N89-21732

1988

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

The Role of Radiation-Dynamics Interaction in Regional Numerical Weather Prediction

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Date: August 8, 1988

Contract No.: NGT 01-002-099
The University of Alabama

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ABSTRACT

This research focuses on the role of radiation-dynamics interaction in regional numerical weather prediction of severe storm environment and mesoscale convective systems over the central United States. Based upon the earlier numerical model simulation experiments, we believe that such interaction can have profound impact on the dynamics and thermodynamics of regional weather systems. The research will be carried out using real-data model forecast experiments performed on the CRAY-X/MP computer at NASA/MSFC.

The forecasting system to be used in this study is a comprehensive mesoscale prediction system which includes analysis and initialization, the dynamic model, and the post-forecast diagnosis codes. The model physics are currently undergoing many improvements in parameterizing radiation processes in the model atmosphere.

The forecast experiments in conjunction with in-depth model verification and diagnosis are aimed at a quantitative understanding of the interaction between atmospheric radiation and regional dynamical processes in mesoscale models as well as in nature. Thus, significant advances in regional numerical weather prediction can be made. Results shall also provide valuable information for observational designs in the area of remote-sensing techniques to study the characteristics of air-land thermal interaction and moist processes under various atmospheric conditions.

ACKNOWLEDGEMENTS

I am grateful for the opportunity to participate in the Summer Faculty Fellowship Program at NASA/MSFC. I would like to express my appreciation to Dr. Mike Freeman and Ms. Ernestine Cothran (CO-Directors) and their staff for very professional management of the program. Also, I like to thank the Department of Mechanical Engineering at UAH for providing a summer faculty ID which allows me to use the University facilities.

I would like to thank my colleagues Dr. F. Robertson of NASA/MSFC and Dr. M. Kalb of USRA for their interest in this research and providing valuable discussions and comments on this work. I wish to thank Mr. M. Seablom, Ms. J. Srikishen, and Mr. M. Smith for technical help in carrying out numerical experiments on the CRAY-X/MP computer at MSFC.

I. INTRODUCTION

One of the central issues in regional numerical weather prediction (NWP) is the forecasting of mesoscale systems driven by latent heating because of their often severe nature. The present study will focus on the role of radiation-dynamics interaction in the numerical forecast of mesoscale convective storms of horizontal scale ranging from 50 km to 500 km in the central United States during severe weather seasons of spring and early summer.

It is well known that radiation is the primary energy source for the generation and maintenance of the dynamic systems in the atmosphere. The dynamic systems develop within baroclinic patterns as a result of horizontal differences in radiation budgets. On the other hand, the cloud and moisture distribution associated with the dynamic systems will modify the radiation field.

However, in short-range (<36 hours) regional NWP, the atmospheric radiation is generally regarded as a minor diabatic process because the rate of radiative warming/cooling in the troposphere is quite small in comparison with that of latent heating. The mean rate of net temperature change in the atmosphere under the clear sky condition due to the absorption of insolation and the emission of infrared irradiance by air is on the order of -1°C per day. To date, an explicit treatment of radiation processes in the model atmosphere does not exist in any comprehensive regional models (Pielke, 1984). And there is still lack of any in-depth study of the role of radiation-dynamics interaction in the short-range numerical forecasting of severe convective storms.

Nevertheless, based on earlier case studies we feel that the radiation-dynamics interaction may exert profound impact on the development of mesoscale storms over the central United States from the standpoint of the following three aspects.

A. Effects of cloudiness associated with mesoscale systems on regional radiation budget.
B. Surface heating and moisture source.
C. Synamic instability in the planetary boundary layer (PBL).

These three aspects will be discussed in some detail in Section II.

Scientific questions concerning the impact will be addressed using real-data model simulation experiments followed by detailed model verification and diagnosis. The prediction system to be used in this study is the Drexel LAMPS (Limited Area and Mesoscale Prediction System) which is a comprehensive mesoscale prediction system. LAMPS includes analysis and initialization, the dynamic model, and the post-forecast diagnosis codes. A detailed description of LAMPS can be found in the papers by Perkey (1976), Kreitzberg (1978), and Chang *et al.* (1981).

The model initial state is obtained from the objective analysis of rawinsonde observations based upon the isentropic scheme designed by Bleck (1975). The dynamic model is a three-dimensional primitive equation model consisting of 15 terrain following vertical levels and a longitude-latitude horizontal grid. The model levels ranging from 0 to 16 km with relatively higher resolution in the PBL. The model physics consist of essential dry and moist processes for the quantitative study of various aspects of convective storms under diverse meteorological conditions. A brief discussion of solving the radiative transfer equations in the model is included in Section III. The numerical experiments and their purposes, and related hypotheses to be tested are described in Section IV.

II. RADIATION-DYNAMICS INTERACTION

A. The Effects of Cloudiness on Radiation Budgets

Clouds are the principal modulators of radiation in the atmosphere. The presence of clouds increases the counter radiation and, hence, decreases the effective outgoing infrared radiation and incoming solar radiation. The infrared cooling near the cloud top can be as high as 5°C per day (Katayama, 1966; Stephens and Webster, 1981) which is much greater than the average cooling rate under the clear sky conditions, while for the layers below the cloud the cooling rates are considerably reduced. Thus, the distribution of horizontal-developing clouds associated with dynamic systems can have strong influences on the vertical temperature profile throughout the troposphere and the regional baroclinic patterns (cloudy vs. clear sky areas).

The significance of the strong cloud-top cooling may be illustrated by some results from regional model simulations of a developing cyclone. Figure 1 shows the 24-h forecast height, temperature and vector wind differences on the 700, 500, and 300 mb pressure surfaces, respectively, between the wet (with latent heat release) and dry simulations for the 20 May 1977 SESAME case (Chang *et al.*, 1982). The maximum differences occurred over the regions of intense precipitation. The model used in the simulations did not include the effects of strong cloud top cooling.

It is conceivable that the temperature differences at 300 mb in the heavy rain areas over Nebraska and Kansas would have been reduced by a few degrees if the strong cloud top cooling had been considered in the wet model. This could greatly modify the upper air circulations and the development of the surface cyclone.

The substantial reflection of solar radiation takes place at the cloud top because of its large albedo which, except for cirrus, is on the order of 0.5 (Stephens and Webster, 1981). This depletion process may be insignificant so far as the absorption of insolation in the atmosphere is concerned. However, it will have controlling effects on surface energy budgets over the land where solar radiation, infrared radiation, and sensible heat flux represent three major heat exchange processes. The horizontal differences in surface energy budgets, again cloudy vs. clear sky conditions, will contribute to the low-level baroclinicities.

B. Surface Heating and Moisture Source

Because the earth's surface receives more radiative energy from the sun than it loses in the form of infrared radiation during the daytime, some of the excess in radiative energy will be transferred from the ground to the atmosphere in the form of sensible heat flux. The intensity of sensible heating is largely dependent upon the characteristics of the earth's surface and the atmospheric conditions. In arid regions, such as the subtropical deserts, surface heating plays a vital role in the low-level circulations (Chang, 1980; Tang and Reiter, 1984).

The moisture sources for the development of convective storm are closely correlated with the low-level circulations. In the central United States, a major source is the northward warm moist air streams originating over the Gulf of Mexico. During the severe weather seasons of spring and early summer, one of the major mechanisms contributing significantly to the maintenance of such northward flows of warm moist air is believed to be surface heating over the arid regions of Mexico and the southwestern United States.

Particularly, over the Mexican highlands due to very low moisture content in the air and the underlying surface, and the near-vertical solar position at local noon solar radiation works very effectively in heating the earth's surface. The thermal low generated as a result of intense surface heating enhances the east-west pressure gradient across the Gulf of Mexico and consequently the northward flows of warm moist air. Hence, surface heating can have a direct impact on severe storm development in the central United States. The neglect of such an impact in regional NWP may result in an underprediction of convection in the model.

Figure 2 shows a) the simulated 24-h 500-mb height and wind speed, b) the corresponding verification map (NMC analyses), and c) the simulated 24-h 300-mb vorticity and 500-mb vertical motion for the severe storm case of 10-11 April 1979. The intensity and patterns of the model systems are in good agreement with the observations. The structure of the upper air jet and low suggests strong synoptic-scale forcing over Oklahoma and Texas where enduring severe convection was observed (Moore and Fuelberg, 1981). Despite these well-simulated dynamic systems, the model did not predict the longevity of the organized convections in the central United States.

The forecast deficency was primarily attributed to the lack of moisture supply. Surface temperature verification maps (not shown) revealed systematically lower model surface temperatures over Mexico were noted. Consequently, the model failed to generate a surface low over the Mexican highlands and shifted the streams of warm moist air toward the Gulf States instead of Oklahoma and Texas as observed.

Also, Carlson *et al.* (1983) suggested that strong surface heating over the Mexican plateau in conjunction with synoptic-scale motion was responsible for the creation of an elevated mixed-layer inversion over Texas. The inversion prevents the outbreak of thunderstorms over a large area and restricts convection to regions of relatively weak stability.

Lanicci (1984) used numerical experiments to test the influences of soil moisture on the severe storm environment. He suggested that the diabatic effects of radiation processes at the land surface were strongly dependent on the soil moisture and its horizontal gradient, and significantly influenced the severe-storm environment including the dryline, low-level jet, latent instability, etc.

C. Dynamic Instability in the Planetary Boundary Layer

Based on linearized perturbation analysis in conjunction with the numerical experiments, Chang (1987) concluded that in summer over the tropical North Africa dynamic instability possessing the prominent characteristics of African wave disturbances can occur in the lower troposphere characterized by relatively marked meridional temperature gradient (~ 1°C per 100 km) and near-neutral stability as in the unstable PBL. The deep near-neutral layer is created by strong surface heating due to solar radiation. As shown in Fig. 3, the instability results in the perturbations of maximum growth rate having a horizontal scale (around 2000 km) very close to the mean wavelength of African disturbances. Reduction in the horizontal thermal gradient shifted the most unstable mode toward the short waves.

Over the southwestern deserts of the United States, the short-wave disturbances of similar horizontal scale as African waves are often observed in the lower troposphere in summer under relatively weak synoptic (undisturbed) conditions. Upon encountering a potentially unstable tropical air mass, the disturbances can trigger heavy convective rainfall. The disturbances appear to originate over the southwestern deserts with a deep PBL. The environmental conditions of the southwestern deserts resemble those of North Africa in summer. The short waves may have an origin similar to African waves. If so, an adequate treatment of radiation processes in regional-scale models is essential for improving some flash flood forecasting.

III. RADIATIVE TRANSFER

The physical processes that differ from those of the LAMPS model used in previous case studies are the treatment of radiative transfers and surface energy balance. In modeling radiative transfers and the vertical heat exchanges over land, the usual constraints of a numerical model, i.e., not to be too time-consuming, must be considered. For example, an exact treatment by integrating the radiative transfer equations over wavelength and optical path in the model atmosphere is not desirable at this time. Some simplifications and approximations as described below are made in modeling these diabatic processes.

To solve the transfer equations for infrared radiation a simplified method based on an emissivity technique will be used. The capability of the emissivity technique has been studied by many researchers (Rodgers, 1967; Fels and Schwarzkopf, 1975; Chang, 1980). The results indicated that the technique is an acceptable method for numerical prediction models. The differences in computed cooling rates between the emissivity approximation and the Goody (1964) random model are on the order of 0.1°C per day under a wide variety of atmospheric conditions (Fels and Schwarzkopf, 1975). For modeling solar radiation, a technique designed for the UCLA general circulation model (Haltiner and Williams, 1980) and also used in the FSU tropical prediction model (Chang, 1980) will be adopted for this study. Only water vapor is considered as an optically active gas in the model atmosphere.

The energy balance at the land surface involves solar and infrared irradiance, and sensible and latent heat flux, assuming zero soil heat capacity. The assumption is anticipated to have little impact on the nature of surface heating in short-term NWP. Surface heating is well known to be a strong function of cloud cover and moisture content in air. The large change of soil temperature in response to radiation occurs in a layer of few cm thick in a 12-h period (Sellers, 1967). The specific heat capacity of most soils is on the order of 0.3 cal $gm^{-1}K^{-1}$. The energy required for a drastic warming rate, for example 3°C per hour, in the thin layer is less than 5 percent of the incoming irradiance or the outgoing heat flux. Also, heat conduction inside the subsurface layer is neglected.

The sensible and latent heat fluxes are related by a ground wetness parameter which is approximated as a linear function of saturation ratio predicted in the model surface layer. The parameter resembling the Bowen ratio ranges from 2 over the dry desert to 0.5 over the wet surface. This energy balance approach in determining heat flux over land appeared to produce quite realistic results in the model simulations of the low-level circulations over North Africa by Chang (1980).

A unique feature of LAMPS is the explicit forecast of cloud water which is treated as an important component of moisture conservation in the model atmosphere. In comparison with the parameterization approach,this represents a more dynamically consistent way in determining the location of model cloud layers. Thus, the influences of cloudiness on radiation field and surface energy balance, and the resultant effects on the dynamical systems can be better resolved.

IV. OBJECTIVES

The purpose of the research is to obtain a quantitative assessment of the impact of radiation-dynamics interaction on the regional NWP of mesoscale storms. For this purpose, we will carry out in-depth model forecast experiments on the severe weather events occurring on 2 April 1982. The experiments to be conducted on the NASA CRAY-X/MP computer for the case study and the related scientific questions to be stressed are summarized below.

1) A 24-h fine-mesh forecast with the complete model physics.
2) Similar to 1), except without the effects of cloudiness in radiative warming/cooling computation.
3) Similar to 1), except without strong surface heating over arid land.

The fine-mesh model ($\Delta x \approx 140$ km) is intended for creating the severe storm environment. The first experiment is also regarded as a control run. The simulated results will be compared with observations for evaluating the model performance. Experiment 2 is designed to test the hypothesis that the efects of cloudiness on radiative temperature changes over the areas of heavy precipitation will cause significant dynamic responses and thus alter the storm's structure. Experiment 3 is designed to test the hypothesis that surface heating over the arid land, for example the Mexican highlands, can affect the moisture availability for storm development in the south-central United States. The case study chosen represents a strongly disturbed situation. Thus, the question concerning the PBL dynamic instability as mentioned in II.c may not be addressed with this case study.

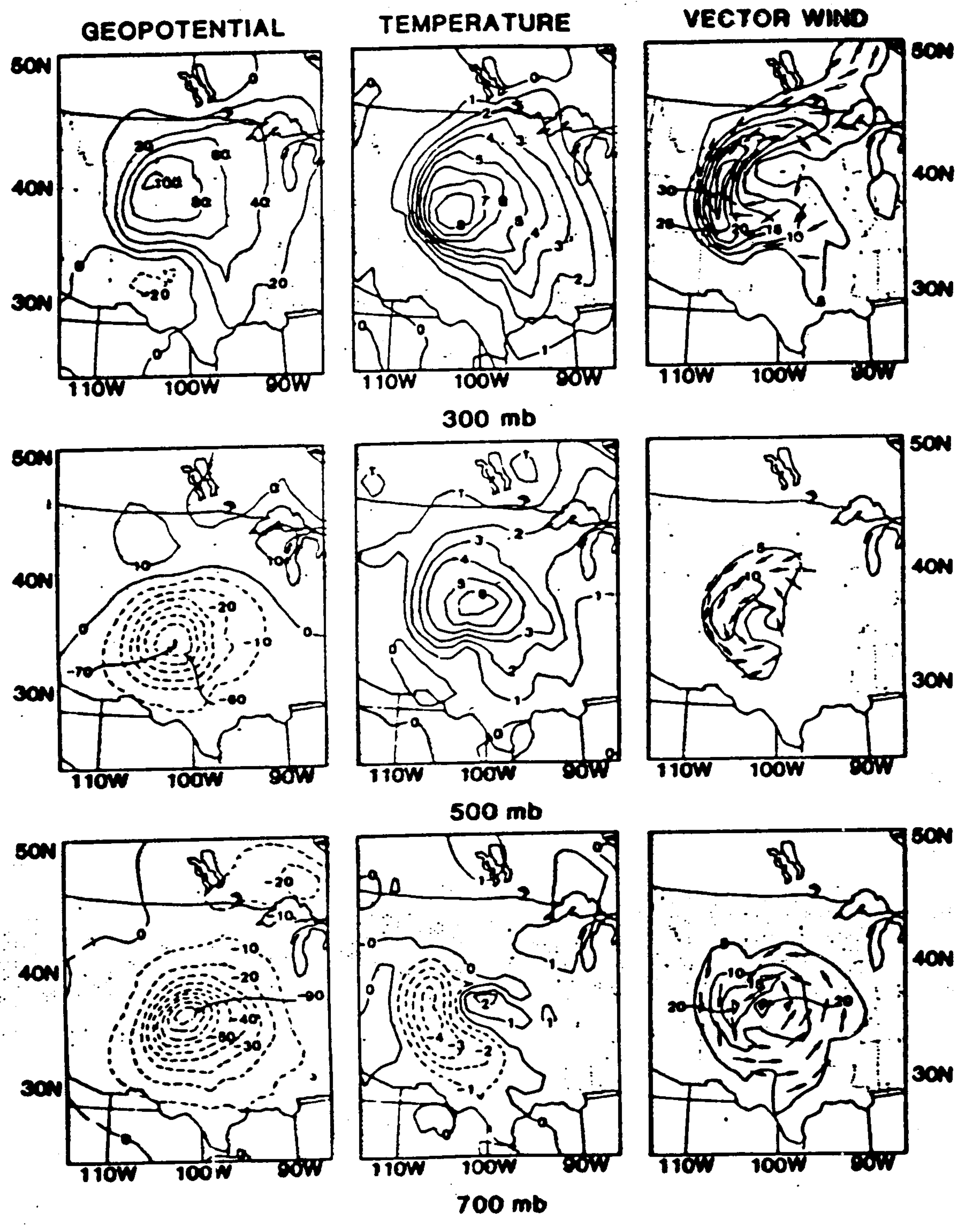

Figure 1. Simulated 24-h difference fields (wet - dry run) at 1200 GMT 21 May 1977. The geopotential height, interval is 10 m on both 700- and 500-mb levels and 20 m on the 300-mb level, the temperature interval is 1°C and the isotach interval is 5 m s^{-1} for all three levels. The dashed contours denote negative values.

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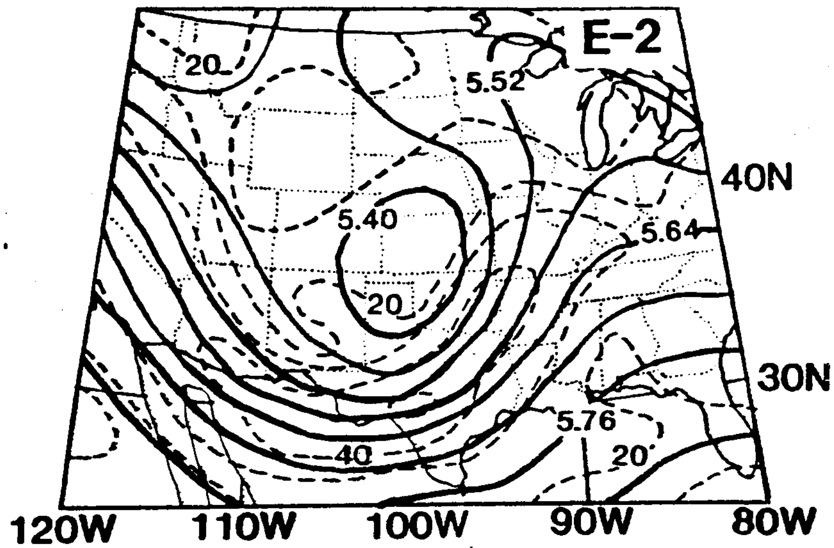
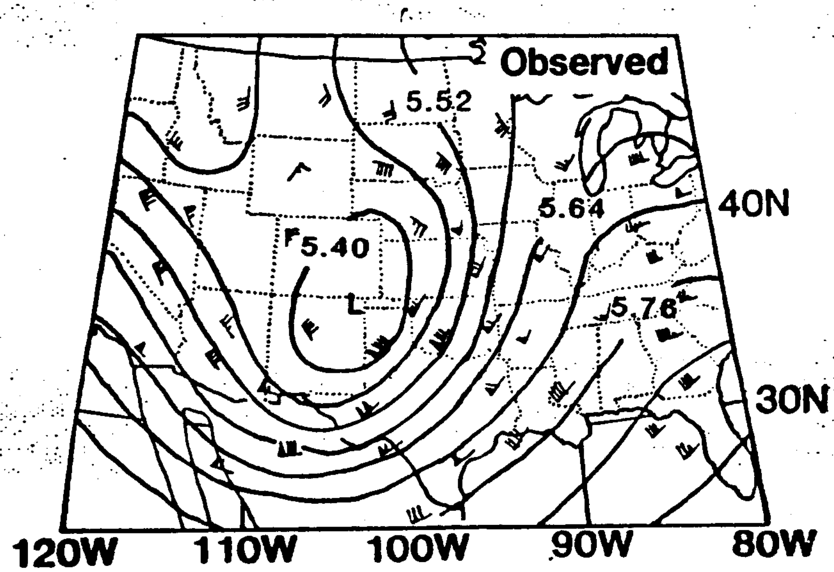


(a)



(b)

Figure 2. (a) Simulated 24-h 500-mb height (solid lines in km) and wind speed (dashed lines in m s^{-1}) at 1200 GMT 11 April 1979, and (b) observed conditions.

V. RESULTS

Some preliminary results of the proposed numerical model experiments performed on 2 April 1982 case are presented. We find that although the atmospheric radiation has shown consistently cooling effects, the mean temperature of the model atmosphere has actually increased due to the increase in latent heating in this case. Figures 3a and 4a show, respectively, the simulated 12-h and 24-h accumulation of convective precipitation for the reference run. The corresponding results for the model with the improved radiative transfer computation including the effects of cloudiness are presented in Figs. 3b and 4b. The differences between the two simulations are quite striking.

The12-h simulations indicate that the improved radiation computation increases the maximum precipitation by about half inch in southeastern Missouri and generates a center of convection off the coast of Florida (Fig. 3b). For the 24-h simulations, Fig. 4a shows one major center with intense convection confined to the central mid-west states and a relatively weak maximum off the coast, while Fig. 4b shows multi-center structure with wide-spread convection over the nation. The former has no convective but substantial non-convective rainfalls (not shown) over Montana. Unfortunately, at this time we do not have adequate precipitation information for a quantitative model verification.

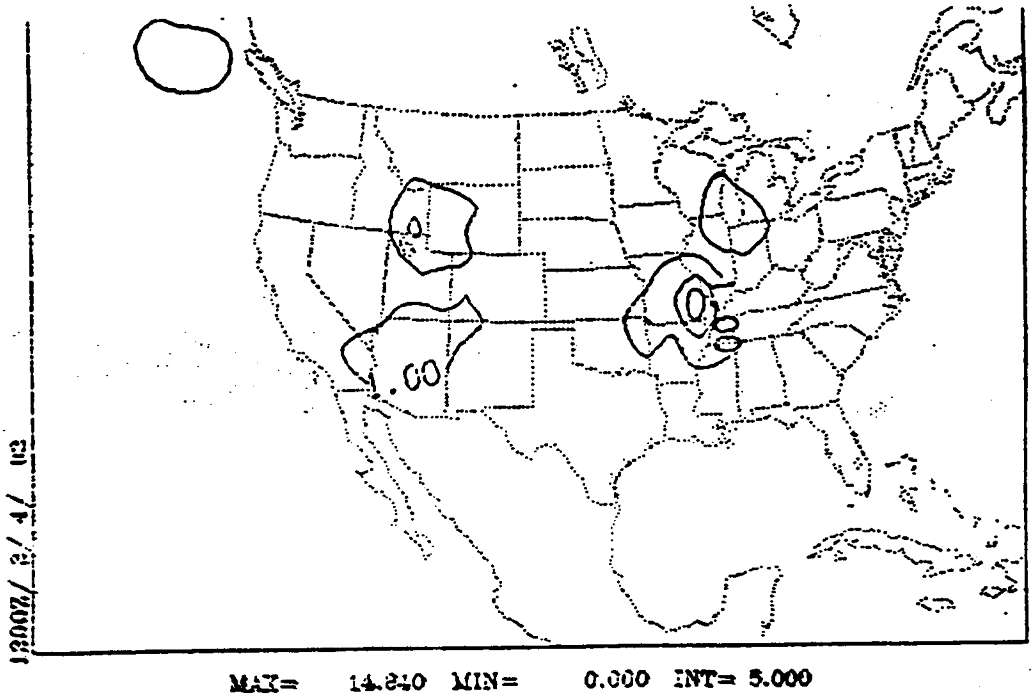
VI. CONCLUSIONS AND RECOMMENDATIONS

The impact of radiation-dynamics interaction on the regional model simulations is obvious. It appears that radiative transfer results in the destabilization of the model atmosphere. The model convective activities are enhanced and the model spin-up processes may be altered.

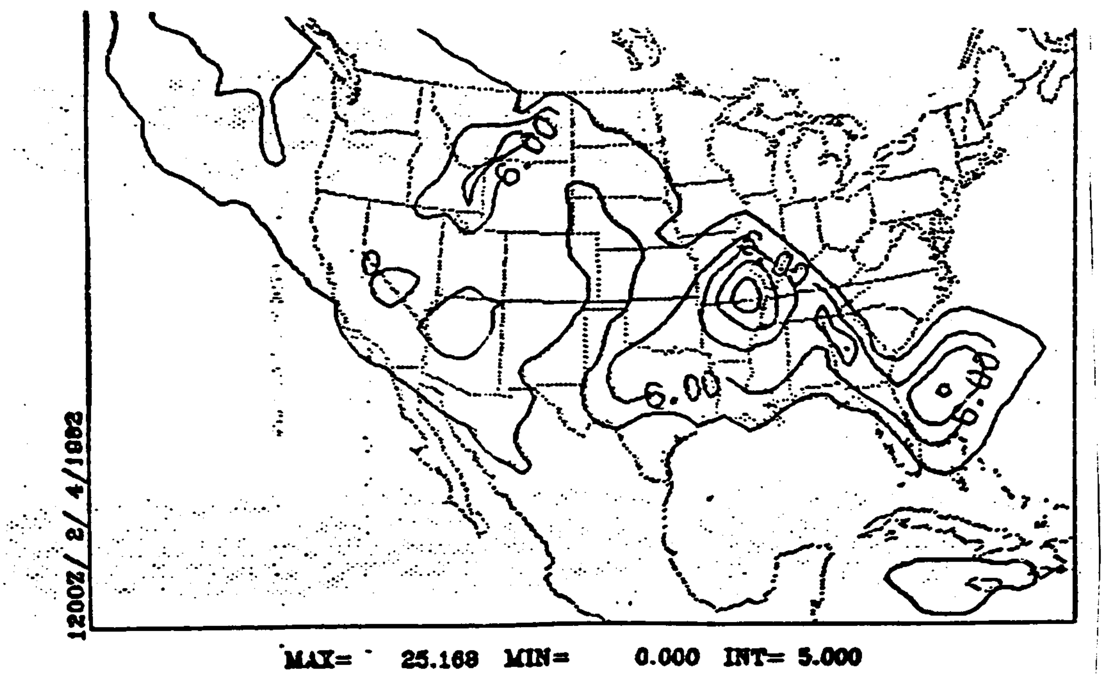
We will carry out more numerical experiments in additional to those proposed earlier and engage in the in-depth diagnoses of model output. This will include other case studies and followed by energy diagnosis, the analysis of relevant thermodynamic and dynamic variables, and the boundary layer convergence of moisture. After some quantitative assessment, we shall next investigate the radiation-dynamics interaction in a finer mesh model (e.g., 70 km grid size).

It is believed that regional models with a realistic treatment of atmospheric radiation provide a tool for testing the usefulness of satellite observations in studying moist processes in the atmosphere. It is also desizable to compare, if possible, the vertical profiles of model-generated with those of satellite-observed irradiance for further improvement in parameterizing model radiative transfer.

The ultimate goal of this effort is to achieve a better understanding of the diabatic effects of radiation on the regional weather systems and to improve regional-scale NWP.

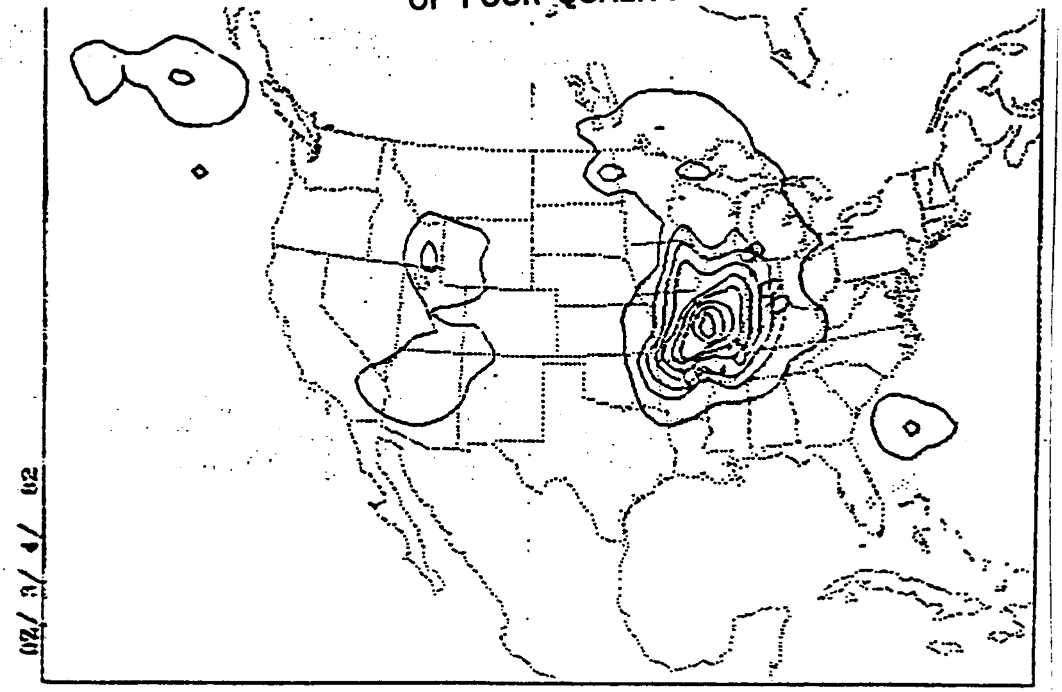


(a)



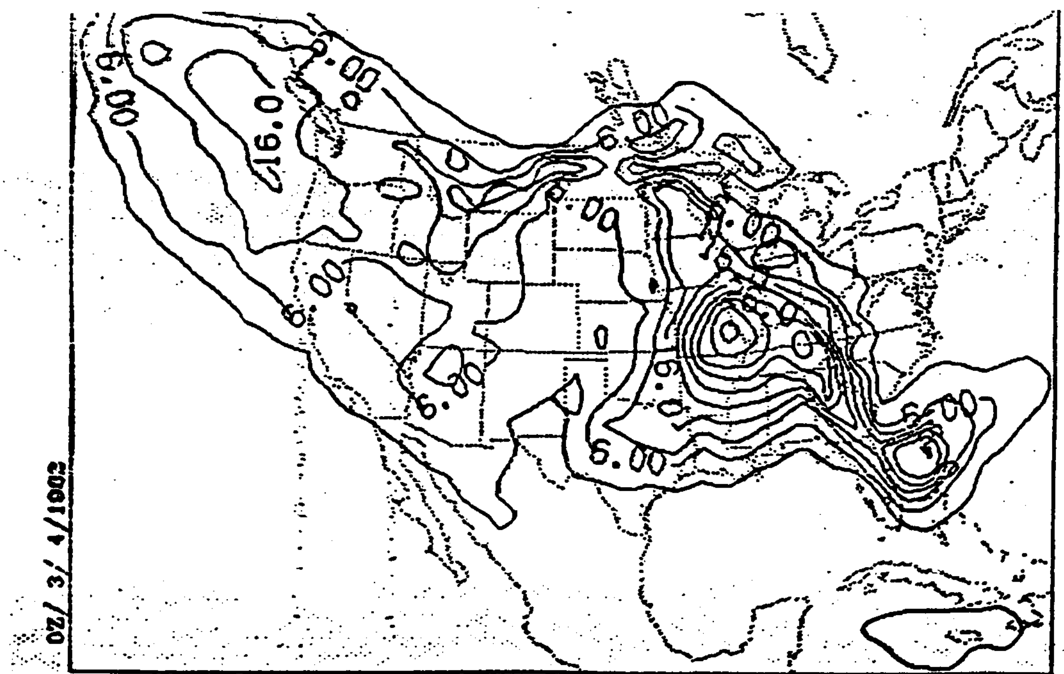
(b)

Figure 3. Simulated 12-h accumulated convective precipitation for the case of 2 April 1982. (a) without and (b) with improved radiative transfer. Contour interval is 5 mm.



MAX= 45.027 MIN= 0.000 INT= 5.000

(a)



MAX= 49.327 MIN= 0.000 INT= 5.000

(b)

Figure 4. Similar to Fig. 3 except for the 24-h simulations.

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