NOTES AND CORRESPONDENCE

Diabatic Initialization Tests Using the Naval Research Laboratory Limited-Area Numerical Weather Prediction Model

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ABSTRACT

Diabatic forcing has been incorporated into a nonlinear normal-mode initialization scheme to provide more realistic initial conditions and to alleviate the problem of the spinup time of the Naval Research Laboratory Limited-Area Numerical Weather Prediction Model. Latent heating profiles are computed from the observed rainfall and from the model-generated convective rainfall at locations where there were no observations. The latent heating is distributed in the vertical according to the cumulus convective parameterization scheme (Kuo scheme) of the model. The results of a case study from the Genesis of Atlantic Lows Experiment indicated that model spinup of forecast rainfall can be reduced when diabatic initialization with merging of heat and/or rain is used.

1. Introduction

The dominant forcing in the troposphere within areas of large precipitation is diabatic heating (convective and radiative heating, and large-scale condensation). The present study deals strictly with diabatic heating from cumulus convection. A convective heating term is incorporated in the balance condition for the high-frequency normal modes (Bengtsson 1981; Errico and Rasch 1988; Kitade 1983; Wergen 1983). With the inclusion of heating corresponding to observed rainfall data in the diabatic forcing term, the initialization can force the model state toward the real atmospheric state. As a result, the diabatic initialization can improve the model's forecast fields. Possibly, the primary benefit of initialization with diabatic forcing and moisture initialization is that the spinup problem can be reduced. That is, diabatic nonlinear normal-mode initialization (DNNMI) produces an initial model state that already includes realistic heating.

Model spinup appears in all numerical forecast systems both in midlatitudes and tropics (Kasahara et al. 1988). It is one of the most serious problems in numerical weather prediction (NWP), and has been documented in research and operational models. Girard and Jarraud (1982) and Heckley (1985) documented spinup in the operational models used by the European Centre for Medium-Range Weather Forecasts, whereas Miyakoda et al. (1978) and Donner (1988) illustrated different aspects of the spinup phenomena in research models at the Geophysical Fluid Dynamics Laboratory and National Center for Atmospheric Research, respectively.

Inadequate physical parameterizations and incorrect initial specifications of divergence, moisture, and thermal fields are the primary causes of spinup (Mohanty et al. 1986). Most normal-mode initialization methods have been adiabatic in nature; that is, the existing latent heating at the initial model time was excluded, leaving out a significant heat source that affected the adjustment between the mass and momentum fields. Lejenas

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(1980) found that adiabatic normal-mode initialization, while providing improved vertical velocity profiles, does not alleviate the spinup problem. Data assimilation techniques that incorporate a more realistic background field in the analysis of observed data have been developed (Lejenas 1980). At the start of each update cycle of the assimilation, the background forecast field is corrected using the observations of mass, momentum, and humidity. During this process, the divergent part of the wind is not represented properly, because the divergence has the same order of magnitude as the errors in the wind field. A consistent diabatic circulation can be generated if the analysis at each cycle of the assimilation is initialized with a diabatic initialization procedure. Turpeinen et al. (1990) concluded that the inclusion of observed low-level latent heat sources with a consistent and higher-resolution moisture analysis are critical components in reducing the underestimation of initial divergence and, hence, precipitation rates.

Throughout the 1980s, NWP models incorporating initial latent heating based on rain rates have been developed. Turpeinen et al. (1990) summarized the main features of some of these models. Mohanty et al. (1986) investigated the inclusion of diabatic heating in the normal-mode initialization (NMI) and found that the divergent circulation was rapidly destroyed by the integrated model heating if it differed too much from the observed heating. In the present study, we have merged the model-produced heating, during the first few hours of integration, with the heating used in the initialization.

The major thrust of this paper is to incorporate the latent heat forcing released due to convective precipitation estimated from the conventional and satellite observations into the normal-mode initialization of the Naval Research Laboratory (NRL) Limited-Area Numerical Weather Prediction Model in an effort to shorten the spinup time. Our goal is also to demonstrate that NMI with diabatic forcing provides improved initialized fields over adiabatic NMI. We have included a diabatic heating term, derived from "spunup" model convective rainfall and observed rainfall, in our nonlinear normal-mode initialization (NNMI) to better define the initial conditions for model integration.

Several model runs (test cases) are made to test the effectiveness of DNNMI as compared to initialization excluding the heating term, or adiabatic NNMI (ANNMI). The NRL mesoscale model is briefly described in the next section. The procedure for computing the diabatic heating for the initialization is then described, followed by the experimental design and results.

2. Model description

The model used in the present study was developed at the Naval Research Laboratory, and is detailed in Holt et al. (1990) and in NRL memorandum reports by Madala et al. (1987) and Sashegyi and Madala (1992). This is a primitive equation model in terrain-following coordinates having a one-way interacting nested grid network. The coarse grid covers a domain including the continental United States from 10° to 70°N and 40° to 140°W, with a horizontal resolution of 2° longitude (170 km at 40°N) × 1.5° latitude (166.5 km). The Genesis of Atlantic Lows Experiment (GALE) (inner or fine) grid covers a smaller domain including the eastern half of the United States and extending out over the Gulf Stream from 23.5° to 56.5°N and 58° to 102°W with a finer horizontal resolution of 0.67° longitude (56.7 km at 40°N) × 0.5° latitude (55.5 km). In the vertical, both grids use 10 equally spaced sigma levels. Model topography for both grid domains is obtained from navy 10-min global topographical data. Even though this paper addresses latent heat release due to convective precipitation, there are two reasons for selecting this extratropical case. One is the availability of a comprehensive GALE dataset. The other is the existence of mesoscale convection over the ocean and the coastal areas due to strong boundary-layer baroclinicity.

The continuous governing equations are written in flux form, and the model's time integration scheme is the split-explicit method that allows larger time steps by effectively separating various terms in the prognostic equations into parts governing the slow-moving Rossby modes and fast-moving gravity modes. A staggered grid network (Arakawa's C grid) is used for horizontal differencing. Lateral boundary conditions suggested by Davies (1976, 1983) are employed in the present version of the model. Monin–Obukhov similarity theory (Yamada 1979) is used to determine the surface transfer of momentum, sensible heat, and latent heat. The cumulus convective parameterization scheme used in this model is the one suggested by Kuo (1974) and modified by Anthes (1977). The parameterization of large-scale or nonconvective precipitation follows Haltiner and Williams (1980); that is, the excess moisture in a supersaturated layer is condensed out isobarically.

3. Diabatic heating in model initialization

Until recently, the NRL model was initialized exclusively using an adiabatic nonlinear normal-mode initialization. The procedure is detailed by Sashegyi and Madala (1990, 1993). In their NNMI, only the first three modes—the external mode and first two internal modes of the model—are initialized. Sashegyi and Madala (1990) showed that the first two modes require only two iterations of the scheme to converge. The third mode converged after five iterations.

Adiabatic NNMI has proven to be extremely effective in controlling spurious large-amplitude gravity-wave oscillations due to initial imbalances between the mass and wind fields in primitive equation models (Puri and Miller 1990; Sashegyi and Madala 1990).

However, the use of adiabatic NNMI (ANNMI) leads to a drastic depletion of the divergent circulation.

Wergen (1983, 1987) introduced a procedure to overcome this problem, in which average diabatic heating is obtained by integrating the model for a few time steps prior to the initialization. The average heating is then included in the nonlinear forcing of the iterative initialization process. The fixed diabatic heating is determined as the time-mean heating generated by model physics (cumulus parameterization and large-scale heating) during the short integration. Unfortunately, most forecast models do not produce realistic heating rates during the first few hours. Therefore, in our experiments we chose to integrate the model for 9 h before accumulating the model latent heating and convective rainfall from which our time-mean heating and rainfall rates were derived. The diabatic NNMI (DNNMI) used in this study is similar to Wergen's, but it is original in that spunup model heating is applied in the initialization rather than the heating from the first few hours of integration, as is usually done. The procedure involves the following steps.

1) The model is integrated for 12 h from adiabatically initialized fields. Convective rainfall, from which the diabatic heating is derived, is accumulated from 9 to 12 h of this initial integration (control run), allowing ample time for model spinup.

2) Time average convective rainfall rates over the 3-h period are derived for all grid points using conventional and satellite-derived observations. Model rainfall was used for locations over the coastal ocean, since satellite rainfall data were unreliable.

3) The model is tested for convective instability at the observed rainfall locations. The average rain rates are converted into vertical profiles of heating using a reverse Kuo cumulus parameterization only at the locations where the atmosphere is convectively unstable. Inversion of the Kuo scheme is essentially straightforward and is done only when the atmosphere is convectively unstable at a location (Harms et al. 1992). This vertical distribution of the latent heating is based on the cumulus convective scheme of the model. Thus, no simplifying hypotheses are needed. The advantage of the present approach is an improved consistency obtained with the physical parameterization scheme of the model.

4) This three-dimensional diabatic heating field is then added as a forcing term in the NNMI thermodynamic energy balance equation as the DNNMI is performed. As a result, diabatic effects are explicitly included in the specification of the heating field.

The aforementioned diabatic initialization is primarily for heating associated with convective precipitation. The heating is nearly zero in the lower troposphere and varies significantly from case to case in the upper troposphere. The first three modes of the model account for 40%–50% of the convective heating in the upper troposphere. Therefore, we assume that the method described here accounts for a significant part of the divergence field. The iterative scheme used in the DNNMI does not converge to a solution with the inclusion of the fourth mode, although it may contribute significantly to convection.

The conversion of rainfall rates into vertical profiles of convective heating depends on the stability of the environment as determined by the cumulus parameterization. If convective instability occurs, a heating function is computed using the reverse Kuo scheme. This heating function is then used to distribute the diabatic heating, derived from the average rainfall rates, in the vertical direction. If the environment is convectively stable, the diabatic heating associated with the two-dimensional rainfall distribution will be taken as zero. Therefore, nonconvective precipitation does not contribute to the diabatic heating in the present initialization scheme.

The persistence of balance achieved by DNNMI during the early stages of the model integration depends heavily on the compatibility between the specified heating during initialization and the model-produced heating during integration (Puri and Miller 1990). Puri (1987) suggested that one possible way of retaining this compatibility in the heating rates would be to adjust the moisture field until the model-produced heating rates determined by the convective parameterization in the model are similar to those used during DNNMI. Here, two procedures are used to retain this desired compatibility in heating rates. First, the model rainfall and heating rates produced during the first 3 h of integration are merged with the corresponding rates from the initialization. A nonlinear weighting factor α is employed where $\alpha = 1$ at $t = 0$ h and $\alpha = 0$ at $t = 3$ h. The relation is given by

$$R_m = \alpha R_i + (1 - \alpha) R_c, \tag{1}$$

where R_i is the convective rainfall rate (from the control) used in DNNMI, R_c is the model-produced convective rainfall rate, R_m is the merged rain rate, and α is given by

$$\alpha = 1 - \frac{[1 + \sin(\pi t/3 - \pi/2)]}{2}. \tag{2}$$

The foregoing relations allow the influence of the initialized heating and rain rates to approach zero in a smoother manner than a simple linear relationship would allow. Merging is applicable only for DNNMI cases, since ANNMI, by definition, does not include a diabatic heating term in its balance equation.

The second method involves adjusting the humidity fields prior to initialization. The importance of moisture adjustment in diabatic initialization was emphasized by Wolcott and Warner (1981). They argued that if the environment is not humid enough, the upward motion associated with the initialized divergence field will not be sustained by latent heat release. In the present study, specific humidity is enhanced only at grid points where convective rainfall is occurring and the relative humidity is less than 95%. At those points, the specific humidity is increased to 95% of the saturation specific humidity at the three lowest model levels. However, we found that the changes in the humidity fields were small and, as a result, the adjustment had minimal effect on the convective rainfall. Since the modeled large-scale condensation occurs only upon supersaturation, not at 95% relative humidity, this moisture adjustment would have little effect on nonconvective precipitation.

4. Experimental design

Before the experiments are described, the synoptic situation for our study is given.

a. Synoptic setting

During the period 0000 UTC 25 January–0000 UTC 27 January 1986, coastal frontogenesis and cyclogenesis took place along the eastern seaboard. At 0000 UTC 26 January, the coastal front extended from Georgia to southern New England. Cold-air damming and warming of the air over the Gulf Stream led to the strong thermal gradient along the coast. By 1200 UTC 26 January 1986, a weak surface disturbance was located across the Carolinas and Georgia. This disturbance would strengthen over the next 12 h due to cold-air advection aloft approaching from the northwest in association with a cold front in the Ohio River valley. The surface cyclone center became evident off the Carolina coast around 0000 UTC 27 January 1986.

By 1200 UTC 27 January 1986, a developing low pressure system was found off the New Jersey coast, replacing the coastal front wave that had moved northward into New England and disappeared. Behind the developing cyclone, cold air associated with a midtropospheric vortex continued southeastward. This influx of cold air over the warm waters of the Gulf Stream fueled coastal frontogenesis south of the developing cyclone.

b. Description of the model experiments

Initially, three test cases (model runs) were performed to determine improvements (if any) in the model initial state and subsequent forecasts using DNNMI versus ANNMI. The first is a control run in which the model is initialized at 1200 UTC 26 January 1986 using the NMC analyzed data. These fields of 2.5° resolution are first interpolated to the model grid and then initialized with the ANNMI for the first three vertical normal modes of the model. The model is then integrated for 24 h. The 12-h forecast from the control run serves as the initial fields for experiments 2 and 3. In case 2, the model is initialized using DNNMI on the forecast fields from case 1 valid at 0000 UTC 27 January 1986. The analyzed rainfall that includes the observations and the model rainfall in data-void areas (2100 UTC 26 January–0000 UTC 27 January 1986 of the control) is used to compute heating rates at each vertical level of the model for the DNNMI. The model is then integrated for 12 h, with heat and/or rain merging. The initialization for the next case (run 3) is simply an ANNMI on the control run's 12-h forecast.

For this study, the control run is compared against the other two cases; from 1200 UTC 26 January to 0000 UTC 27 January 1986 of the control run, the model should have developed the divergent part of the wind reasonably well. By using model-generated rainfall rates in the DNNMI (case 2), one would expect a negligible spinup during the subsequent forecast. Also, one might expect little change due to the initialization using model rain since the model heating function is consistent with other model parameters. By comparing the initialized and subsequent forecast fields from case 2 with the corresponding fields from the control, one can determine if the model-generated rainfall, which is a 2D distribution, can re-create the 3D distribution of vertical heating rates accurately.

5. Results

The results obtained by making qualitative comparisons of meteorological fields from the different model initializations and forecasts of the three test cases indicate that the differences between cases 2 and 3 of their respective initialized fields of 1000-, 500-, and 250-mb geopotential height, temperature, and winds are extremely small. As expected, the first-order analysis fields (12-h forecast of run 1) changed little with each initialization in these test cases, and as a result, the forecasts (valid at 1200 UTC 27 January 1986) of these variables from these two runs are almost identical and agree well with the control run forecast.

a. Comparison of initialized vertical velocity

Since vertical velocity or ω (dp/dt) is directly related to diabatic heating, we can expect noticeable differences between the initial states of omega from cases 2 and 3. Furthermore, the effectiveness of diabatic heating in inducing divergent circulations can be seen by comparing omega fields from DNNMI and those resulting from ANNMI. As expected, in geographic areas absent of precipitation, vertical velocity patterns in cases 2 (DNNMI) and 3 (ANNMI) are approximately the same and very close to the "control simulation" (Fig. 1). Off the East Coast, an area of strong ascent stretches along the eastern seaboard, and is associated with the old frontal boundary and the developing cyclone off the North Carolina coast. In this region, where the control run ("truth") predicts heavy rain at initialization time (0000 UTC 27 January 1986), the initialized state for run 2 is very close to the control simulation. The pattern and positions of maxima and minima in

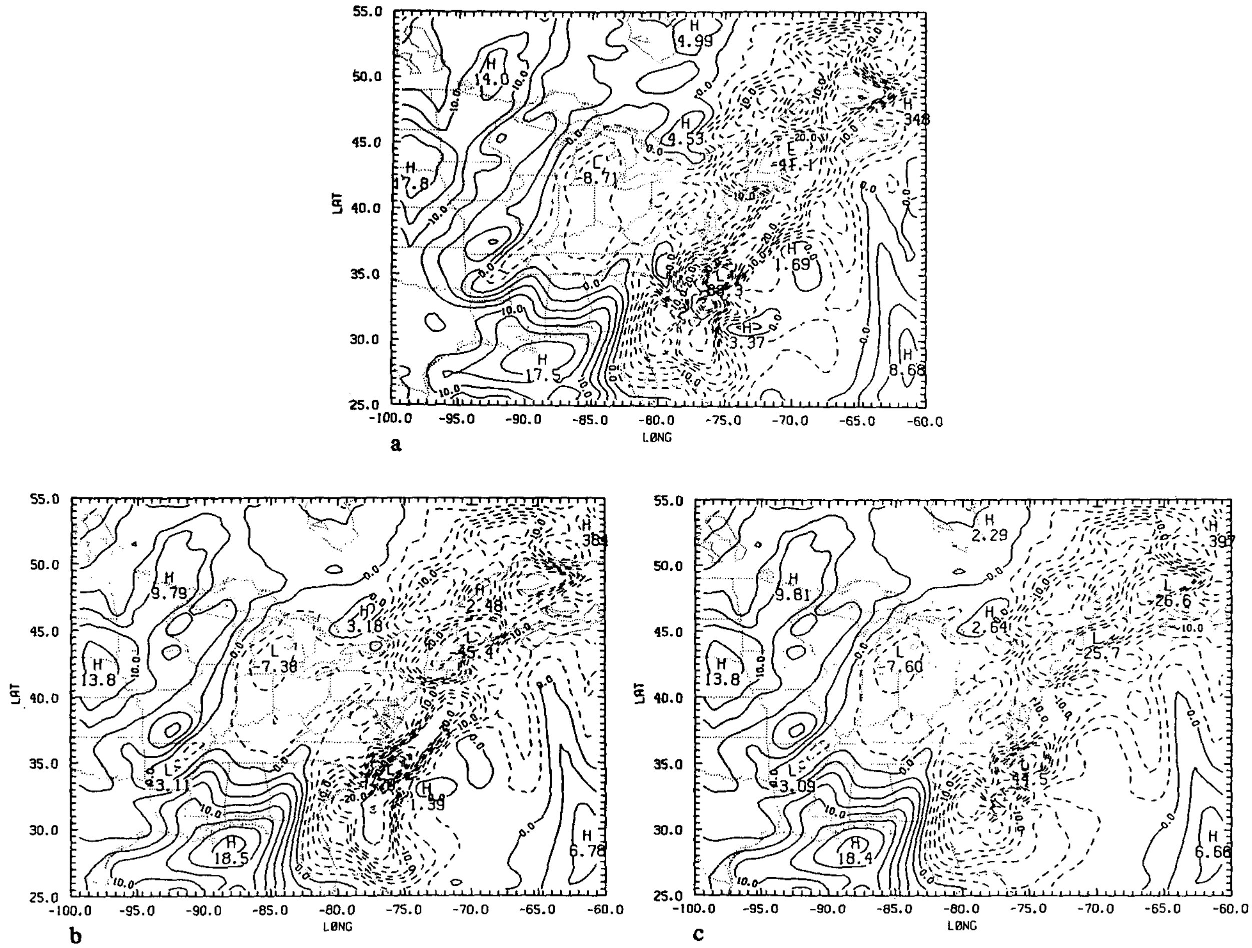

FIG. 1. Vertical-motion fields (mb h^{-1}) for 500 mb valid at 0000 UTC 27 January 1986: (a) from 12-h forecast of the control run, (b) after DNNMI (case 2), and (c) after ANNMI (case 3).

the omega field show little change from the control run, suggesting the 3D structure of model convective heating can be re-created from a 2D rain distribution. A further comparison between case 2 and case 3 reveals the deficiency of ANNMI. In the vicinity of the developing cyclone, the magnitude of ω has changed substantially using ANNMI; the maximum upward velocity is only about 60% of that resulting from DNNMI. Since a significant amount of the divergence (and hence vertical motions) associated with heavy precipitation events may be forced by latent heat release, and since the nonlinear step in the ANNMI does not include this diabatic forcing, the divergence due to this forcing will be removed as if it were associated with unwanted gravity waves. As a result, the vertical velocities are underestimated.

b. Forecast precipitation comparisons

The patterns of 12-h (0000–1200 UTC 27 January 1986) rainfall in runs 2 and 3 are very similar to each other and to the control (run 1) in areal coverage and accumulation. The 12-h rainfall forecast from the adiabatically initialized fields is just as good as the forecast originating from the diabatically initialized fields. Since the physics and dynamics of the nonlinear normal-mode procedure are internally consistent with the numerical model (which provided the analysis fields), the initialization procedure, whether with or without diabatic heating, changes the model forecast fields only a small amount. As a result, the subsequent forecasts are essentially the same. Therefore, additional model experiments were performed in which GALE 3-h surface and upper-air data at 0000 UTC 27 January 1986 were analyzed using a multivariate, successive correction objective analysis scheme (Sashegyi et al. 1993). Model forecast fields served as the first guess for the analyses. Adiabatic (ANNMI) and diabatic (DNNMI) initializations were performed on the analysis fields. In the latter case, rain data from conventional raingages over land and from satellite-based observations over water were combined with the model-produced rainfall for computation of the 3D heating function in the model initialization procedure.

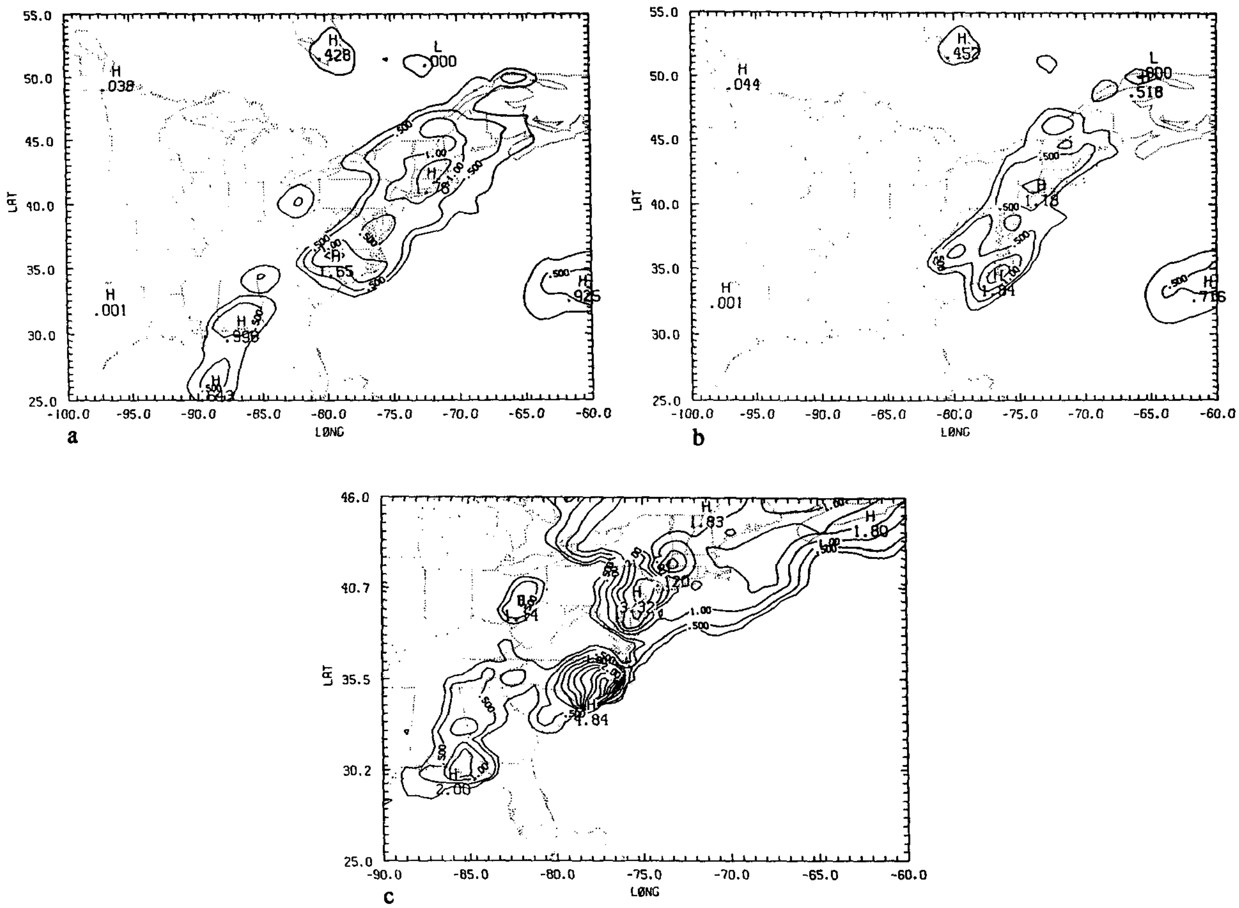

FIG. 2. Forecasts of accumulated total precipitation (cm) (0000–0600 UTC 26 January 1986) originating from (a) DNNMI and (b) ANNMI. (c) Observed precipitation (cm) for the same period.

Figure 2 shows 6-h observed rainfall and accumulated forecast rainfall valid 0000–0600 UTC 26 January 1986. The observations over the GALE area were obtained using raingages and were averaged over 6 h. Over the open ocean away from coastal regions and over the land west of 90°W and north of 45°N, where conventional rainfall data were not available, data were obtained from the University of Wisconsin and consisted of rainfall rates derived from the outgoing longwave radiation (OLR) sensor aboard *GOES-6* with 1° resolution. Near the coastal ocean where OLR data is not reliable, model-produced rainfall rates are used. These three datasets are blended in a way to ensure smooth transition. Forecast and observed rainfalls in this figure include both convective and nonconvective precipitation. Since this version of the model is the same as the NORAPS (Navy Operational Regional Analysis Prediction System) used by Liou et al. (1990), the breakdown of the convective versus stratiform precipitation is essentially similar to their results. The forecast in Fig. 2a was initialized with DNNMI at 0000 UTC 26 January. The rainfall pattern is similar to the observed; in particular, over Alabama and along the central Gulf coast region, the model was able to predict the precipitation during this short-range forecast. However, the forecast originating from ANNMI (Fig. 2b) fails to capture any rainfall over the Gulf coast associated with the developing short wave. The absence of diabatic heating from the NNMI has caused a spinup problem in this case. Root-mean-square differences between these forecasts and observed rainfall were computed. The differences were computed only at grid points in which at least 0.01 cm of either forecast or observed rainfall accumulated during the 6-h period. When initializing with ANNMI and DNNMI, the rms differences were 0.9 and 0.7 cm, respectively. The larger rms difference in the ANNMI case is due to model spinup. The disparity between these two cases would be even greater, if only the accumulated rainfall from the first 3 h of model integration was compared.

6. Summary and conclusions

In this study, we took the viewpoint that the "best" initialized states were those that were least altered by initialization. From comparisons of vertical velocity fields, we found that DNNMI with the analyzed rain produced an initial state very similar to the control simulation and, thus, successfully re-created the 3D distribution of convective heating from the 2D model rain distribution. The ANNMI (case 3) changed the analysis significantly by reducing the maximum vertical velocities to about 60% of that resulting from DNNMI. With the diabatic heating term that forces (to a large degree) convective precipitation, the DNNMI (unlike the ANNMI) retains the divergence (or vertical motion) associated with the convection.

When DNNMI is performed on the analysis fields, model spinup time is reduced. The preforecast integration of the model ensures that the analyses are spun up and that the circulations in these analyses are consistent with the model resolution and external parameters such as topography. The initializations and forecasts were performed in this study for the midlatitudes, which dictates a relatively short spinup. In the data-sparse tropics, spinup can be expected to be much greater. In the tropical case, DNNMI with merging will be critical in reducing spinup time.

In the present study, we considered only diabatic heating associated with convective precipitation. We plan to investigate the latent heating resulting from large-scale, nonconvective rainfall in the near future. The spunup model heating approach will again be incorporated and tested.

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