Sensitivities of Numerical Model Forecasts of Extreme Cyclone Events

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ABSTRACT

A global forecast model is used to examine various sensitivities of numerical predictions of three extreme winter storms that occurred near the eastern continental margin of North America: the Ohio Valley blizzard of January 1978, the New England blizzard of February 1978, and the Mid–Atlantic cyclone of February 1979. While medium–resolution simulations capture much of the intensification, the forecasts of the precise timing and intensity levels suffer from various degrees of error. The coastal cyclones show a 5–10 hPa dependence on the western North Atlantic sea surface temperature, which is varied within a range (± 2.5℃) compatible with interannual fluctuations. The associated vertical velocities and precipitation rates show proportionately stronger dependences on the ocean temperature perturbations. The Ohio Valley blizzard, which intensified along a track 700–800 km from the coast, shows little sensitivity to ocean temperature. The effect of a shift of ~ 10° latitude in the position of the snow boundary is negligible in each case. The forecasts depend strongly on the model resolution, and the coarse–resolution forecasts are consistently inferior to the medium–resolution forecasts. Studies of the corresponding sensitivities of extreme cyclonic events over eastern Asia are encouraged in order to identify characteristics that are common to numerical forecasts for the two regions.

I. INTRODUCTION

Extreme synoptic events present weather forecasters with exciting but severe challenges. During the winter season, these events often take the form of rapidly deepening cyclones that evolve into major winter storms. When the associated weather includes heavy rain and snow, strong winds and / or blizzard conditions in populated areas, these systems can make lasting impressions on the general public as well as on forecasters. It is in such situations that the accuracy of weather forecasts is often subject to the most critical evaluation by the public and by the forecasting community.

As numerical models become increasingly important tools of the operational forecaster, the success of forecasts of extreme cyclonic development becomes strongly dependent on the models' ability to capture the rapid intensification. The present work is an examination of the performance and sensitivities of a numerical model in three cases of major cyclone intensification over eastern North America and its coastal margin. Each of these cyclones evolved into a strong winter storm and produced severe impacts on major metropolitan areas.

This study focuses on two sensitivities over which operational modeling centers have direct control: the resolution of the model and the lower boundary conditions. Such sensitivities have been addressed by Mailhot and Chouinard (1989) in mesoscale numerical forecasts of three explosively developing Atlantic cyclones during the Canadian Atlantic Storms Program (CASP). Orlanski and Katzfey (1987) also addressed the resolution–dependence of forecasts of the Mid–Atlantic cyclone of 18–19 February 1979. Additional studies of mesoscale model forecasts of strong cyclogenesis have been made by Atlas (1987), Kocin et al. (1985), Uccellini et al. (1983) and Anthes et al. (1983). In several of these studies, the roles of the surface fluxes of sensible and latent heat have been addressed in a first–order way by completely eliminating these fluxes in one or more simulations. The experiments described in this paper permit a more detailed and arguably more realistic examination of dependences on the lower boundary conditions. Prescribed perturbations of sea surface temperature (and continental snow cover) will be given magnitudes comparable to those observed on an interannual basis. We then evaluate the impacts on the forecasts of a global model. In order to provide some perspective for the boundary sensitivities, we also compare the forecasts of the model run at various resolutions.

Our study is distinguished from most of the studies cited above by its use of a global model in an assessment of the forecast sensitivities. While mesoscale models permit thorough diagnostic studies of past systems in a research mode, forecasters will generally need to rely on large–scale models in an operational mode when there is no *a priori* knowledge that a particular cyclone in a particular region is destined to become an extreme winter storm.

We emphasize that the present work has a specific focus: the sensitivities of global model forecasts of rapidly developing cyclones to surface boundary conditions and to model resolution. Given this focus, we do not address various aspects of synoptic evolution that have been examined in detail in the studies referenced elsewhere in this paper.

II. THE MODEL

The model used here is version CCM1 of the Community Forecast Model (CFM) of the National Center for Atmospheric Research (NCAR). This model is the same as the so–called Community Climate Model (CCM) except for the use of observational analyses to initialize the forecast model. Details of the formulation are provided by Williamson et al. (1987). Briefly, the model is global and spectral. It contains twelve vertical levels and uses a sigma coordinate system. In the experiments performed here, the model was used with three horizontal resolutions corresponding to rhomboidal truncation at wave number 15 or 30 (R15 or R30) and to a triangular truncation at wave number 42 (T42). The corresponding grid–point resolutions are approximately 4.5° lat × 7.5° lon for R15; 2.2° lat × 3.7° lon for R30; and 2.8° lat × 2.8° lon for T42. The model includes interactive cloudiness and radiation as well as a convective adjustment scheme. Sea surface temperatures are prescribed, but land surface temperatures are computed from a surface energy balance. The vertical turbulent fluxes are computed using a bulk transfer formulation, while vertical mixing is formulated in terms of a stability–dependent mixing length. The presence of snow cover changes the shortwave albedo of the land surface from 0.13 to 0.85, the longwave albedo from 0.13 to 0.55, the surface drag coefficient from 0.004 to 0.001, and the surface wetness factor from 0.25 to 1.00.

The NMC analyses and a normal mode initialization are used to provide the initial atmospheric fields for each forecast. The snow, sea ice and SST boundary conditions are prescribed and temporally invariant.

III. SYNOPTIC CASES

The three cases for which the forecast experiments were performed are summarized in Table 1, which also lists the largest 24–hour pressure changes (from 00 UTC or 12 UTC) associated with each system.

Table 1. The Three Simulated Cyclones. Largest 24–Hour Pressure Changes (from 00 UTC or 12 UTC) are listed with Corresponding date / time in Parentheses

"Identifier"	Date	Largest 24–hour pressure change	
1. New England blizzard	5–7 Feb 1978	1023 hPa (05 / 12)	1000 hPa (06 / 12)
2. Mid–Atlantic cyclone	18–20 Feb 1979	1020 hPa (19 / 00)	992 hPa (20 / 00)
3. Ohio Valley blizzard	25–27 Jan 1978	998 hPa (25 / 12)	960 hPa (26 / 12)

Figure 1 shows the analyses of sea level pressure for the time of the model's initial state and for the subsequent two days of each case. It is apparent from Fig.1 that the New England and Mid–Atlantic systems are coastal cyclones that intensified along the boundary between the cold continent and the relatively warm ocean. The Ohio Valley blizzard, on the other hand, developed over land as two initially weak cyclones merged into a large and rapidly intensifying system over the Ohio Valley. Figure 2 shows the corresponding pair of relatively weak upper–level waves, the phase–locking of which coincided with the rapid intensification of the Ohio Valley blizzard. The New England blizzard also intensified as two upper–level vorticity maxima merged (Fig.3), although the vorticity maxima were not as strong as in the Ohio Valley case. The Mid–Atlantic cyclone was not accompanied by the merger of two distinct synoptic systems. A diagnostic analysis of the Mid–Atlantic cyclone is provided by Uccellini et al. (1984). For the times chosen here to initialize the model, the Mid–Atlantic case differs from the other two systems in the sense that a pre–existing disturbance was not present at the surface.

IV. FORECAST EXPERIMENTS

Each of the three cases was simulated with the T42 resolution in a so–called "control" forecast for which the sea surface temperature (SST) and snow cover (SN) boundaries were prescribed climatologically. Each case was also run with the same boundary conditions but a coarser resolution, R15 or R30. The T42 control simulation was then repeated with SST increased by 2.5°C in the coastal waters (40–100°W, 20–70°N) surrounding eastern North America and with SST decreased by 2.5°C in the same region. These two runs are denoted as SST+ and SST–, respectively. The anomaly "envelope" of ± 2.5°C was chosen to coincide with the approximate range of departures from normal SST during the winters of 1951–1980 as deduced from the COADS (Comprehensivs Ocean–Atmosphere Dataset) sea surface temperatures (Woodruff et al., 1987). Finally, simulations were also made with the eastern North American snow limit near its climatological position (42°N) and its equatorward extreme (33°N). The simulations with the two snow boundaries are denoted as SN– and SN+, respectively.

The control forecasts for the approximate times of minimum low pressure are illustrated in Fig.4. When the results are compared with the observational analyses in Fig.1, it is apparent that the development of the cyclone is captured at least qualitatively in each case. The errors of intensity and location of the storm centers vary from case to case. The 48–hour forecast of the New England blizzard(Fig. 4a), for example, represents an intensification from 1023 hPa to 1000 hPa, while the actual intensification was from 1023 hPa to 992 hPa. The forecast location of the intensified system is only ~200 km east of the observed center.

The 48–hour forecast of the Mid–Atlantic cyclone (Fig. 4b) shows that the formation of the storm was indeed captured. However, the forecast intensity and location contain substantial errors. Strong intensification was not forecast by the model until 00 UTC 20 Feb, nearly 24 hours after the actual system entered its period of most rapid deepening. Despite the phase error of approximately 24 hours, the formation and trajectory of the model cyclone agreed fairly well with the observed track.

Finally, the Ohio Valley blizzard (Fig. 4c) was forecast quite well in terms of its timing and trajectory. The forecast low pressure center over Lake Erie nearly coincides with the observed low center, although the forecast central pressure of 983 hPa is considerably higher than the observed record–low pressure of 960 hPa. It should be noted that an additional simulation at R30 resolution produced lower central pressures: 972 hPa at 12 UTC 26 Jan and 968 hPa at 12 UTC 27 Jan. Extremely strong gradients of pressure were present in all model forecasts of this case.

In order to illustrate the sensitivity to the lower boundary conditions, Fig.5 summarizes the forecasts of the central low pressure in the T42 control simulations as well as in the T42 simulations SST+ and SST–. All three cyclones are forecast to be more intense when the SST anomaly is positive. The impact of the SST anomalies is clearly larger in the New England and Mid–Atlantic storms than in the Ohio Valley blizzard. The difference between the 48–hour forecasts of central pressure in simulations SST+ and SST– is 6 hPa for the New England blizzard, 9 hPa for the Mid–Atlantic cyclone, and 2 hPa for the Ohio Valley blizzard. The SST sensitivity of the two coastal storms is comparable to or slightly greater than that found by Mailhot and Chouinard (1989), whose simulations of developing Canadian coastal cyclones were subjected to SST perturbations generally less than 2.5°C.

While the SST perturbations produce differences of 5–10 hPa in the central pressures of the coastal cyclones, the effects on vertical velocity and precipitation rate are proportionally much larger. For the Mid–Atlantic storm, Fig.6 shows that the 48–hour forecast maximum vertical velocities (Pa s^{-1}) at 700 hPa over the mid–Atlantic coast are approximately 80% larger (–1.25 vs –0.74) in SST+ than in SST– (1 Pa $s^{-1} \approx 10$ cm s^{-1}). The associated downward motion east and west of the storm center is also stronger in SST+, although the ω_{700} fields over other regions differ little between SST+ and SST–. The corresponding precipitation rates forecast for 12 UTC 19 Feb are 2.95 cm per 12 hr in SST+ and 2.03 cm per 12 hr in SST– (Fig.7). Observed precipitation amounts in the North Carolina–Virginia coastal area were 3–6 cm for the 24 hours ending 12 UTC 19 Feb. Thus, despite the phase lag noted earlier in the forecast development of the pressure center at sea level, the location and amount of the forecast precipitation are in reasonably good agreement with observations. The enhancement of upward motion and precipitation in SST+ is consistent with the findings of Bosart (1981), who showed that an underestimation of the sensible heat flux was at least partially responsible for the failure of the then–operational LFM model to predict this storm.

Figures 8 and 9 show the fields of ω_{700} and precipitation rate for 00 UTC 7 Feb in the New England blizzard. As in the case of the Mid–Atlantic cyclone, SST+ is characterized by stronger vertical velocity (–1.14 Pa s^{-1}vs. –0.97 Pa s^{-1}) and heavier precipitation (4.11 cm per 12 hr vs. 3.13 cm per 12 hr). Observational data for the 24 hours ending 12 UTC 7 Feb showed 3–5 cm of precipitation in southeastern New England and much smaller amounts inland, in good agreement with Fig.9.

Finally, the forecast of the Ohio Valley blizzard was found to be affected little by the SST perturbations: the 48–hour forecast central pressure was 981 hPa in SST+ and 983 hPa in SST– (Fig.4). This system's relative insensitivity to North Atlantic SST is attributable to two factors. First, the Ohio Valley blizzard is the only one of the three systems that was not a coastal cyclone. The track of this storm remained 700–800 km or more from the coast during its period of rapid development. Unlike the other two systems, the Ohio Valley blizzard did not form along the baroclinic zone created by the juxtaposition of the cold continent and the relatively warm ocean. The development of this system must therefore have depended little on the sensible and latent fluxes from the ocean surface. Second, the mid–tropospheric dynamics of the initial state were much more favorable for strong intensification than in the other two cases. As shown in Fig 2, the 500 hPa field of the initial state of the Ohio Valley simulation contained two closed low centers associated with strong vorticity maxima, which then merged to form the single major system. Neither of the other two cases contained two closed low centers at 500 hPa. Thus the favorable mid–tropospheric dynamics were evidently able to more than offset the absence of low–level coastal baroclinicity in the development of the Ohio Valley blizzard. The hypothesis that this system depended primarily on the initial dynamics rather than on the sensible and latent heat fluxes from the ocean surface is supported by the results of experiments SST+ and SST–, as well as by the stronger dependence on the model's resolution of the initial state (see below).

The impact of continental snow cover was negligible in all cases. Figure 10 shows that the central pressure of the Mid–Atlantic and Ohio Valley systems changed by no more than 1 hPa when the snow boundary over the eastern United States was moved equatorward from 42°N to 33°N. There are at least two reasons for this relative insensitivity to snow cover. First, the initial surface temperatures were unchanged by the presence or absence of snow. Second, incoming solar radiation is sufficiently weak during January–February that substantial albedo–induced changes in the atmosphere cannot develop over the 1–2 day timescale addressed here, especially when widespread cloudiness is present. In previously–reported 30–day forecast experiments with this same NCAR model, positive anomalies of snow cover led to a significant reduction of 30–day mean surface air temperatures over eastern North America, although the atmospheric temperature response was considerably stronger in days 21–30 than in days 1–10 (Walsh and Ross 1988, Fig.9).

The resolution–dependence of the model forecasts was found to be considerable. Figure 11 shows the 24–hour "control" forecast of the Ohio Valley blizzard produced by R15 and R30 model simulations. The forecast central pressures are 990 hPa with R15 resolution and 972 hPa with R30 resolution (vs. the observed 960 hPa). The R30 forecast also places the low center closer to its observed position (Fig.1) than does the R15 forecast. Figure 12a shows the 36–hour forecast of the Mid–Atlantic cyclone from an R15 simulation. The corresponding T42 forecast is shown in Fig.12b. While the T42 forecast contains a closed cyclone off the South Carolina coast, there is no closed cyclone in the R15 forecast. Sea level pressures offshore of South Carolina are approximately 10 hPa higher in the R15 forecast than in the T42 forecast.

The substantial degradation of the cyclone forecasts in the R15 simulations indicates that coarse resolution is inadequate for simulations requiring realistic depiction of extreme cyclogenesis. The resolution–dependence obtained here is consistent with the results of

Mailhot and Chouinard (1989), Orlanski and Katzfey (1987), and Kocin et al. (1985), all of whom found that an increase in horizontal resolution improved the representation of nonlinear feedbacks that enhanced the vertical motion in rapidly intensifying cyclones.

It should be noted that coarse resolution not only degrades a model's physical formulation or parameterizations, but it can also result in a highly truncated representation of the initial state. For example, the R15 truncation of the 12 UTC 26 Jan field in Fig.1c produces an Ohio Valley low with a central pressure of 978 hPa (vs. the "analyzed"960 hPa).

V. SUMMARY

The experiments described here show that a medium–resolution global forecast model can capture much of the intensification of extreme winter cyclones affecting the eastern United States. However, the forecasts of the precise timing and ultimate intensity levels suffer from various degrees of error. The sensitivities of the forecasts to the lower boundary conditions and the model resolution can be summarized as follows:

(1) The coastal cyclones studied here exhibited a 5–10 hPa dependence on the western North Atlantic sea surface temperature, which was varied within a range ($\pm$ 2.5°C) compatible with interannual fluctuations of SST in the same region. The associated vertical velocities and precipitation rates show proportionately stronger dependences on the SST perturbations. The inland cyclone that developed rapidly over the Ohio Valley showed little dependence on SST.

(2) In none of the cases did the cyclone intensity change by more than 1 hPa in response to a shift of $\sim 10^\circ$ latitude in the position of the snow boundary over eastern North America.

(3) The forecasts depended strongly on the model resolution, and the coarse–resolution forecasts were consistently inferior to the medium–resolution forecasts.

The movement of operational centers toward high–resolution NWP models reduces the practical significance of (3), although the resolution–dependence found here and by others may have relevance for long–term simulations using truncated models in a research mode. A practical implication of (1) and (2) is that operational forecasts of extreme cyclonic events can be improved by the use of actual rather than climatological sea surface temperatures. There is no indication in the results obtained here that short–term forecasts of cyclogenetic events will be improved by more accurate specifications of snow cover. It must be emphasized, however, that the findings obtained here are based on only one model at one stage of its evolution. Generalization of these findings will require, at the minimum, systematic experimentation with other models.

With regard to the use of non–climatological SST, the implication is that the forecasts will be improved if the prescribed SST field contains anomalies of the same sign as observed. Prescribed anomalies of the incorrect sign are likely to degrade the forecasts. It should also be noted that actual SST anomaly fields generally contain some spatial complexity in the sense that concurrent anomalies of both signs are often found within the experimental domain used in the present work. However, there are indications in the Comprehensive Ocean–Atmosphere Dataset (Woodruff et al., 1987) that above–normal SST's were indeed present offshore of the East Coast of the United States prior to the development of the New England blizzard in 1978 and the Mid–Atlantic cyclone in 1979. The issue of the necessary resolution of the SST anomalies is complicated by the sensitivity of the forecast to the resolution of the atmospheric model, as shown in Section 4.

It is quite likely that there are at least some similarities in the evolution of major winter storms along the eastern margins of North America and Asia. However, details of geography and land–sea thermal contrasts near the two continental margins are sufficiently dissimilar that the sensitivities of cyclones in the two regions may differ, particularly with respect to the surface boundary conditions. We encourage similar studies of extreme synoptic systems along the eastern coast of Asia.

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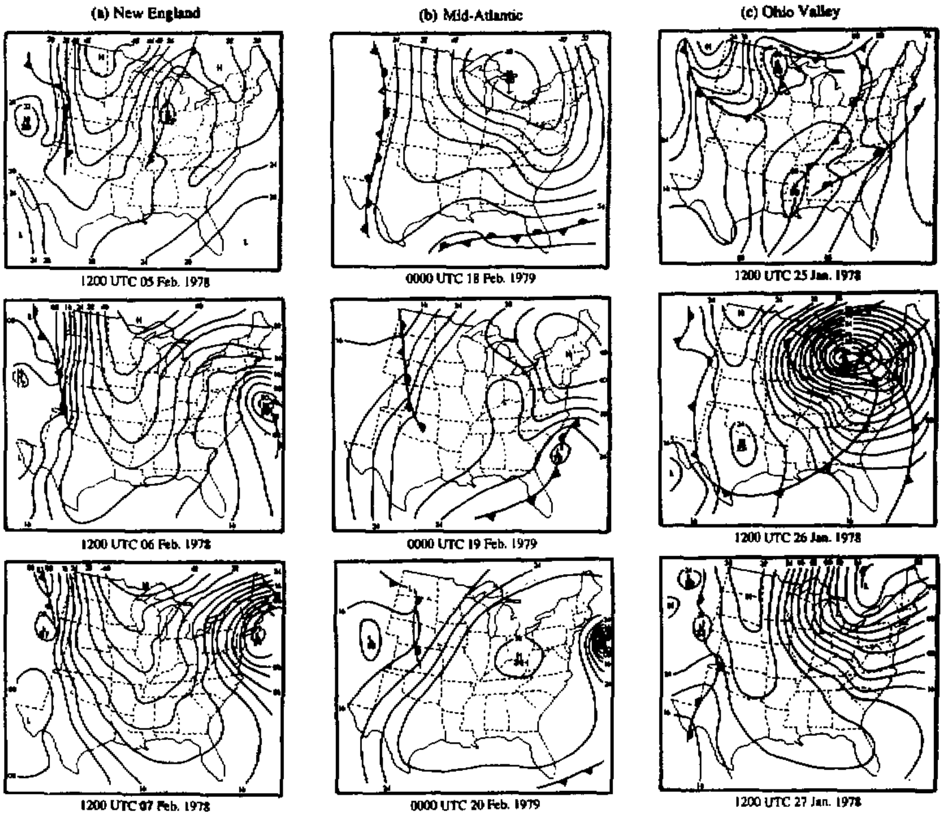
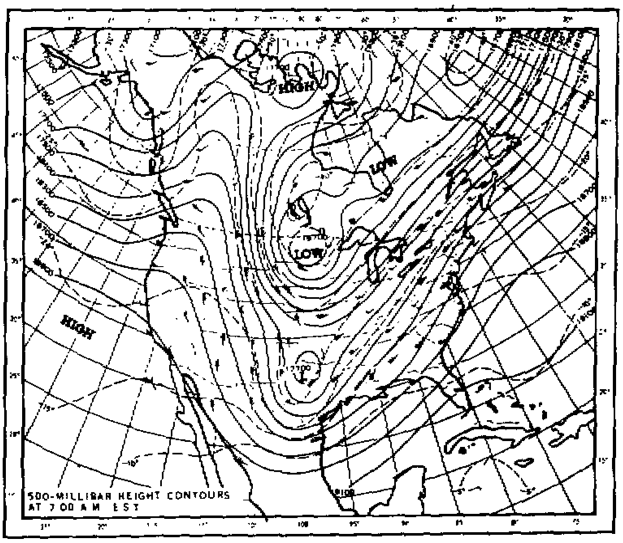
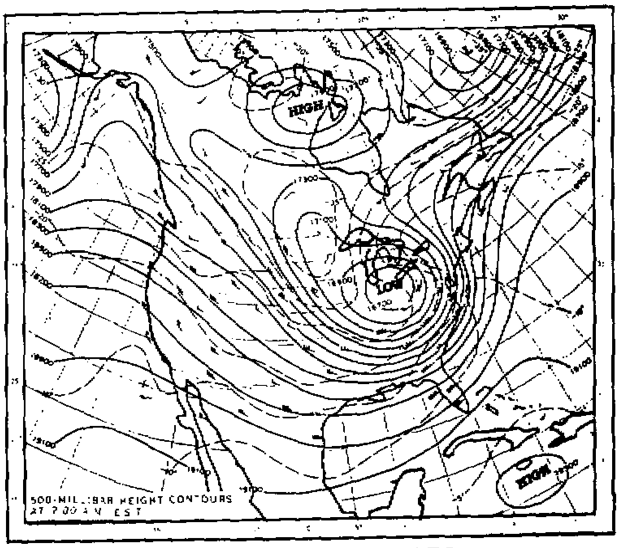


Fig.1. Analyses of sea level pressure at 24–hour intervals for (a) the New England blizzard of 5–7 February 1978, (b) the Mid–Atlantic cyclone of 18–20 February 1979, (c) the Ohio Valley blizzard of 25–27 January 1978.

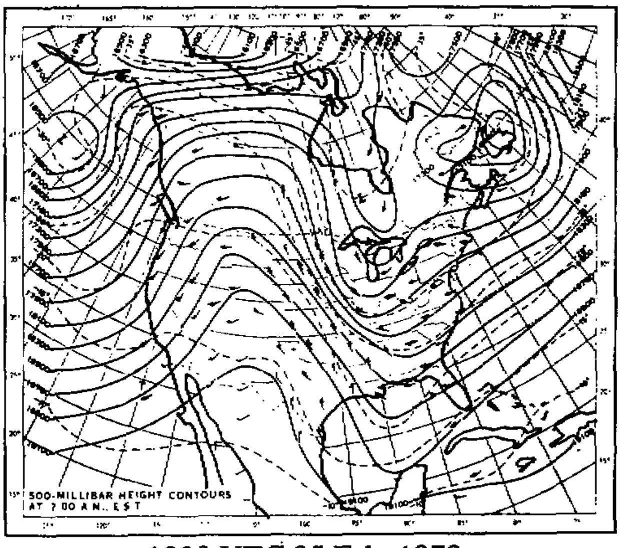


1200 UTC 25 Jan. 1978

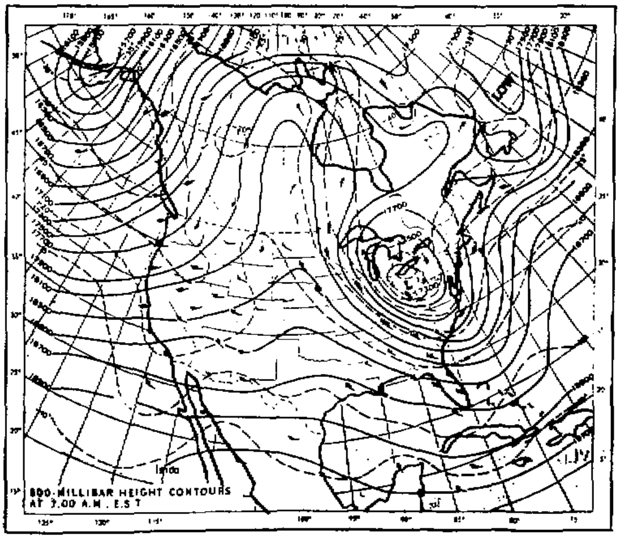


1200 UTC 26 Jan. 1978

Fig.2. 500 hPa analyses produced by the National Weather Service for the Ohio Valley blizzard: 1200 UTC 25 January 1978 (upper) and 1200 UTC 26 January 1978 (lower).

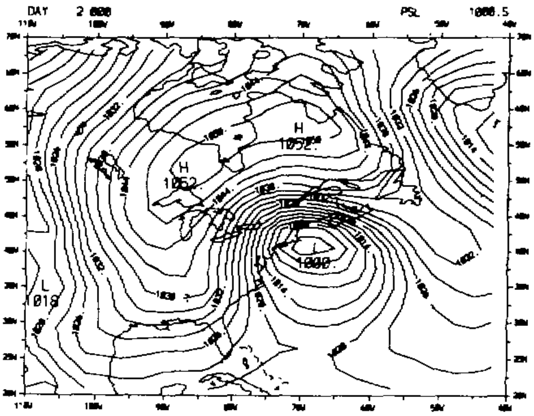


1200 UTC 05 Feb. 1978

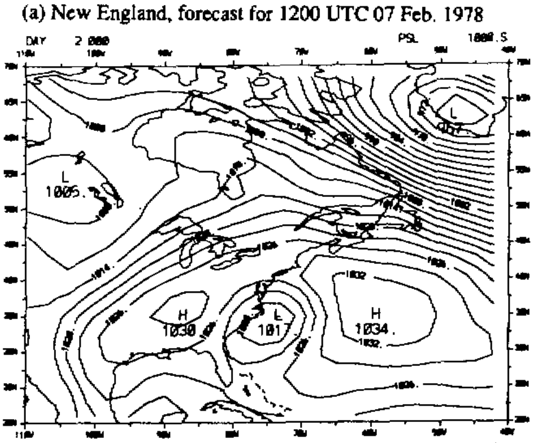


1200 UTC 06 Feb. 1978

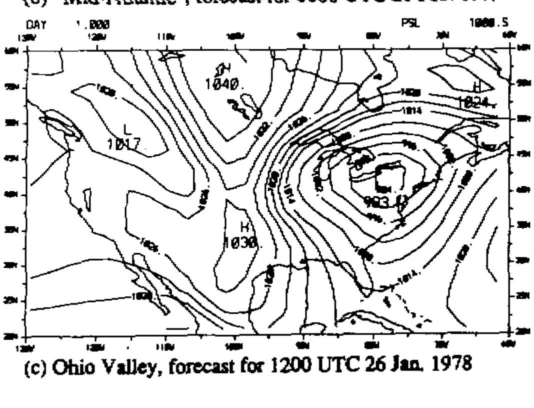
Fig.3. 500 hPa analyses produced by the National Weather Service for the New England blizzard: 1200 UTC 05 February 1978 (upper) and 1200 UTC 06 February 1978 (lower).



(a) New England, forecast for 1200 UTC 07 Feb. 1978



(b) Mid-Atlantic , forecast for 0000 UTC 20 Feb. 1979



(c) Ohio Valley, forecast for 1200 UTC 26 Jan. 1978

Fig.4. Model forecasts of sea level pressure produced by T42 control runs for (a) the New England blizzard at 1200 UTC 07 Feb 1978, 48–hour forecast; (b) the Mid–Atlantic cyclone at 0000 UTC 20 Feb 1979, 48–hour forecast; (c) the Ohio Valley blizzard at 1200 UTC 26 Jan 1978, 24–hour forecast.

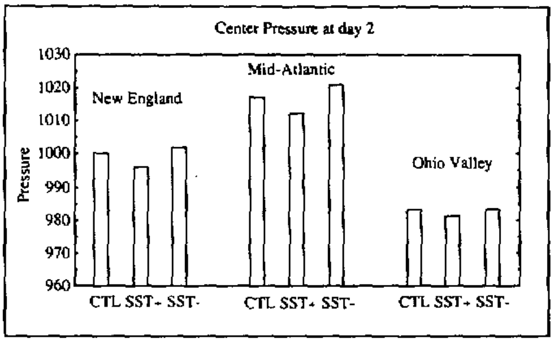


Fig.5. 48–hour model forecasts of central low pressure (hPa) from the T42 control (CTL), SST+ and SST– forecasts.

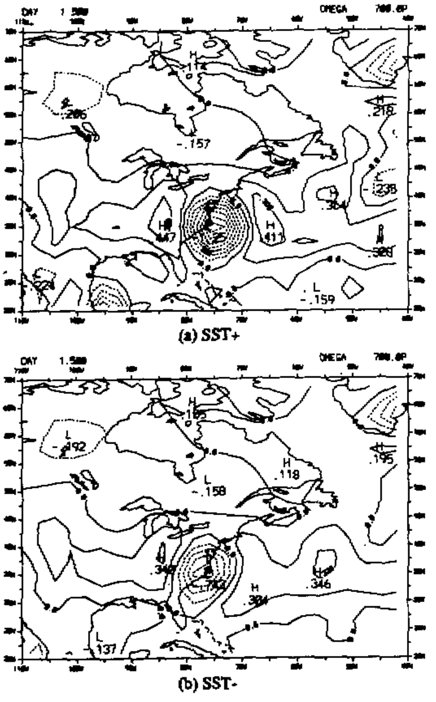
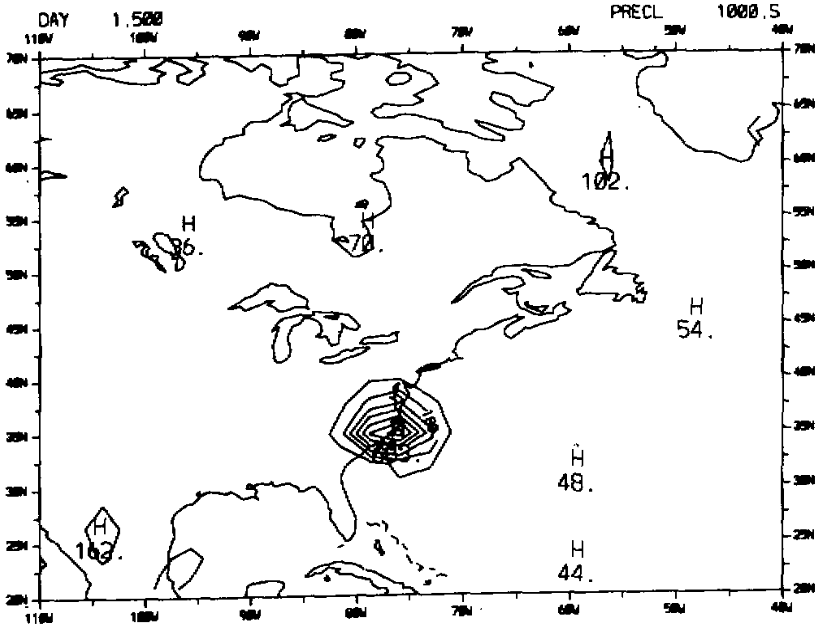
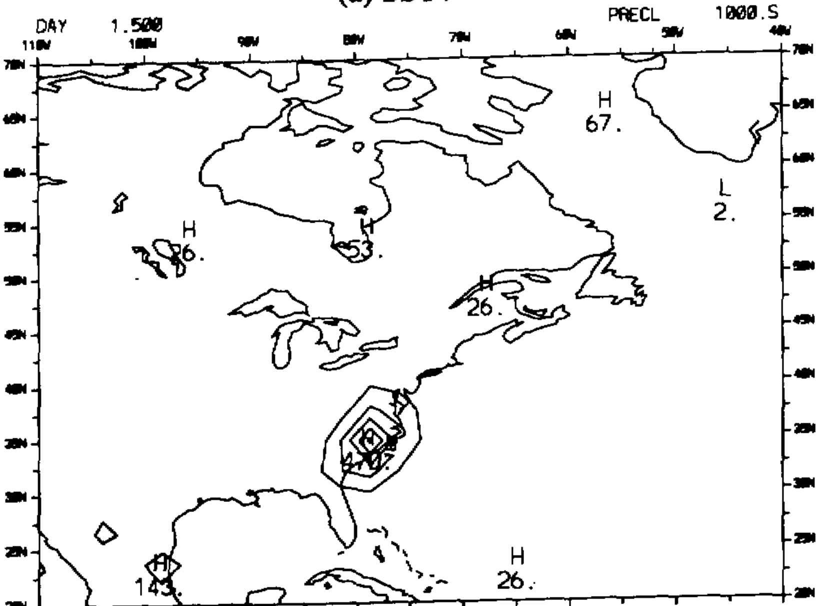


Fig.6. Vertical velocities (Pa s^{-1}) in the 48–hour forecast (0000 UTC 20 Feb 1979) of the Mid–Atlantic cyclone from simulations (a) SST+ and (b) SST–. Contour interval is 0.16 Pa s^{-1}. Negative contours indicate upward motion.



(a) SST+



(b) SST-

Fig.7. Precipitation rates (m s^{-1}) in the 48-hour forecasts (0000 UTC 20 Feb 1979) of the Mid-Atlantic cyclone from simulations (a) SST+ and (b) SST-. *Units* are 10^{-9} ms^{-1} = .0043 cm per 12 hr; contour interval is $90x10^{-9}ms^{-1}$ = 0.39 cm per 12 hr.

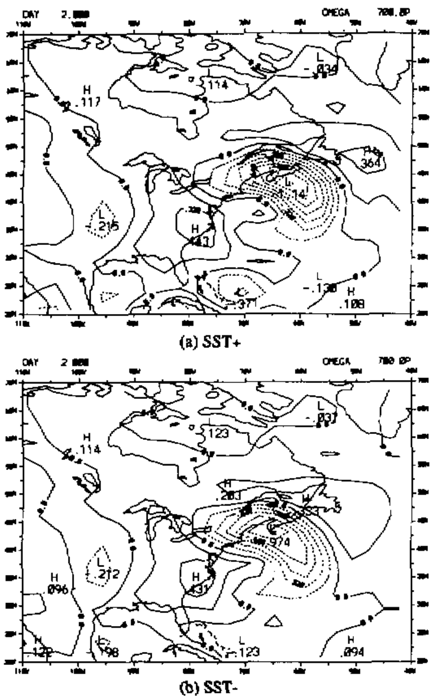


Fig.8. Vertical velocities (Pa s^{-1}) in the 36–hour forecast (0000 UTC 07 Feb 1978) of the New England blizzard from simulations (a) SST+ and (b) SST–. Contour interval is 0.16 Pa s^{-1}. Negative contours denote upward motion.

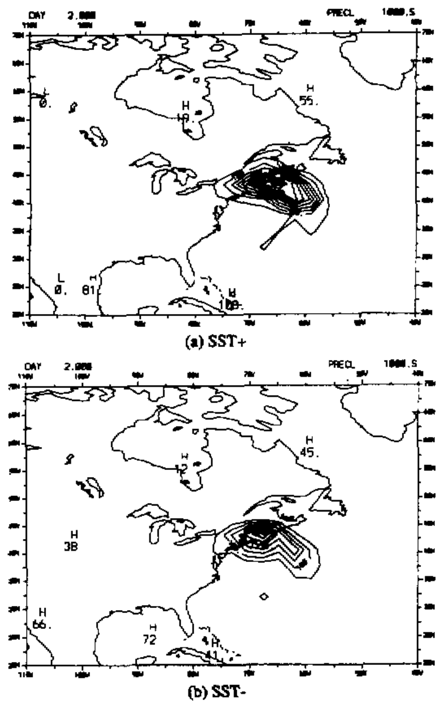


Fig.9. Precipitation rate (m s^{-1}) in the 36–hour forecasts (0000 UTC 07 Feb 1978) of the New England blizzard from simulations (a) SST+ and (b) SST–. Units are 10^{-9} ms^{-1} = .0043 cm per 12 hr; contour interval is 90x10^{-9} ms^{-1} = 0.39 cm per 12 hr.

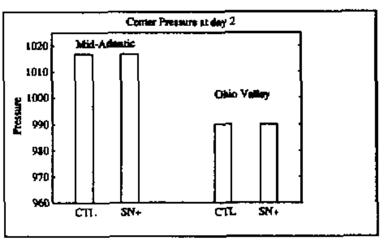
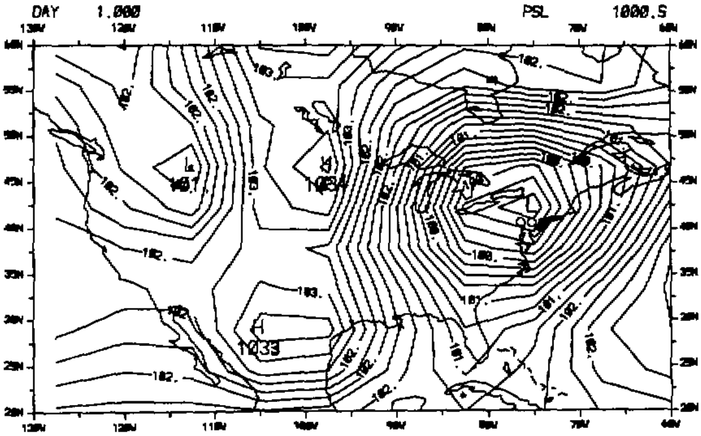
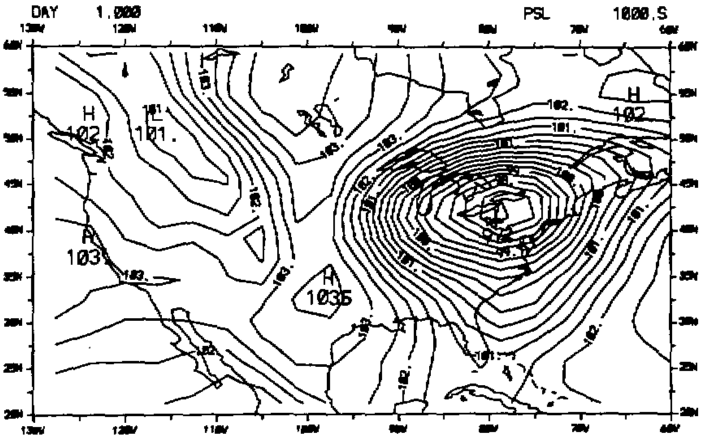


Fig.10. 48–hour model forecasts of central low pressure (hPa) from the T42 control (CTL) and heavy–snow (SN+) simulations.

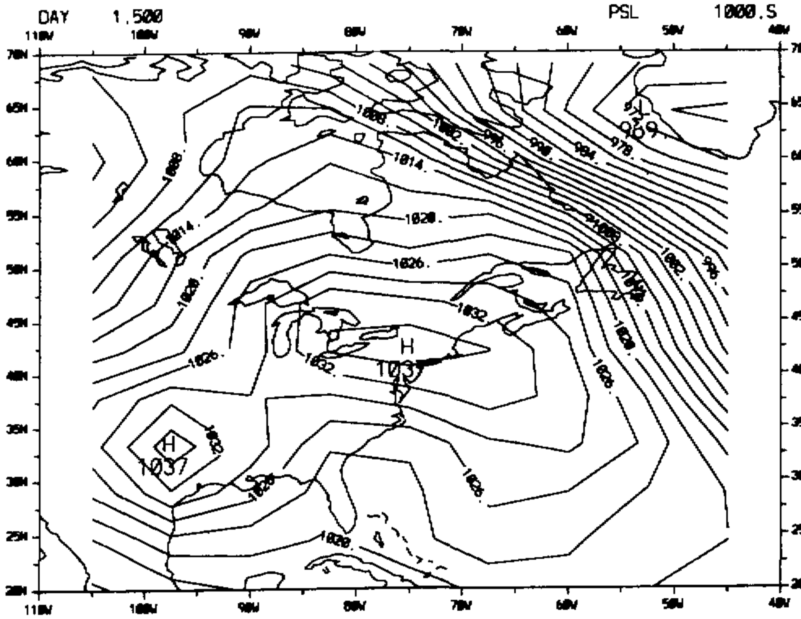


(a) R15

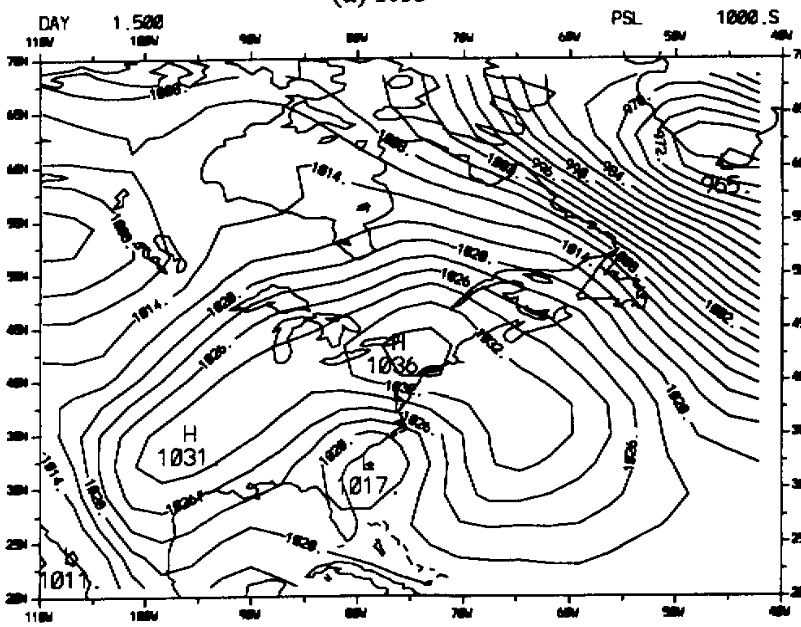


(b) R30

Fig.11. 24-hour "control" forecasts of sea level pressure (for 1200 UTC 26 Jan 1978) obtained with (a) R15 resolution and (b) R30 resolution.



(a) R15



(b) T42

Fig.12. 36-hour "control" forecasts of sea level pressure (for 1200 UTC 19 Feb 1979) obtained with (a) R15 resolution and (b) T42 resolution.