moist processes, the parameterization of sub-grid scale convection, coupled land surface/hydrology/mesoscale models, coupled chemistry/atmospheric models, boundary layer and radiative transfer processes, the validation of coupled multiscale models, and techniques and resources for storm-scale numerical weather prediction. Since many of these ideas appear as recommendations from the workshop (see section 4), they are not recorded here.

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3.2 Next generation initialization techniques

Tom Warner: Overview of the Mesoscale Data-Assimilation Problem

John Derber:	*An overview of variational data assimilation techniques, and practical approximations for operational implementation*
Milija Zupanski:	*Current status and plans for regional four-dimensional variational data assimilation research at NMC*
Steve Cohn:	*Some fundamental problems in data assimilation*
Hans Verlinde:	*Overview of the state of the art for initialization of cloud models*

Four-dimensional data assimilation strategies can generally be classified as either current or next generation, depending upon whether they are used operationally or not. *Current-generation* data-assimilation techniques are those that are presently used routinely in operational-forecasting or research applications. They can be classified into the following categories: intermittent assimilation, Newtonian relaxation, and physical initialization. It should be noted that these techniques are the subject of continued research, and their improvement will parallel the development of next generation techniques described by the other speakers in this session. *Next generation* assimilation techniques are those that are under development but are not yet used operationally. Most of these procedures are derived from control theory or variational methods and primarily represent continuous assimilation approaches, in which the data and model dynamics are "fitted" to each other in an optimal way. Another "next generation" category is the initialization of convective-scale models, a topic which was reviewed by Hans Verlinde.

Intermittent assimilation systems use an objective analysis to combine all observations within a time window that is centered on the analysis time. The background or first-guess field is obtained from a model forecast that is valid at the analysis time. The model is then integrated forward for a short period of time, and the analysis step is repeated. Through this sequence of analyses and short forecasts, a four-dimensional data set is produced. *Continuous first-generation assimilation systems* are usually based on the Newtonian-relaxation or "nudging" techniques. Here the observations are inserted at each time step during a preforecast model integration cycle. In this procedure, the model simulation can be relaxed toward observations, objective analyses of the observations, or both observations and objective analyses simultaneously. *Physical initialization procedures* generally involve the use of standard or nonstandard data to force some physical process in the model during an assimilation period. An example is the use of precipitation-rate data to infer latent-heating rates which can be substituted for the model-defined rates during the assimilation period. Other hydrologic information such as cloud distribution and surface moisture can be utilized to specify model-predicted variables during the assimilation period.

Under the topic of next-generation assimilation techniques, variational approaches are currently being actively developed. *Variational approaches* seek to minimize a cost or penalty function which measures a model's fit to observations, background fields and other imposed constraints. Minimization of the cost function will, in principle, yield the initial conditions that produce the best forecast from that model. In the "adjoint" approach, the adjoint of the numerical model is integrated backward over the data assimilation period (after a forward integration of the forecast model), during which the observations are introduced. This allows the computation of the gradient of the cost function which is required to compute a minimum. The process is iterated until "suitable" convergence to the optimal initial conditions is obtained. Alternatively, the *Kalman filter technique*, which is also under investigation as a data assimilation procedure for numerical weather prediction, can yield acceptable initial conditions for mesoscale models. A model error covariance term which is carried forward in time (thus allowing the minimization procedure to know the model error) is part of this assimilation system. The calculation of this term, however, is very expensive, and current research efforts are concentrating on how to reduce the computational cost while retaining the benefit of error covariance evolution.

The third kind of next-generation technique involves *strategies to initialize convective scale (non-hydrostatic) models*. This is required for a wide range of potential applications, ranging from the prediction of fog, visibility and ceilings, to the evolution of boundary layer phenomena such as plume dispersion and outflow boundaries, to the forecasting of severe thunderstorms. Since the primary observing tool for many of these applications will be Doppler radars, the key issue is the determination of initial conditions for all model variables from measurements of radial velocity and reflectivity in combination with other larger-scale data. It can be shown that simple insertion or nudging of wind data in a non-hydrostatic model will not recover the correct temperature field. However, modified forward insertion and dynamic relaxation techniques have shown some success if thermodynamic retrieval methods (or thermodynamic data) and/or other dynamical 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/ John Snook:	*The use of MAPS and LAPS to generate short-term (0-12 h) forecasts with the CSU-RAMS model*
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.*