

constraints are incorporated. Nudging or specification of moisture/water/ice parameters during assimilation is also being explored. Multi-parameter radar data are being exploited for use in the initialization of hydrometeors and other cloud microphysical parameters. These techniques usually assume the presence of a two- or three-dimensional wind field (say, from dual-Doppler analysis). If data from only one Doppler radar are available, then single-Doppler retrieval methods need to be applied. A wide variety of such methods exist to get two or three dimensional winds near the radar. Velocity azimuth display (VAD) and related methods just provide a vertical sounding of the horizontal wind for a volume around the radar. Tracking reflectivity echoes by correlation (TREC) deduces the horizontal wind field in a clean-air environment, primarily in the boundary layer. TREC winds have been combined with the thermodynamic retrieval technique to analyze and predict the movement of gust fronts. Other techniques, such as an adjoint advective retrieval have also done well in estimating boundary layer flows, in some cases using only reflectivity data. Finally, three dimensional winds as well as temperature and pressure have been estimated using radial velocity and reflectivity data in an adjoint dynamical retrieval method using a dry Boussinesq model. This technique has been demonstrated for a real-data gust front case but application to severe thunderstorm prediction awaits further progress in the adjoint formulation as well as in moisture initialization.

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3.3 Examples of data assimilation in mesoscale models

Fred Carr: Overview of Physical Initialization Techniques

- John Zack: The assimilation of asynoptic data into a mesobeta scale model*
- Jerry Schmidt/ The use of MAPS and LAPS to generate short-term (0-12 h) forecasts with the CSU-RAMS model*
- John Snook:*
- Stan Benjamin: The Mesoscale Analysis and Prediction System- a 3h data assimilation system in isentropic-sigma coordinates*
- David Stauffer: Dynamic initialization by Newtonian relaxation with the Penn State/NCAR mesoscale model*

Fred Carr gave the keynote address on the problem of physical initialization of mesoscale models. The classic purpose of physical or diabatic initialization is to reduce or eliminate the spin-up error caused by the lack, at the initial time, of the fully developed vertical circulations required to support regions of large rainfall rates. However, even if a model has no spin-up problem, imposition of observed moisture and heating rate information during assimilation can improve quantitative precipitation forecasts, especially early in the forecast. *The two key issues in physical initialization are the choice of assimilating technique and sources of hydrologic/hydrometeor data.*

One of the current techniques in use today includes the use of diabatic heating information in nonlinear normal mode initialization; the heating may either be from model estimates or from observed rainfall data (Fiorino and Warner 1981; Molinari 1982; Danard 1985; Ninomiya and Kurihara 1987; Wang and Warner 1988). A second technique in use is the direct specification of moisture and/or heating rates during a preforecast integration (dynamic initialization); this may or may not be accompanied by nudging of the primary variables. Finally, imposition of internal consistency among the observed precipitation and the model's initial temperature and moisture fields can be used; most often, the model's initial fields (sometimes including the divergent wind component) are modified in the process (e.g., Krishnamurti et al. 1988). *A major problem in all of the techniques is the need for accurate vertical distribution of the heating and moistening rates.*

Although suitable assimilation strategies will no doubt evolve, the data problem is more acute. Surface raingauge information represents a true source of mesoscale data but only a small fraction of it is available on an hourly, real-time basis. *Rawinsonde* data are of insufficient horizontal density while *ground- and space-based remote sensors* lack vertical resolution. Attempts have been made to overcome these problems by combining *infrared and microwave satellite estimates* with conventional surface and upper air observations to improve estimates of rainfall, precipitable water, and cloud and hydrometeor distributions (Kummerow et al. 1989; Manobianco et al. 1993). Detailed cloud water and ice data will be required to initialize meso-gamma scale models; these data will need to be deduced from the network of Doppler radars now being installed across the nation. The radar data will also be an excellent source of detailed precipitation estimates. Since no single observing system will be complete, retrieval techniques will be needed to deduce unobserved quantities from variables that are observed.

John Zack presented a series of meso-beta scale model experiments with an 11 km version of the MASS model designed to investigate the sensitivity of convective initiation forced by thermally direct circulations resulting from differential surface heating to four dimensional assimilation of surface and radar data. During the morning hours of this case, an east to west cloud band was present over the northern portion of the Florida peninsula. An isolated area of convection developed in the clear air just to the south of the cloud band in the well-heated surface air at the intersection between a line of convergence forced by the sea breeze circulation and a line forced by a thermally direct circulation between the cloudy air to the north and the clear air to the south. The model run which assimilated surface temperature, dew point and wind information during the first three hours of the simulation developed a more realistic temperature gradient during the nudging period.

However, as soon as the nudging period was over, the temperature reverted back to the pattern produced by the control simulation, because the surface temperature forcing functions (e.g., the amount of solar radiation reaching the surface) had not been significantly changed. The new afternoon convection also failed to develop in this simulation. Assimilation of heating and moistening rates inferred from manually digitized radar (MDR) data during the same 3-hour period dramatically improved the forecast by lowering the short wave transmissivity in the cloud band, forcing a more realistic temperature gradient between the clear and cloudy air, and initiating an isolated area of convection within 50 km and 1 hour of its observed location. The experiments suggest that the assimilation of surface data may not be an effective way to improve short-term forecasts for cases in which gradients in surface energy budget forcing functions are the primary factor in determining the evolution of mesoscale low level circulations and convective initiation. In these cases it may be more effective to assimilate actual or even synthetic data (e.g. moistening rates inferred from MDR data) which can improve the representation of the forcing function. The results of these simulations underscore the need to accurately initialize and simulate grid and sub-grid scale clouds in meso- beta scale models.

Jerry Schmidt reported on the status of the application of the CSU-RAMS mesoscale model by the NOAA Forecast Systems Lab for producing real-time forecasts with 10-60 km mesh resolutions over $(4000 \text{ km})^2$ domains for use by the aviation community. The model is currently run over four separate regions of the country on a sigma-z coordinate system with fully compressible nonhydrostatic physics and grid nesting (the value of Δx dependent upon the application). Either MAPS or LAPS model data are used to initialize the RAMS model on a 12-h cycle. The physical parameterizations currently used in the model include the Chen-Cotton radiation scheme, the Tremback-Kessler 11 layer soil model, deformation-dependent K closure, an upper absorbing layer, and a bulk ice/microphysics package, and a choice of cumulus parameterizations. An example application of the model to a Front Range blizzard case showed that the model successfully reproduced the observed mountain top westerlies, and the strong northwesterly flow residing on the eastern flank of a lee anticyclone, but only was able to capture the anticyclone with the LAPS-initialized run. A better representation of topography in the LAPS model may be one key to explaining these differences. Only a few wintertime cases have been run thus far, and it remains to be seen whether summertime flow conditions generate less favorable results. Future work will address the possible importance of the effects of low-level thermal boundaries, bands of mesoscale vertical motion, and other inhomogeneities in the initial state of the model.

Stan Benjamin discussed the use of the MAPS (Mesoscale Analysis and Prediction System) model. MAPS is the first mesoscale model to employ a 3h data assimilation in isentropic-sigma coordinates. He discussed the benefits realized by the use of isentropic coordinates, in particular the improvement in the analysis of upper-level frontal structures. The isentropic optimal interpolation procedure used in MAPS was also presented. Additional detail concerning MAPS sensitivity tests appears in Section 3.10.

David Stauffer first briefly discussed the demonstrated importance of data assimilation during the STORM-FEST project. Comparison of a control experiment using MAPS data for a static initialization with a dynamic initialization run performed on the 4 March 1992 case showed that the low-level rain water concentration agreed well with the composite radar imagery only when dynamic initialization was used, since the model's explicit moisture scheme was able to develop realistic fields of clouds and rainfall during the 12-h preforecast period while the larger-scale features were corrected via the analysis nudging. Other work at PSU has shown that more realistic precipitation forecasts result during the first few hours of simulation when the model is initialized with latent heating profiles inferred from radar-based rainfall rates and hourly raingage data. Research is currently underway to use 10-minute radar data on a 25-km nested grid to identify convection during the model assimilation cycle for the 10-11 June 1985 PRE-STORM squall-line case.

The focus of Stauffer's talk was on mesobeta-scale data assimilation using a triply-nested nonhydrostatic version of the MM5 model. Three meshes of 36-km, 12-km and 4-km resolution were used to model the meteorology in the San Joaquin Valley of California. Conventional 3-hourly surface and 12-hourly upper-air data are analyzed on the 36-km grid and interpolated to the 12-km grid. Analysis nudging is used to continuously assimilate these gridded data on both meshes by interpolating in time between successive analyses. In addition, special asynoptic data (rawinsondes, profilers, acoustic sounders, etc.) are assimilated over the 12-km and 4-km domains via an obs-nudging technique, in which the data directly influence a mesoscale region (based on topography and the height above ground) surrounding each observation during a prescribed time window. Local features such as the San Joaquin Valley nocturnal low-level jet and the Fresno eddy are realistically simulated by the model. Without data assimilation, the model-simulated diurnal surface temperatures agree well with observations, but afternoon mixing depths in the San Joaquin Valley are too high. When obs-nudging is used during the continuous assimilation period to assimilate 3-hourly multi-layer thermal data, mixing depths in the valley are more realistic; however, there are some interesting effects in the model wind field caused by the

nonuniform data distribution of the mass field. That is, anomalous circulations can develop at the edge of a data-dense region.

Finally, Stauffer discussed the use of the adjoint equations of a numerical model for internal parameter estimation. In an example using a 1-D shallow-fluid model, optimal control theory is applied to the determination of an "optimal" set of weighting coefficients used in the nudging approach, which relaxes the model state toward the observed state by adding to one or more of the prognostic equations artificial tendency terms which are proportional to the difference between the two states. The "proportionality constants" are usually based on scaling arguments, and modified by weighting functions which reflect the time and space separation of the model solution from the data, as well as data quality and representativeness. He demonstrated that the magnitude and distribution of these coefficients can be determined using the shallow-fluid model and its adjoint such that the model error during the assimilation period is optimally reduced subject to some constraints.

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3.4 Measurement and modeling of moist processes

William Cotton: Explicit Simulation of Mesoscale Convective Systems

<i>David Starr:</i>	<i>Measurement of water vapor and other constituents of the hydrologic cycle</i>
<i>Kenneth Mitchell:</i>	<i>NMC plans for initializing soil hydrology for mesoscale models</i>
<i>Rex Fleming:</i>	<i>Water vapor measurement concepts for GCIP</i>
<i>Steve Koch:</i>	<i>Mesoscale moisture analysis using satellite data</i>
<i>Steve Smith:</i>	<i>Mesoscale wind analysis using satellite data</i>
<i>Jocelyn Mailhot:</i>	<i>Recent activities in modeling of moist processes in mesoscale systems</i>
<i>Don Perkey:</i>	<i>Effects of temporal resolution on heat and moisture budgets for cumulus parameterization</i>
<i>Greg Tripoli:</i>	<i>Modeling scale interaction processes</i>

The keynote talk given by William Cotton summarized five years of his work simulating observed mesoscale convective systems with the RAMS (Regional Atmospheric Modeling System) model. *Excellent results are obtained when simulating squall line or other convective systems that are strongly forced by fronts or other lifting mechanisms.* Although the overall existence of convection was reproduced, the Doppler-observed mesoscale circulations could not be reproduced, even when exploiting alternate analysis software and using grids with sufficient resolution ($\Delta x = 2.2$ km) to explicitly resolve cloud-scale motions. *Less highly forced systems are difficult to model (e.g., the 3-4 June and 23-24 June 1985 PRE-STORM MCCs (Fig. 11)).* It was surmised that in such weakly sheared, nearly barotropic environments, accurate predictions of MCSs may require: (a) details about the surface forcing (e.g., soil moisture and vegetation, outflow boundaries and gravity waves