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EXPERIMENTS WITH THE MESOSCALE ATMOSPHERIC SIMULATION SYSTEM (MASS) USING THE SYNTHETIC RELATIVE HUMIDITY

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ABSTRACT

This study is intended to examine the impact of the synthetic relative humidity on the model simulation of mesoscale convective storm environment. The synthetic relative humidity is derived from the National Weather Services surface observations, and non-conventional sources including aircraft, radar, and satellite observations. The latter sources provide the mesoscale data of very high spatial and temporal resolution. The synthetic humidity data is used to complement the National Weather Services rawinsonde observations. It is believed that a realistic representation of initial moisture field in a mesoscale model is critical for the model simulation of thunderstorm development, and the formation of non-convective clouds as well as their effects on the surface energy budget. The impact will be investigated based on a real-data case study using the mesoscale atmospheric simulation system developed by Mesoscale Environmental Simulations Operations, Inc.

The mesoscale atmospheric simulation system consists of objective analysis and initialization codes, and the coarse-mesh and fine-mesh dynamic prediction models. Both models are a three dimensional, primitive equation model containing the essential moist physics for simulating and forecasting mesoscale convective processes in the atmosphere. The modeling system is currently implemented at the Applied Meteorology Unit, the Kennedy Space Center. Two procedures involving the synthetic relative humidity to define the model initial moisture fields are considered. It is proposed to perform several short-range (~ 6 hours) comparative coarse-mesh simulation experiments with and without the synthetic data. They are aimed at revealing the model sensitivities to the changes in the initial moisture conditions. Investigations of these sensitivities should allow us both to refine the specification of the observational requirements, and to develop more accurate and efficient objective analysis schemes. The goal is to advance the MASS modeling expertise so that the model output can provide reliable guidance for thunderstorm forecasting.

SUMMARY

Thunderstorm-related hazards such as hail, lightning, heavy rain, and strong winds represent a major threat to the space shuttle operations at the Kennedy Space Center (KSC). The operational forecasting needs at KSC require an accurate portray of mesoscale convective storm environment in the vicinity of the center for the period of 2 to 12 hours. Version 5.5 of mesoscale atmospheric simulation system (MASS) is currently under evaluation at the Applied Meteorology Unit (AMU) for its practicability in providing reliable short-range thunderstorm forecasting. There are many environmental factors influencing the development of thunderstorms. One of the most significant factors is three-dimensional (3-D) moisture structure. For the Florida peninsula, because of the adjacent data sparse waters it is difficult to obtain a realistic initial moisture field for mesoscale modeling from the regular National Weather Services (NWS) rawinsonde and surface observations. An alternative is the use of the so-called synthetic relative humidity (RH). This study examines the impact of the synthetic RH on the MASS model simulation of convective storm environment.

Two procedures involving the synthetic RH in the moisture analysis are considered. One is the approach currently employed at AMU. It invokes a bogusing and enhancing procedure to assimilate the synthetic RH data into the objectively analyzed moisture field based on the NWS rawinsonde observations. The bogus RH soundings are derived from the surface and aircraft observations, while the enhancing process is carried out according to the satellite images and radar data. Small scale features as a result of the enhancement are present in the final analysis. The other procedure is to combine the rawinsonde and synthetic RH observations as part of the objective analysis of the moisture field. The second approach is designed to test whether the small-scale features, which are too fine to be resolved in the model, can be suppressed.

It is proposed to construct the 3-D profiles of convection-related humidity parameters including precipitable water, low-level moisture flux convergence, and moist static energy. These parameters are often well correlated temporally and spatially with convective activity; for example, the low-level moisture flux convergence and the resultant rapid increase in precipitable water frequently occur prior to the outbreak of convective storms. It is proposed to examine in detail the differences in the horizontal and vertical profiles of these parameters between the analyses with and without the

synthetic RH. The purpose is to reveal whether the synthetic RH significantly alters the fundamental structure of the humidity field.

It is proposed to perform several short-range (~ 6 hours) comparative experiments using the MASS coarse-mesh (45-km grid interval) model over a domain of 55 by 50 grid points in the horizontal and 20 levels in the vertical. The experiments will include one without and the others with the synthetic RH. It is intended to find out how much information from the synthetic RH observations persists in the first 6 h simulation. RH signals incompatible with the model dynamics could be considerably reduced in a short time period. It is proposed to invoke scale decomposition technique to isolate the model dynamic responses to the inclusion of the synthetic RH data.

The plan was to process and analyze the data using the MASS preprocessor on the IBM personal computer (PC), and to perform the coarse-mesh model simulations on the UNIX-based Stardent 3000 workstation at AMU. However, because of many unexpected difficulties with the preprocessor we were not able to complete the data analysis. One primary cause of the delay is that the PC was not a suitable tool for this work.

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ABBREVIATIONS AND ACRONYMS LIST

AMU	Applied Meteorology Unit
KSC	Kennedy Space Center
MASS	Mesoscale Atmospheric Simulation System
MCS	Mesoscale Convective System
MDR	Manually Digitized Radar
MESO	Mesoscale Environmental Simulations Operations
NMC	National Meteorological Center
NWP	Numerical Weather Prediction
NWS	National Weather Services
OI	Optimum Interpolation
PBL	Planetary Boundary Layer
PC	Personal Computer
RAM	Random Access Memory
RH	Relative Humidity
SST	Sea Surface Temperature
3-D	Three-Dimensional

I. INTRODUCTION

Meteorological knowledge and operational forecasting techniques were revolutionized during the 1960s by dynamical model forecasting, also known as numerical weather prediction (NWP). Numerical modeling enables us to have a quantitative understanding and prediction of large scale (~1000 km) weather systems. However, NWP has had limited impact on the forecast problems associated with mesoscale convective systems (MCSs). The characteristic scale of convective storms varies from less than 10 km (e.g., isolated cumulonimbus cells) to 100 km (e.g., mesoscale convective complex and hurricane). One of the crucial factors determining NWP model performance in simulating convective storms is the model mesh size. The limitation of large mesh size prevents model from resolving the fine scale structure of MCSs. Consequently, the models cannot respond dynamically to the concentrated latent heat release, which is the principal energy source responsible for the continued existence of MCSs.

Because of the enormous number of calculations involved, the development of supercomputers in the late 1970s made the mesoscale NWP of convective storms practical (Pielke 1984). During the past years, the National Meteorological Center (NMC) and various mesoscale research groups at universities have moved progressively toward finer mesh size in their NWP models. Numerical experiments using the models of mesh sizes ranging from 30 to 100 km have indicated significant improvements in the simulation of MCSs. Recently, the rapid development of inexpensive workstation computers allows atmospheric scientists to conduct mesoscale NWP for research and operational applications aimed at regional meteorological forecasting problems. Advanced workstations are capable of executing complex large-scale model integrations at a comparable speed to that of supercomputers at a much lower cost.

The characteristics and development of mesoscale systems are strongly influenced by the regional environmental conditions. KSC is located in the area dominated by relatively unstable tropical maritime air mass and hence has one of the highest frequency of thunderstorm occurrences in the United States. Slightly upper-air forcings or the sea- and land-breeze circulations often lead to the rapid development of thunderstorms. It has been suggested that KSC has the most lightning strikes per unit area in the whole world. At KSC the most critical issue concerning the weather support to the center operations is the prediction of hazardous conditions (e.g., hail, lightning, heavy rain, and strong winds) caused by convective storms. In particular, such conditions represent a major threat to the space shuttle launch and landing operations. The regional operational models currently available at the National Meteorological Center (NMC) are not designed for providing thunderstorm-scale forecast. To enhance the weather support, NASA funded Mesoscale Environmental Simulations Operations (MESO) Inc. to develop a version of MASS for operational applications at KSC. The version 5.5 of MASS is recently implemented on the UNIX-based Stardent 3000 workstation and under evaluation for its performance at AMU.

One of the major difficulties associated with mesoscale NWP is model initialization. To have a successful and timely prediction of future atmospheric state for operational forecasting, the present state of the atmosphere must be characterized as accurately as possible. However, the NWS upper-air network with the average spacing of about 400 km and observation frequency of twice per day is not aimed at resolving mesoscale structure. The NWS surface network with the average spacing of about 150 km provides more complete and frequent observations, but the relatively high resolution surface data alone is insufficient for initializing a 3-D mesoscale model. For the Florida peninsula, the problem is further compounded by the lack of data over the adjacent waters.

In order to obtain an improved estimate of model initial state, MASS adopts an approach known as 4-D data assimilation. The approach is designed to blend data of various sources at different spatial and temporal resolutions into a 3-D data set that consists of synoptic-scale as well as mesoscale features desirable for mesoscale model initialization. The data sources include the NWS synoptic upper-air and surface networks, and data taken at asynoptic times such as radar, satellite, and aircraft observations.

This research focuses on the impact of the synthetic RH, a 3-D product of the MASS data assimilation cycle, on the MASS model simulation of convective storm environment in the vicinity of KSC. It is believed that the development and evolution of convection in Florida are strongly influenced by the fine-scale detail in the 3-D moisture stricture over the peninsula and surrounding waters. It is intended to address the impact using real-data model simulation experiments on the 2 June 1994 case. The research goal is to improve MASS modeling expertise so that the model output can provide reliable guidance for thunderstorm forecasting.

2. MODELING SYSTEM

Several versions of MASS have been developed since the early 1980s. Version 5.5 currently used at AMU/KSC has two major components, a preprocessor for data processing and analysis, and a dynamic prediction system consisting of coarse-mesh (~ 45 km grid size) and fine-mesh (~ 11 km grid size) models. A brief description of the modeling system summarized from the MASS reference manual (MESO Inc. 1993) is presented below.

2.1 Data Preprocessor

The data preprocessor prepares 3-D gridded fields including temperature, horizontal wind, surface pressure, and humidity for the coarse-mesh model initial state. The following tasks are performed.

a. Generation of grid and surface characteristics data
b. Ingestion of atmospheric data
c. Data analysis and initialization
d. Synthesizing RH based on indirect observations
e. Processing of lateral boundary condition data
f. Preparation of nudging data sets

In Task a, the model domain and grid size are specified. Over land surface parameters include land/water distribution, terrain elevation, and types of canopy at individual grid points are determined. Over the waters, monthly mean sea surface temperature (SST) data is prepared for the use as a first-guess field in the SST analysis. These surface variables specify the lower boundary conditions for the model, and they are also required in the parameterization of the model PBL processes.

In Task b, gridded first-guess fields to be used in objective analysis are prepared. The NWS surface and upper air data, and SST data are checked for errors and written out in a standard format that can be used in Task c. Two options are available for the objective analysis: the optimum interpolation (OI) scheme and the Barnes' scheme. Both schemes, using a linear estimate, interpolate the values of a observed variable at irregularly distributed observation sites to a set of regularly spaced grid points. The linear estimate can be expressed as follow:

$$\phi_a(i.j) = \sum_{k=n}^{N} w_k \phi_{ok}$$

where $\phi_a(i.j)$ is the analyzed value at grid point (i.j), ϕ_{ok} is the observed value at site k, N is the number of observations. In the current MASS preprocessor, N = 8 indicating that the eight closest stations are involved in defining the gridded value. The principal difference between the two schemes is in the determination of weight functions (w_k) in the linear estimate. The weights are determined using a spatial correlation function derived from raw data in the OI scheme, while the weights are specified in the Barnes' scheme as a function of the distance between the grid point and observations.

In Task d, the synthetic RH is derived from four sources of cloud and precipitation information. They are the NWS surface observations, pilot reports, satellite infrared and visible images, and radar data. The surface observations used to retrieve the vertical profile of RH include the height of clouds (low, middle, high), the cloud coverage (scattered, broken, overcast), and the weather (precipitation, no precipitation, fog). The pilot reports used are the cloud base and top, and sky coverage. The empirical formula are employed to estimate RH values from the information. Bogus RH soundings are created from the surface observations and the pilot reports. Using the Barnes' scheme, these bogus soundings are merged into the RH analysis obtained from the regular NWS rawindsonde data. Adjustments of the analyzed RH field are then performed based on the satellite images and manually digitized radar (MDR) data. For example, the entire air column for those grid points under deep convective clouds detected in the satellite infrared images will be moistened.

Task e is to generate time-dependent lateral boundary conditions to be used in the MASS model research simulations or operational forecasts. In the case of research simulations of past weather events, the model boundary conditions can be defined from observations. In the forecast mode, one approach is to generate such conditions from global or much larger domain model forecasts. Task f is to prepare nudging data sets for the MASS model 4-D data assimilation, which will not be considered in this research.

The initial and time dependent boundary conditions of the fine-mesh model, usually covering a much smaller area of interest than the coarse-mesh model, are obtained by interpolating the coarse-mesh model simulations onto the fine-mesh model grid points. The boundary conditions provide large-scale forcing for the fine-mesh simulation. This so-called one-way nesting method, which is relatively simple and straightforward, has been employed by many research groups in studying mesoscale meteorological processes (Anthes 1983; Chang et al. 1981). As mentioned earlier, for this study our interest is in the coarse-mesh model.

2.2 Dynamic Models

The MASS dynamic prediction system is a limited-area multi-level primitive equation model. A complete description of the model equations and physics can be found in the MASS user reference manual (MESO Inc. 1993). The early versions of MASS prediction system were developed in 1980s and have been used in many successful real-data simulation studies (Kaplan et al. 1982; Kaplan et al. 1985; Zack and Kaplan 1987). Major improvements in the model convective parameterization and surface physics were made in 1992.

The model equations are:

a. Conservation of horizontal momentum,
b. Hydrostatic equation in the vertical,
c. Conservation of energy,
d. Conservation of mass,
e. Conservation of moisture including water vapor, cloud water, and rain water,
f. Equation of state.

These equations are formulated in a (x, y, σ_p) coordinate system, in which x and y are Cartesian coordinates on a plane and σ_p (a normalized pressure) is a terrain following vertical coordinate. The six basic grid-scale prognostic variables are the u (= dx/dt) and v (= dy/dt) components of the wind, temperature, air density, humidity, cloud water content, and rain water content. For most mesoscale models, the basic equations are generally very similar, however, the treatment of physical processes varies considerably among the models.

The model physical processes include:

a. Surface energy budget,
b. Solar and infrared radiation,
c. PBL processes,
d. Soil hydrology,

e. Grid scale moisture physics,
f. Sub-grid moist convective parameterization.

The surface energy budget used to predict the ground temperature involves sensible and latent heat fluxes, solar heating and infrared cooling, and ground heat flux. The effects of cloudiness on the model radiative transfer are considered. The model PBL is divided into the surface layer and mixed layer. In the surface later, similarity theory is used to determine the eddy mixing coefficients, while in the mixed layer, the K-theory and mass exchange approach are applied in stable and unstable air, respectively. The PBL processes, radiative transfer, and surface heat budget are closely interrelated.

The soil is divided into two layers, a 5-cm layer at the surface and a layer of 5 cm to 30 cm deep below. The model soil hydrology involves the prediction of soil moisture fractions for the two layers as well as the parameterization of moisture reservoir on the surface.

Two methods are available for resolving the grid-scale moist physics: a diagnostic scheme computing latent heating as a function of water vapor mixing ratio and a prognostic scheme preferred in fine-mesh simulations based on the conservation of cloud and rain water. Three different schemes may be invoked for parameterizing sub-grid scale convection. Two are modified Kuo schemes, of which Kuo-MESO incorporates the cloud-scale downdraft plumes, and the third one is the Fritsch-Chappell scheme most suitable for simulating meso-β systems.

The major numerical aspects of the model are as follows:

a. Arakawa "A" grid in the horizontal and staggered grid in the vertical,
b. Fourth order centered difference in the horizontal and second order centered difference in the vertical,
c. Split time integration scheme with a longer timestep used for integrating the advection terms and a shorter timestep for integrating gravity-inertial terms,
d. Either Kreitzberg-Perkey sponge condition or Orlanski radiative formulation may be applied along the lateral boundaries,
e. Lateral diffusion to remove short-wave ($2\Delta x$ to $4\Delta x$) oscillations.

3. PROPOSED WORK

3.1 Analysis

Two procedures involving the synthetic RH data to obtain moisture analysis will be adopted. The first is the approach mentioned earlier and currently employed at AMU. It invokes two steps, bogusing and moistening, as summarized in 2.1. Small scale features associated with the satellite infrared and MDR data are present in the final analysis. Example of moisture analyses with and without the synthetic RH is shown in Figs. 1 and 2. Clearly, the first-order discontinuity is indicated in the analysis with the synthetic RH (Fig. 1).

The second procedure proposed by Dr. John Manobianco of AMU is to combine the rawinsonde and synthetic RH including satellite and radar observations as part of the objective analysis of moisture field. This approach is designed to test whether the small-scale features, which are too fine to be resolved in the coarse-mesh model, can be suppressed. However, the author feels that the first procedure in conjunction with spatial smoothing, i. e., applying a digital filter to the gridded field will have the similar effect on eliminating the discontinuity.

3.2 Diagnosis and Model Experiments

The horizontal maps and vertical cross-sections of analyzed humidity fields (e.g. specific humidity) before and after incorporating the synthetic RH will be carefully compared. For a quantitative comparison, a display code capable of mapping the difference fields between the RH analyses will be most useful. The convection-related humidity parameters including the precipitable water, low-level moisture flux convergence, and moist static energy will be computed. These parameters are correlated well temporally and spatially with convective activity; for example, the low-level moisture flux convergence and resultant rapid increase in precipitable water often occur prior to the outbreak of convective storms. Again, differences in the horizontal and vertical profiles of the parameters between the analyses with and without the synthetic RH will be examined. The purpose is to reveal any significant improvements in the basic structure of humidity field when the synthetic RH is invoked.

Several short-range (~ 6 hours) comparative experiments using the coarse-mesh MASS model over a relatively small domain will be conducted. The experiments include one with and the other without the synthetic RH. We like to find out how much information from the synthetic RH observations persists in the 6 h simulation. The RH signal incompatible with the model dynamics could be considerably reduced in a short time period. Also, we will have an in-depth examination of the thermodynamic and dynamic responses of the model to the enhanced moisture content.

3.3 Scale Decomposition

In the model simulated solutions, there exist complex interactions between motions of different scales. Such scale interactions will be further complicated by latent heat release, which is of course directly related to the moisture distribution in the model. The synthetic RH possesses scales different from those of motion and thermal fields derived from the NWS regular networks. The comparisons of model solutions may not explain physically the role of the synthetic RH in the simulations. In order to reveal the true impact the characteristic scales of the synthetic RH have to be identified, and the model simulated motion and temperature fields may be decomposed into selected space-scale ranges using a digital filter. The correlation between the enhanced RH and model responses can then be examined in a more meaningful way.

Figure 2 shows primarily the large-scale RH patterns, while Fig. 1 shows many meso-β scale (on the order of 100 km) features, for example, over the southeastern states and Florida. The circulation of the comparable scale may be generated in the model in response to the mesoscale features. It is also possible that both model simulations regardless of with and without the synthetic RH produce the similar mesoscale circulation. However, whether there is impact can be determined by the relative intensity of such motions between the two model simulations. In this case study, a digital band-pass filter centered around 300 km may be desired to isolated the mesoscale motion field.

A simple 2-D digital filter can be expressed in the following form.

$$\langle Z \rangle_{i,j} = \sum_{L=n}^{n} W_L Z_{i+L,j+L}$$

where L is the filter length and $z_{i,j}$ represents a gridded field at point (i,j), w_L represents smoothing weight factors. For this study, we may set n = 2, and the above filter represents a 9-point operator as follows:

$$\begin{array}{ccccc}
1/16 & — & 1/8 & — & 1/16 \\
| & & | & & | \\
1/8 & — & 1/4 & — & 1/8 \\
| & & | & & | \\
1/16 & — & 1/8 & — & 1/16
\end{array}$$

where 1/4, 1/8, 1/16 are the weight factors.

The response function of the filter is

$$R(\lambda) = [1 - \sin^4(\pi\Delta/\lambda)]^2$$

where λ is wavelength, Δ grid size. For m number of repeated applications of the filter, the response function will be $R^m(\lambda)$. We can produce two different low-pass filters by choosing two values of m and then isolate any band-pass filter by taking differences between the two low-pass filters. For example, two low-pass filters are made by taking m = 3 and 50 which remove the small scale features up to the wavelength of 3Δ and 8Δ, respectively. The difference between the two low-pass filters gives the band-pass filter whose peak response is located near 8Δ with a bandwidth of about 12Δ, i.e., 4 to 16 Δ. The waves of length less than 4Δ are not examined because they are suppressed strongly by the fourth-order lateral diffusion.

4. SUMMARY REMARKS

The comprehensive mesoscale modeling system (MASS) and multiple data sources available at KSC provide a unique opportunity to address many pressing issues concerning the weather forecasting support for the space operations. However, this study is intended to focus on the sensitivities of the MASS model simulation of convective storm environment to the use of the synthetic RH. The synthetic RH provides very high resolution data for initializing the model moisture field. Investigations of the sensitivities should help us both to refine the specification of the observational requirements, and to develop more accurate and efficient objective analysis schemes in dealing with multiple sources of observations.

The proposed work is well-defined. We anticipated a certain degree of success. The plan was that using the MASS preprocessor the author performed data processing and analysis on the IBM PC, while Dr. Manobianco performed the proposed coarse-mesh model simulations on the Stardent 3000 workstation at AMU. But the author encountered considerable difficulties during the earlier phase of the work partially due to our inexperience in the PC and MS-DOS operating system.

The MASS preprocessor codes are fairly well structured and documented. However, because of its size and complexity (involving about 50 sub-programs with nearly 5000 lines of codes) to shift the codes from the UNIX-based workstation to the DOS-based PC was indeed a major undertaking for a first-time user of MASS. The 3-D analysis as well as model domain consisted of 55 by 50 grid points in the horizontal and 20 levels in the vertical. The size of grid points was not unusually large for a mesoscale model. Nevertheless, it was discovered unexpectedly that to execute the preprocessor analysis codes required a computer of more than ten megabytes of random access memory (RAM) far exceeding the PC's capacity. Furthermore, after considerable efforts, we eventually realized that with the FORTRAN application programs, MS-DOS did not provide an easy access to the so-called extended memory, which was the bulk of RAM.

We were fortunately able to locate a sixteen megabyte PC in conjunction with IBM Operating System 2 (OS-2). This enabled the author to tackle the preprocessor programs. But the PC was extremely slow in processing the satellite data; it took more than twelve hours to complete one run for the 2 June 1994 case. Also, the machine lacked sophisticated graphics software (e.g., contouring capability) for displaying the analyzed results. In any events the PC was not a proper tool for MASS; a more advanced computer was needed to carry out the proposed work. Because of many unexpected obstacles and difficulties we have not reached the point of conducting the model simulations.

Finally, the role of high-resolution non-conventional data in mesoscale NWP is a worthwhile research topic. A quantitative understanding of such role is essential to the further improvement of mesoscale model initialization and forecast.

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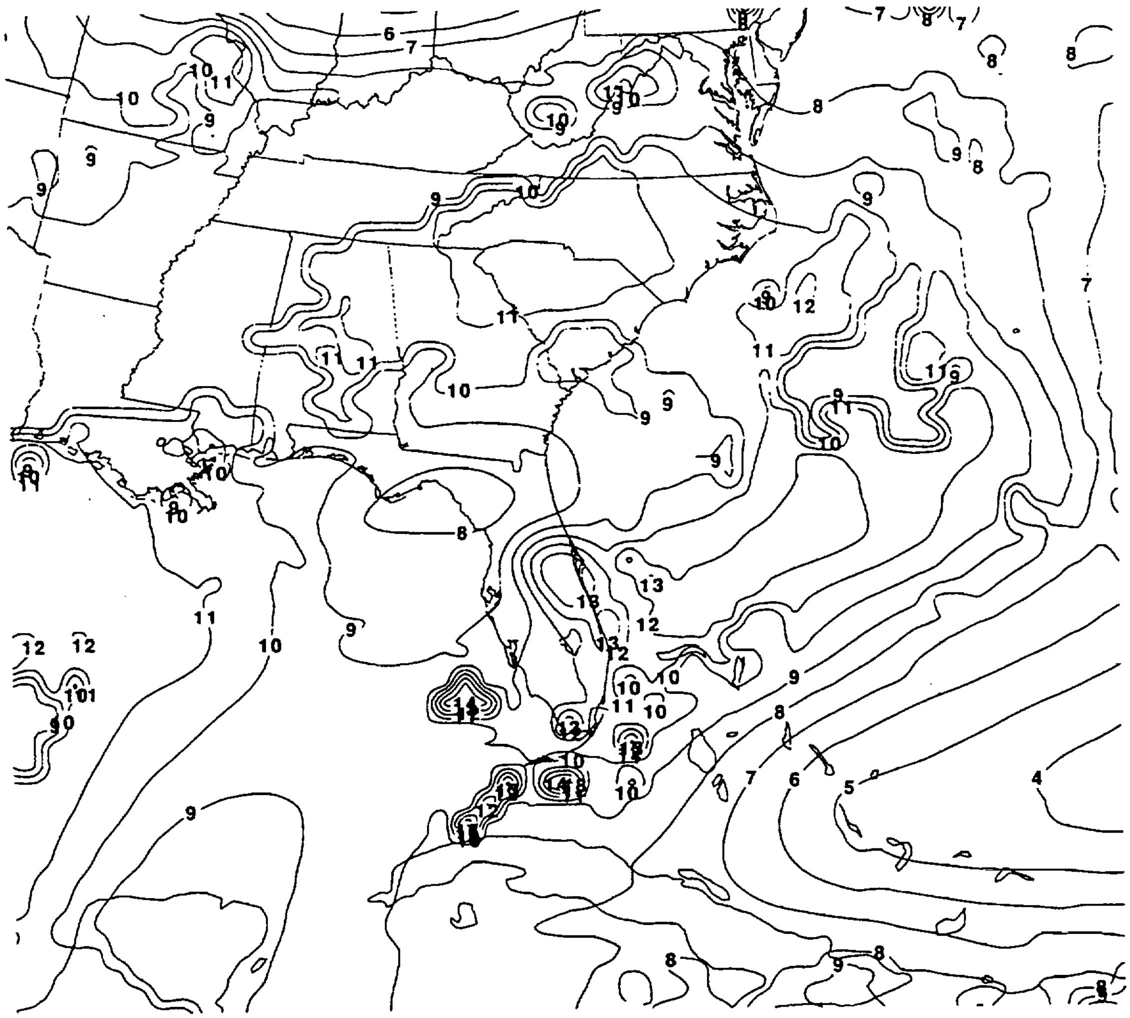

Fig. 1. 850 mb specific humidity (gm/kg) analysis with the synthetic RH at 1200 GMT 1 June 1994.

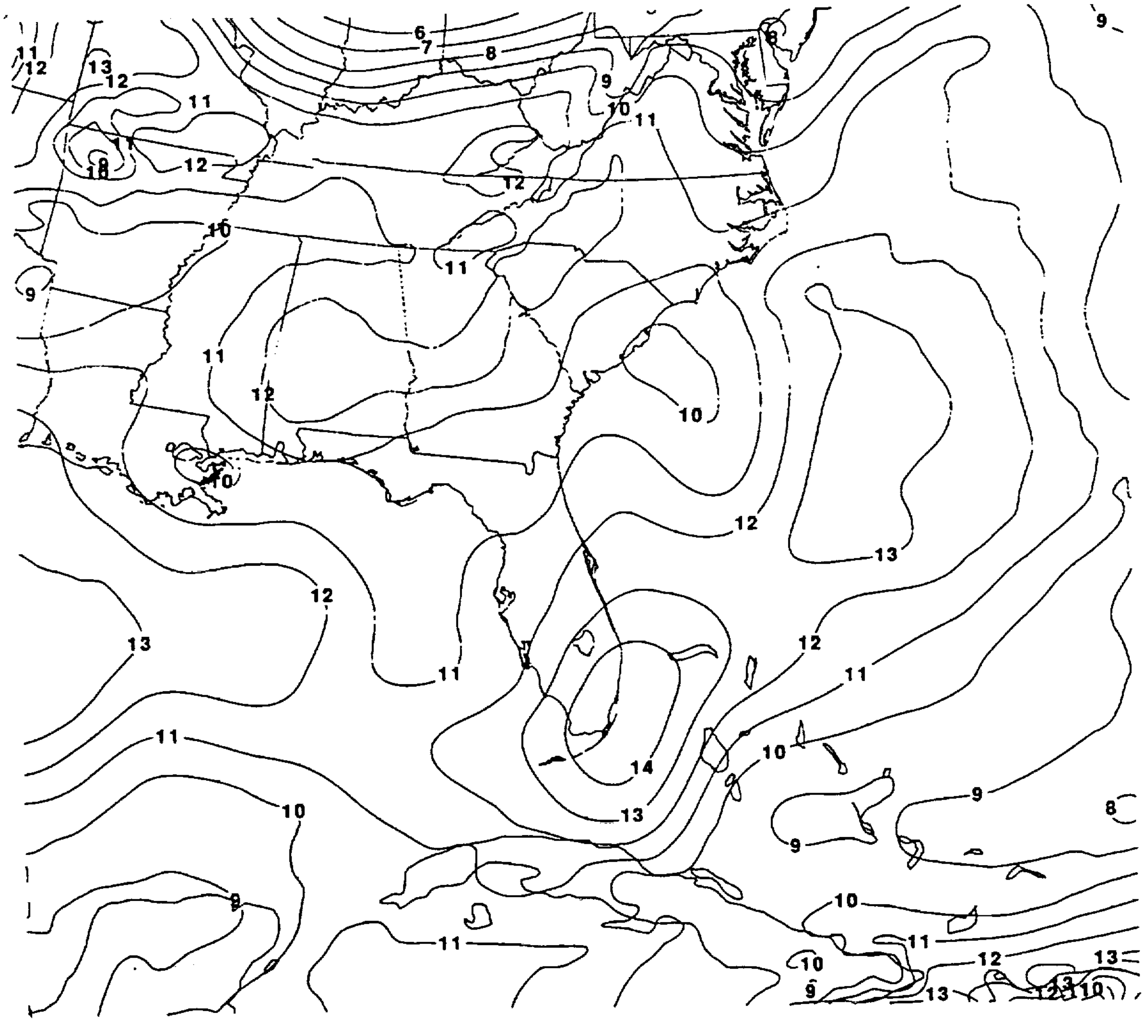

Fig. 2. As in Fig. 1 except without the synthetic RH.