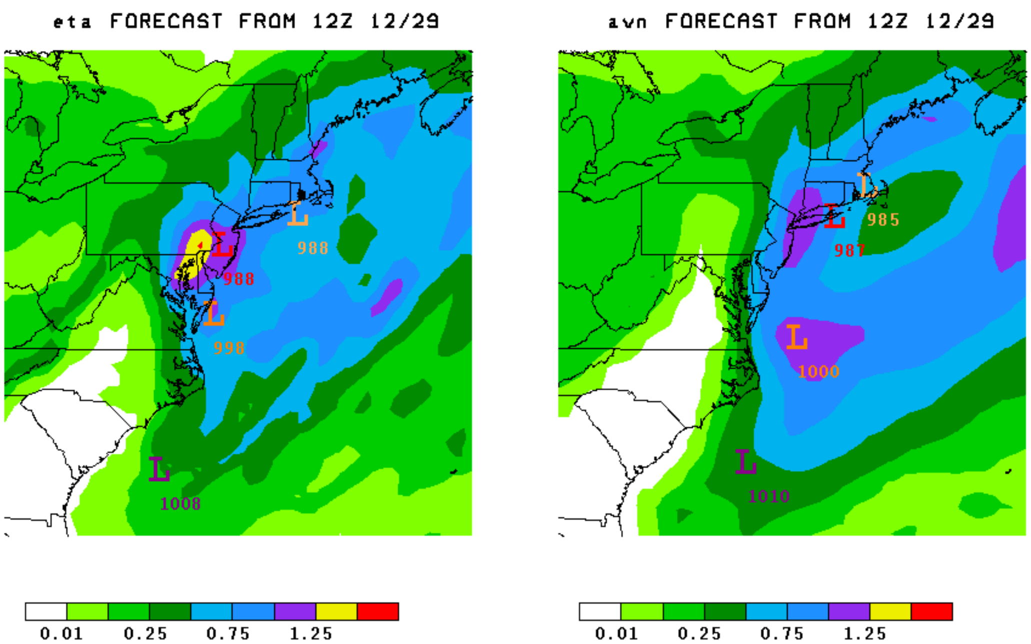

Figure 4. 12 UTC 29 December, 2000 model runs of a) Eta and b) AVN 48 hr forecast accumulated precipitation (inches) valid at 12 UTC 31 December, 2000. Eta and AVN forecasted low positions are also shown at f12, f24, f36, and f48 times.

The Eta model QPF forecasted too much moisture to be wrapped westward around an overly intense surface cyclone (Fig. 4), producing a precipitation shield that was too large and extended too far west and south of the surface cyclone center. Precipitation amounts were also over-predicted, especially north and west of the surface cyclone. This sequence of errors can be traced to the 12 hour forecast vertical motion fields (0000 UTC 30 December 2000), which show excessive upward vertical motion too far west and directly along the North Carolina and Virginia coasts. In response to the excessive ascent forecast too far west, the Eta model both overdeveloped the surface cyclone and placed the center too close to the coast. Moist air from the warm ocean surface was then transported around the cyclone, ascended over the cold air entrained east of the mountains, and then precipitated too far behind the cyclone to the south and west

The Eta model erroneously forecast heights in the middle and upper-tropospheric trough located over the southeastern US (Fig. 5) to be too deep. Large-scale features, while less important for this case, also need to be examined as to their potential contribution to both the overall predictability and specific error patterns. This may also have contributed to the cyclone developing too far south and west, i.e., closer to the coast. There is also evidence that the

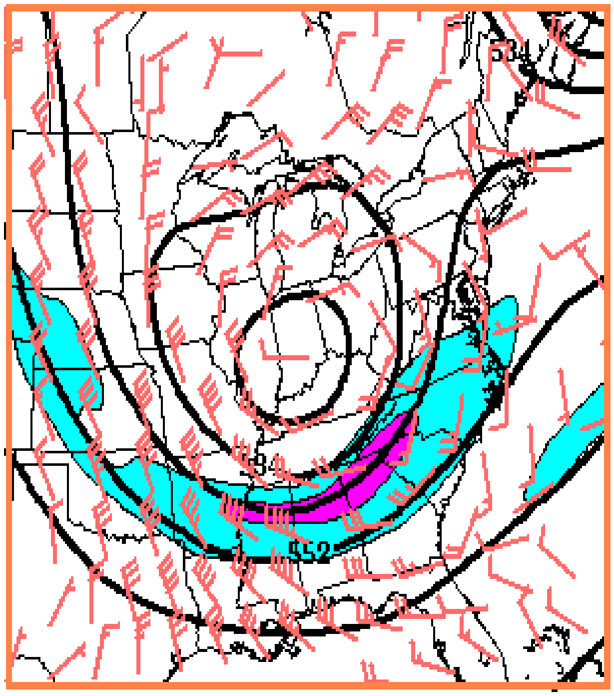

Figure 5. 300-mb jet streak shaded to denote 110 to 130 and greater than 130 knots (cyan and magenta, respectively);500-mb height contours (dm, heavy black); and 850-mb wind barbs (knots, light red). All fields are from the 12hr Eta forecast valid 00 UTC 30 December, 2000.

subtropical jet (STJ) was mis-analyzed in the EDAS relative to the GDAS.

The Eta model forecasts also showed large vacillations in overall precipitation amounts forecast from run to run, accompanied by changes in storm strength and location. In general, the Eta forecasts indicated more precipitation at 1200 and 0000 UTC cycles than for 0600 and 1800 UTC runs. Also the 1200 UTC cycle predicted slightly more precipitation over most areas than the 0000 UTC runs, with deeper cyclones forecast to be located further west.

4. Causes of Model Errors

Several possible sources of model error were identified by the analysis team. These included error in the sea surface temperature initialization, the initial analysis used by Eta and the choice of convective parameterization. Only those sources of error thought to be significant are discussed here.

4.1 Error in Atlantic Ocean Sea Surface Temperature (SST) specification along the East Coast of US.

By far the most significant source of model forecast error is thought to be related to errors in the specification of SSTs over the coastal waters along the middle Atlantic States. Figure 6a shows the input used for the December 29 Eta model runs; it is a weekly average of SST on a 1E x 1 E grid. Figure 6b shows a 0.5 x 0.5E grid of the daily December 29 SST analysis based on an assimilation of ship and buoy observations and IR satellite data. Note the differences

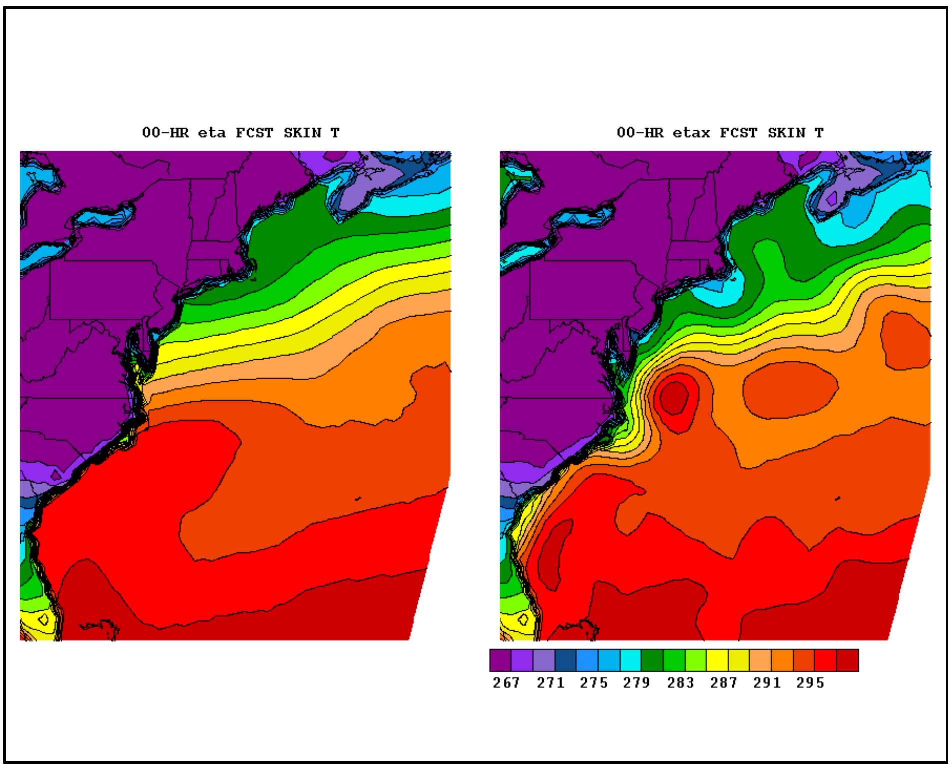

Figure 6. a) 1x1Edegree Reynolds weekly SST (K) analysis used for the operational Eta model and b) 0.5x0.5Edaily SST analysis for the 12 UTC December 29, 2000 runs.

between the two along the coast from North Carolina to Massachusetts-in some cases, differences of greater than 10EC are seen with the high resolution analysis showing significantly cooler coastal shelf waters off of North Carolina (Fig. 7) .

The erroneous warm SSTs would contribute to erroneously high Convective Available Potential Energy (CAPE) in the areas off the North Carolina to New Jersey coast caused by surface sensible and latent heat fluxes in this area. This would, in turn, provide "fuel" needed to support the initial precipitation indicated by the operational Eta simulation. The erroneously large latent heating would induce lower tropospheric thickness increases and lower-middle tropospheric height rises which resulted in the cyclogenesis.

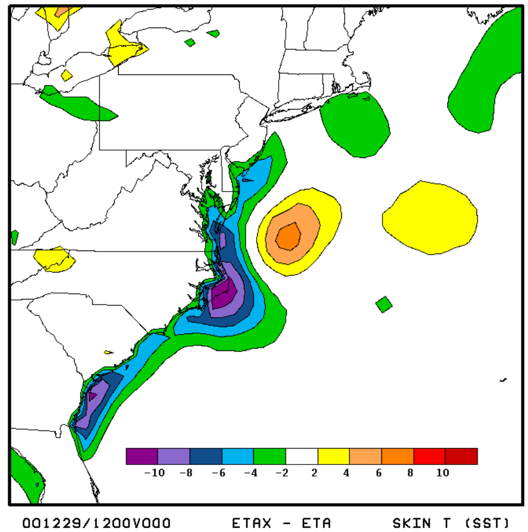

Figure 7. Initial sea surface temperature differences (K) between high resolution assimilation analysis and 1 E Reynolds SST analysis at 12 UTC Dec 29, 2000.

To determine the significance of the error in Atlantic SST specification, the Eta model was rerun in test mode (referred to as Eta-X) using the 0.5Ex0.5E SST fields described above. All other input to the run was identical to the operational run. Results shown in figure 8, indicate that the Eta-X simulation produced an improved storm track and precipitation forecast. The predicted storm track error was substantially reduced while the predicted precipitation over the Baltimore-Washington area was reduced to 80-90% from the operational run. These results indicate that primary errors in the mean sea level pressure and precipitation forecasts were either directly coupled or indirectly dependent on the SST distribution close to and along the Atlantic coast.

4.2 Errors in the Initial Analysis used by the Operational Eta Model

Another possible source of error relates to the quality of the initial upper level analysis used by Eta. Analysis errors could have caused: 1) a slight error in location of the northern (polar) jet relative to the southern jet resulting in a bias towards somewhat higher heights over the southeastern part of the Eta domain and 2) vacillations in precipitation distribution from run to run related to moisture and mass initialization. The latter could very easily perturb both the convective and grid resolvable precipitation schemes, resulting in inconsistencies between runs. These analysis errors are likely related to either 1) to differences in the mixes of data used at different analysis times and in different models or 2) to improper mass/wind balances in the Eta analyses. Results of a stand-alone run of the Eta model using not only high-resolution SSTs but also initial conditions from the Global analysis system showed improvements in both cyclone evolution and precipitation patterns that exceeded those obtained using the high-resolution SSTs alone. Further tests will be needed to determine the full impact of these factors.

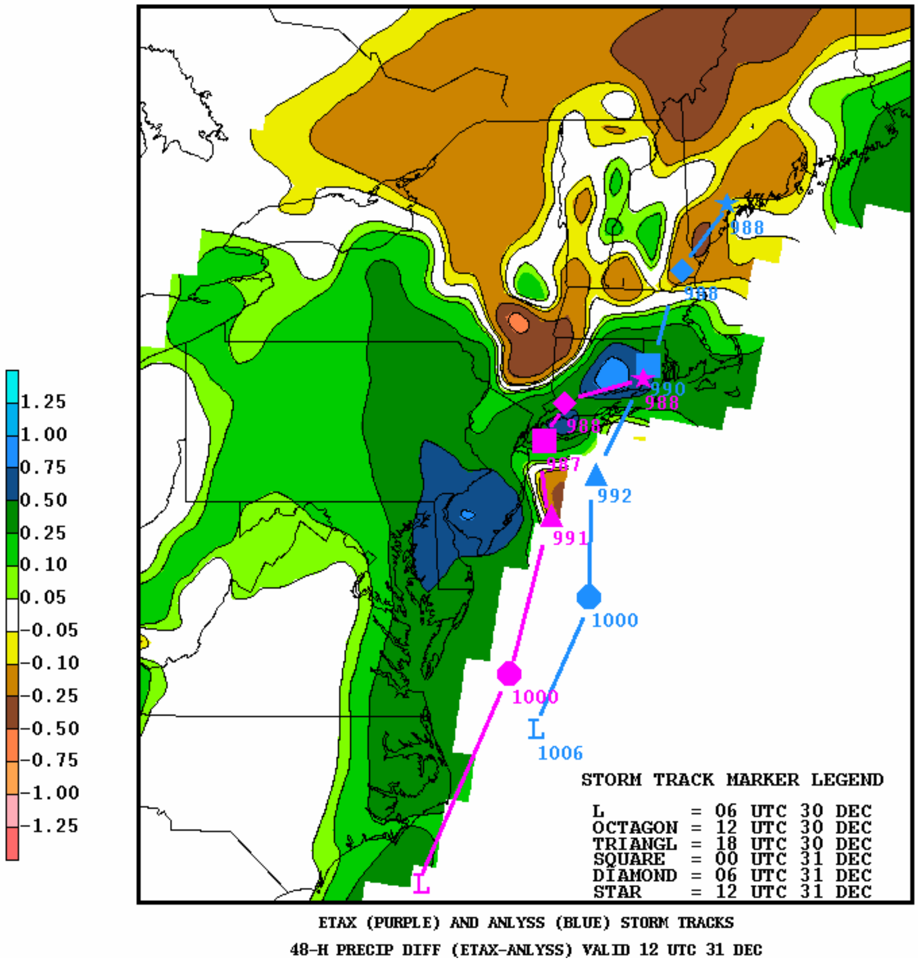

Figure 8. Precipitation differences between 48 hr parallel Eta-X forecast and analysis shown on cover (inches) valid at 12 UTC 31 December 2000. Observed (blue) and predicted Eta-X storm track (magenta) beginning at 06 UTC 30 and ending at 12 UTC 31 December 2000 (at 6 hr intervals) also shown.

4.3 Other Possible Causes of Error

Another cause of model error mentioned in other forecast situations is related to the Eta model's convective parameterization. It could be hypothesized that the scheme produces erroneously intense precipitation that results in rapid cyclone development. Examples where this error occurred in other models are available in the literature. Results of a stand-alone Eta test run using the Kain/Fritsch convective parameterization showed only small differences from the operational run. Based on these results, this hypothesis was rejected

5. Other Considerations Investigated by the Team

Although the team's primary focus was on the Eta model performance, several other observations about the end-to-end forecast process were noted during the analysis. These observations relate primarily to forecaster communication, and identify apparent weaknesses which could have contributed to errors in forecasts provided to the public.

These observations are listed below:

1. **HPC forecasters had access to experimental model runs which were useful in establishing confidence (or lack there of) in individual model runs.** This information was generally not available to field and other forecasters.

2. **The value of HPC plain language bulletins does not appear to be well understood by field and other forecasters.** These bulletins can provide an additional means of conveying confidence information about model performance to field forecasters.

3. Although Eta model runs are produced at 6 hourly intervals, there are techniques available which allow forecasters to "adjust" model forecasts during the intervening hours. **Techniques such as real-time verification could allow field forecasters to quality control model output between scheduled runs and evaluate confidence in model output for their areas of responsibility.** It is thought that use of real-time verification product tools would have alerted forecasters to the "overforecast" problem in Virginia and Maryland earlier in the forecast process.

4. **Field forecasters were not aware of many of the latest Eta model bias and performance information**, such as biases in coastal storm track and intensification caused by differing SST analyses.

5. **The non-NWS members of the Review Team that NWS forecasters receive more NWP training than forecasters outside NWS.** As a result, forecasters without sufficient NWP training had difficulty in reconciling conflicting forecasts from the regional and global models.

6. **The 0600 and 1800 UTC AVN runs are not available to field forecasters**. In rapidly evolving weather situations, such information would allow forecasters access to more recent model guidance.

6. S & T Recommendations

The working group identified several recommendations regarding improvements specific to the Eta model as well as suggestions to improve other areas of the forecast process. Some of these recommendations were considered primary, while others were minor. Some of these recommendations can be accomplished quickly while others would require a longer term implementation.

6.1 <u>Improvements to the Eta model</u>

Primary Recommendations:

- Implement high-resolution SST analyses into all NCEP weather forecast models.
  Action: NCEP/EMC ***Status - Eta & RUC completed - 1/31/01***
  - AVN under testing

- Further investigation is needed regarding the relationship of potential storm location and vacillation errors with the Eta Data Assimilation System (EDAS) and the sensitivity of the forecast to different analyses, including data distribution/selection and appropriate mass/wind balances. Incorporate significant improvements identified in the operational initialization after thorough testing. *Action: NCEP/EMC* ***Status - Underway***

Other Recommendations:

- In the longer term, an operationally robust, higher-resolution 4D variational SST data assimilation system based on satellite and conventional data should be established. It should include microwave SST retrievals of SST. This initiative should involve NESDIS and the US Navy.
  Action: NCEP/EMC ***Status - Initial discussions begun***

- To facilitate thorough and rapid testing of major model changes, a regionally diverse collection of select recent extreme and null weather events should be established for use in testing the effect of major model (such as at the proposed NCEP/OAR Model Test Facility) would reduce the likelihood of surprise model behavior for future high profile extreme events. Results from these tests should be shared with the broad forecast community to aid in the education of all forecasters on the potential impacts of major model enhancements.
  Action: NCEP/EMC and NWS/OCWWS & OST ***Status - NCEP run-histories saved***

6.2. Other Issues:

Primary Recommendations:

- Improve the exchange of additional NCEP experimental and other forecast information between HPC/NCEP and the field - especially for winter storm watches, warnings and advisories. Also, confidence information on NCEP models should be conveyed to the field. Better coordination could be accomplished by implementing a forecaster intranet chat room and by employing interactive graphical display tools using existing NWS products (e.g.: Watch/Warning advisory software in IFPS). A pilot project using these tools for East Coast winter storm by Winter, 2002 is recommended, depending on available resources. *Action: NCEP, Regions and NWS/OS*
  Status - Underway, information already included in forecast discussions.

- Exploit realtime model verification tools (such as pressure tendency and precipitation fields) to help forecasters monitor current model forecast biases and trends. Include use of the Rapid Update Cycle (RUC) analysis and Local Analysis and Prediction System (LAPS), which are already available on AWIPS. Proper verification would require improved methods of obtaining adequate precipitation and snowfall data.
  Action: NWS/OS and NCEP

- Develop procedures to better publicize and share NWS training materials with private sector forecasters (e.g.: through AMS training classes). Evaluate the utility of recent updates ("vignettes") being added to the current COMET training materials.
  Action: NWS/OS **Status -** ***SST Vignette in COMET/NWP Module***

Other Recommendations:

- In addition to improving the deterministic Eta model runs, develop, implement and distribute Short-Range Ensemble Forecasts (SREF) to better describe the likelihood and range of potential forecast solutions including measures of quantitative precipitation forecast confidence and precipitation type.
  Action: NCEP/EMC and NWS/HQ ***Status - SREFs to be run operational by 5/01***

- Develop methods for making NCEP developmental models available for display at WFOs through the web or on AWIPS.
  Action: NCEP, NWS/OS & OST ***Status -NCEP upgrading web pages***

- Make all off-time NCEP models runs available via AWIPS. *Action: NWS/OS & OST*