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2.5 CYCLED SNOW STATE IN RUC COUPLED DATA ASSIMILATION SYSTEM (CDAS)

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1. INTRODUCTION

Accurate estimation of snow water equivalent over the United States and adjacent areas is obviously critical for subsequent seasonal and short-range atmospheric and hydrological model forecasts. It is also essential for water planning for a variety of important activities in the western United States, including agriculture, recreation, and public use in cities. Quantitative precipitation estimates (QPEs) based on observations only are often deficient in the cold season, especially for orographic precipitation. The recent approaches toward development of land data assimilation systems (LDASs) and precipitation assimilation used in the NCEP Regional Reanalysis are largely focused on improvements in specification of land-surface state for the warm season, but are not generally applicable to the problem of snow water equivalent initialization.

The best QPEs available at the current time, and those used to drive the current NOAA/NASA LDAS (Mitchell et al. 2000, Houser et al. 2000) are taken from the NOAA/Climate Prediction Center 24h gauge precipitation analysis (Higgins et al. 1996, http://www.cpc.ncep.noaa.gov/products/precip/realtime/) allocated into hourly amounts using the NCEP/NWS Stage IV hourly precipitation analysis. The limitations of this analysis include insufficient density of rain gauges in the mountainous areas, day-to-day variations of the reporting gauges, errors in 24-hour time variations, inaccuracies of gauge observations for frozen precipitation, and difficulties in assigning the precipitation phase.

A four-dimensional Coupled Data Assimilation System (CDAS) using a forward, full-physics model in which the precipitation and clouds are an optimized combination of observed and forecast fields has been developed at the Forecast Systems Laboratory to reduce the negative effects from the limitations of the precipitation analysis mentioned above. The CDAS is based on the Rapid Update Cycle (RUC) model assimilation system (Benjamin et al. 2003a,b), and the precipitation and cloud fields are updated hourly using GOES cloud-top pressure, NEXRAD radar reflectivity, lightning data, and GPS precipitable water. The RUC CDAS is designed specifically to provide improved QPEs for orographic precipitation in the cold season leading to more accurate cycling of snow state over the United States.

2. RUC CDAS FORECAST MODEL

The RUC CDAS is a coupled land-surface/atmospheric model with an hourly assimilation cycle including radar reflectivity, satellite, and other remotely sensed data to update the 3-d hydrometeor fields evolving through explicit mixed-phase cloud microphysics in the RUC model. The RUC is the only NCEP operational model that currently provides explicit forecasts of precipitation in liquid and solid phases. Model precipitation has consistent spatial variability from day to day, and could therefore be used to mitigate the effect of missing stations. It is also likely to provide better orographic precipitation, especially if constrained by satellite, radar, and even gauges in the CDAS optimization. Because of the 1-h updating used in the RUC, the model is also constrained by the hourly input of surface observations to have fairly accurate short-term forecasts of low-level temperatures. The explicit microphysics and representation of the near-surface thermal structure of the atmosphere in the RUC may be expected to provide better information on precipitation type than that available from an estimate of surface temperature alone.

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2.1 *Precipitation physics*

a. Explicit mixed-phase cloud microphysics

RUC CDAS uses the improved version (Thompson et al. 2003) of the level 4 mixed-phase bulk microphysics scheme of Reisner et al. (1998). This scheme was originally developed for MM5, and has been used operationally in the RUC for the past 5 years (Brown et al. 2000). The mixing ratios of 5 hydrometeor species are explicitly predicted: cloud water, rain water, cloud ice, snow and graupel (the latter formed by riming of ice or snow, or by freezing of rain drops, in which circumstance it might be regarded as ice pellets or sleet); the number concentration of cloud ice particles is also predicted. The explicit prediction of these hydrometeors allows direct feedback between simulated clouds and long- and short-wave radiation. The RUC/MM5 explicit microphysics also allows an explicit forecast of snow and snow water equivalent, rather than a diagnostic for precipitation phase type based on temperature.

The original version of the scheme used in the RUC had a tendency to strongly overpredict graupel under certain conditions, leading to unrealistic distributions of surface-precipitation type. The new version of the scheme, now operational in the RUC, exhibits much improved predictions of supercooled liquid water, as well as of precipitation type at the ground. Continued enhancements to the RUC microphysics scheme are expected, with a focus on ice nucleation and explicit prediction of freezing drizzle in weakly forced synoptic situations.

b. Ensemble cumulus parameterization

A new convective parameterization (Grell and Devenyi 2002) is used now in the RUC. The original scheme was first expanded to include lateral entrainment and detrainment, including detrainment of cloud water and ice to the microphysics scheme discussed in the previous section. In addition, the scheme draws on uncertainties in convective parameterizations by allowing an ensemble of various closure and feedback assumptions (related to how the explicitly predicted flow modifies the parameterized convection, which in turn modifies the environment) to be used every time the parameterization is called. The four main groups of closures that are used in the RUC application are based on: removal of convective available potential energy (CAPE), destabilization effects, moisture convergence, and low-level vertical velocity.

These four groups are then perturbed by 27 sensitive parameters related to feedback as well as strength of convection, which give a total of 108 ensemble members that contribute to the convective scheme. Output from the parameterization may be the ensemble mean, the most probable value, a probability density function as well as other statistical values (see also Grell and Devenyi 2002). Currently only the ensemble mean is fed back to the dynamic model.

The application of the Grell/Devenyi convective scheme in the RUC model also includes a removal of the negative buoyancy capping constraint at the initial time of each model forecast in areas where the GOES sounder effective cloud amount (Schreiner et al. 2001) indicates that convection may be present. This technique can aid the initiation of modeled convection at grid points where positive CAPE observed, although it cannot create positive CAPE. In addition, an upstream dependence is introduced through relaxation of static stability (convective inhibition) constraints at adjacent downstream points based on 0-5 km mean wind, and through allowing the downdraft mass flux at the previous convective timestep to force convection at the downstream location.

2.2 *Land-surface model in RUC*

The sophistication of the RUC/MAPS land-surface model (LSM) (Smirnova et al. 2000, 1998) has also grown in the past few years, and is now being used in the operational RUC at NCEP, in experimental real-time RUC runs at FSL, and in regional climate versions of the RUC and MM5 models (Grell et al 2000a, 2000b). The RUC LSM has also made a strong performance in the Program for Intercomparison of Land-surface Process Models (PILPS, Schlosser et al. 1999) and in the intercomparison of the snow models (SNOWMIP, Etchevers et al., 2003)

The RUC LSM contains multilevel soil and snow models, and treatment of vegetation (Fig. 1), all operating on the same horizontal grid as the atmospheric model (Smirnova et al. 1997). Heat and moisture transfer equations are solved at six levels for each soil column together with the energy and moisture budget equations for the ground surface, and an implicit scheme is used for the computation of the surface fluxes. The energy and moisture budgets are applied to a thin layer spanning the ground surface and including both the soil and the atmosphere with corresponding heat capacities and densities. The RUC frozen soil parameterization considers latent heat of phase changes in soil by applying an apparent heat capacity, augmented to account for phase changes inside the soil, to the heat transfer equation in frozen soil in place of the volumetric heat capacity for unfrozen soil. The effect of ice in soil on water transport is also considered in formulating the hydraulic and diffusional conductivities.

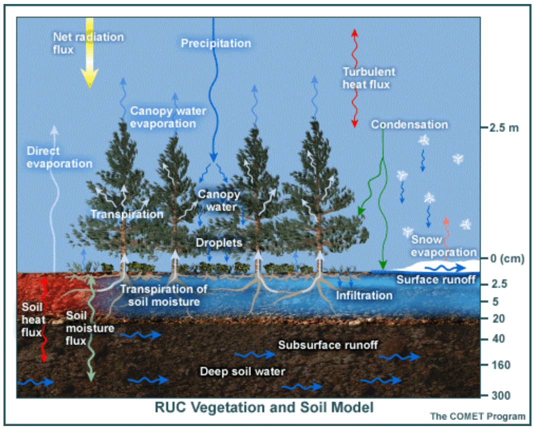

Figure 1. RUC/MAPS land-surface model

Accumulation of precipitation at the surface, as well as its partitioning between liquid and solid phases, is provided by the mixed-phase cloud microphysics routine (described above). In the RUC, the convective parameterization also contributes to the snow accumulation if the surface air temperature is at or below 0°C. With or without snow cover, surface runoff occurs if the rate at which liquid phase becomes available for infiltration at the ground surface exceeds the maximum infiltration rate. The solid phase in the form of snow or graupel (treated identically by the LSM) is accumulated on the ground/snow surface to subsequently affect soil hydrology and thermodynamics of the low atmosphere.

The most recent version of the LSM implemented in the RUC has a number of improvements in treatment of snow cover and frozen soil physics over those described in Smirnova et al. (2000). These improvements include allowing evolution of snow density as a function of snow age and depth (Koren et al., 1999), the potential for refreezing of melted water inside the snowpack, and simple representation of patchy snow through reduction of the albedo when the snow depth is small. If the snow layer is thinner than a 2-cm threshold, it is combined with the top soil layer to permit a more accurate solution of the energy budget. This strategy gives improved prediction of nighttime surface temperatures under clear conditions and melting of shallow snow cover. The RUC LSM also has an improved algorithm for frozen soil physics for spring thaw conditions.

These changes were tested off-line in a one-dimensional setting with the dataset from Valdai, Russia, and showed positive impact on the model performance. The evolution of snow density provides a more realistic representation of processes in snow, especially when fresh snow is falling onto the bare soil or an existing snow pack, and improves simulation of the snow-melting season (Fig. 2). The effects of patchy snow cover were tested in the experimental version of RUC and improved prediction of the nighttime surface temperatures under clear conditions as well as melting of shallow snow cover. More accurate predictions of the surface temperature have positive effects on the verification of 2-m temperature (Fig. 3). We will also investigate adding improvements to the vegetation treatment such as interactive vegetation in the RUC land-surface model to improve its capability for regional climate prediction and simulation.

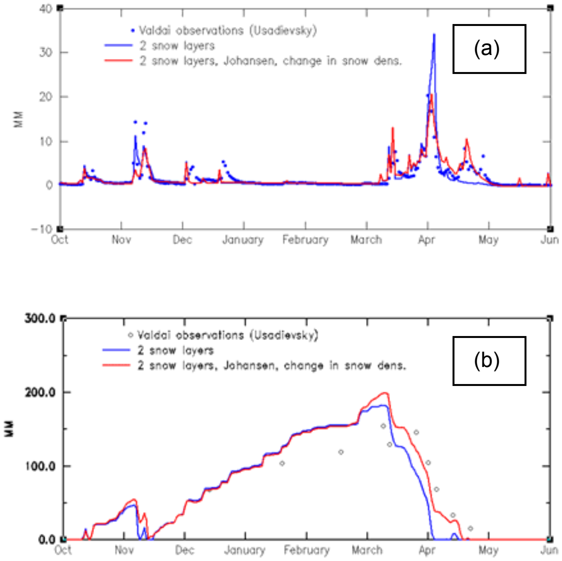

Figure 2. Results from 1-d simulations with RUC/MAPS land-surface model for winter 1980-81 for Valdai, Russia (PILPS 2d experiment, 18-year simulation). Results show improvement from allowing variability of snow density and addition of the Johansen formulation for thermal conductivity. a) Total runoff (mm) from top 1 m of soil, b) snow water equivalent (mm).

In applications of the RUC LSM in current and previous versions of the RUC, volumetric soil moisture and soil temperature at the six soil model levels, as well as canopy water, snow depth, and snow temperature are cycled. Cycling of the snow temperature of the second layer (where needed) is also performed. The RUC continues to be unique among operational models in its specification of snow cover and snow water content through cycling (Smirnova et al. 2000). The 2-layer snow model in the RUC improves the evolution of these fields, especially in spring time, more accurately depicting the snow melting season and spring spike in total runoff.

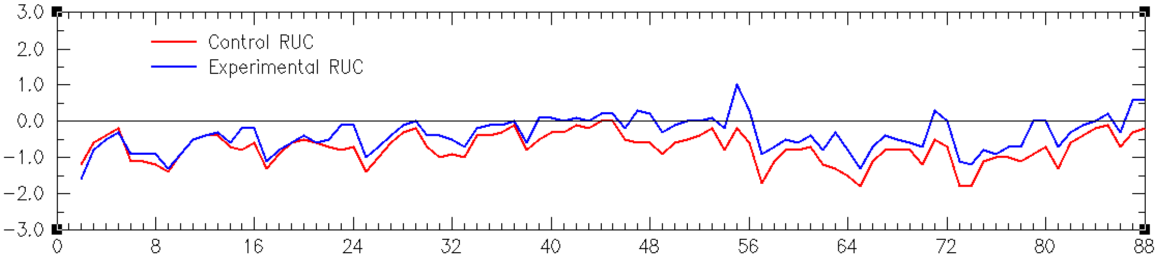

Figure 3. Surface temperature biases (^{o} C) from 3-h forecasts for stations with the snow depth less than 10cm averaged for the period 4-14 February 2001.

3. RUC CDAS EVALUATION

The resolution of the RUC CDAS is 20 km, with high-resolution fixed surface fields from USGS (land-use) and STATSGO soil types. This system has run in real time since April 2002. The RUC/MAPS system made a transition to a 3-d variational analysis (Devenyi and Benjamin, 2003) in spring 2003 replacing the previous optimal interpolation atmospheric analysis scheme. The primary reason for this change is because of the flexibility and rigor of the variational approach in assimilating data not directly forecast by the model (e.g., satellite radiances, radar radial winds). The RUC CDAS currently assimilates hourly data from wind profilers (NOAA network and 915 MHz boundary layer), commercial aircraft (growing rapidly in volume over the US and worldwide), surface stations and buoys, available radiosonde data, and GOES satellite-estimated cloud drift winds, precipitable water measurements, and cloud-top pressure (Benjamin et al. 2002). Testing of assimilation of GPS integrated precipitable water measurements had been ongoing for three years with the RUC (Gutman and Benjamin 2001) and was also implemented operationally. The most critical recent improvements in RUC assimilation were done to the cloud and moisture analysis through the assimilation of satellite and radar data (Kim et al. 2002).

RUC CDAS provides refinements to the 0-1 hour precipitation forecasts that drive a land-surface climate in the model by accounting for errors in both observations and model precipitation forecasts. As a result cycled soil moisture and snow water equivalent are improved compared to the operational RUC without assimilation of the radar, lightning, and GPS data. Most improvements occur from more accurate placement of predicted precipitation.

The impact of using the radar assimilation technique to modify 3-d hydrometeor fields from the national mosaic 2-km resolution maximum reflectivity data has been monitored and evaluated on a regular basis. The operational RUC20 without radar reflectivity assimilation is used as the control experiment.

The NCEP Stage II hourly quantitative precipitation estimation (QPE) is used to verify the 3-hour accumulated precipitation, and quality controlled Stage IV is used for the verification of 24-hour accumulations. The Stage IV precipitation data are at 4-km resolution and are derived from both NEXRAD reflectivity and gauge observations and include quality control. The original 4-km resolution Stage IV precipitation data are remapped to the RUC grid by taking the maximum value in the grid box to represent the grid point. The verification of accumulated forecast precipitation from eight 3-h forecasts in RUC assimilation cycles over a 24-h period is performed daily, and Figure 4 depicts an example of this verification.

A spatial correlation field was computed as a measure of precipitation verification. The spatial cross-correlation is a function of x-y displacement between two fields, QPF and QPE within a predetermined evaluation window (60 x 60 grid points on a 20-km grid, Fig. 4 (d-f)). The distance of maximum correlation to the center (zero displacement) is a measure of QPF phase error, and the maximum value of correlation coefficient provides an approximate measure of forecast accuracy modulated by spatial variability of rainfall amount. The shape of the contours gives information on the directional dependency of precipitation forecast accuracy.

The two contour fields were compared with the spatial autocorrelation field, which is computed from QPE against itself. The preferred orientation of precipitation isopleths during this period is evident, with strong anisotropy oriented from WSW to NNE. The spatial patterns also depend on the duration of accumulation. As an overall assessment, better QPF should result in a QPF-QPE correlation pattern similar to that of the spatial auto correlation. In the example shown in Fig. 4, the maximum value of cross correlation coefficient of parallel run (with radar reflectivity assimilation) is 0.67, better than 0.58 for the control run (without radar reflectivity assimilation) indicating that the QPF error in the parallel run is reduced from that of the control run. Also, the contour lines of the parallel run result are better defined, suggesting that its spatial scales and directional orientations are more accurate than those of the control run in this case.

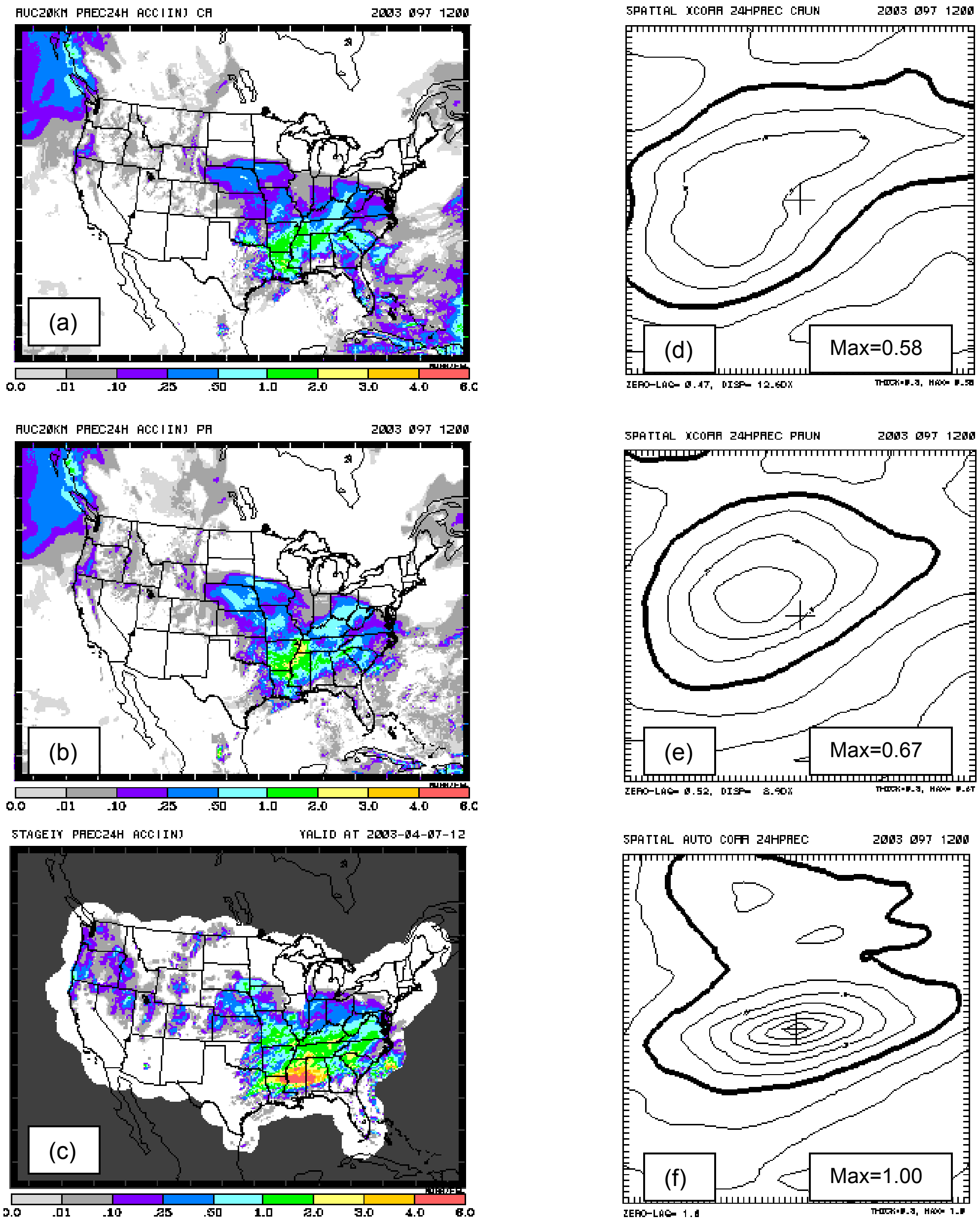

Figure 4. A 24-h accumulation of precipitation for the period ending 1200 UTC 7 April 2003 from (a) control run, without radar reflectivity assimilation, (b) from parallel run with radar reflectivity, and (c) Stage IV precipitation amounts (sum of four 6-h totals). Forecast amounts are for eight consecutive 3-h forecasts from RUC cycles. d), e), and f) are spatial correlation functions corresponding to a), b), and c), and the maximum correlation is also shown. See text for more explanation.

4. SNOW STATE CYCLING IN RUC CDAS

The winter of 2002/2003 was the first cold season when RUC Control and RUC CDAS were run in parallel, and the advantages of the RUC CDAS could be monitored in the evolution of the snow depth field driven by the 1-h precipitation forecast. Although the atmospheric forcing from the RUC 1-h cycle often corrects misplaced snow precipitation by providing the energy for snow melting, still the snow field is a very good indicator of the improvements in the precipitation forecasts in the RUC CDAS.

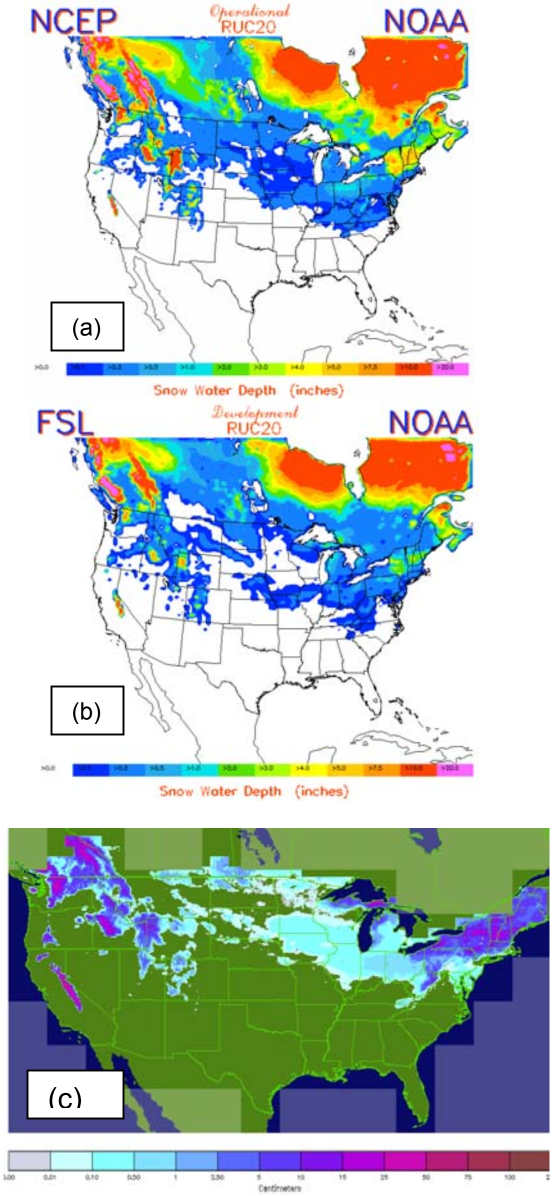

Figure 5. Snow depth from the (a) control RUC and (b) RUC CDAS verified against NOHRSC snow analysis (c) valid 30 January 2003.

The example on Figure 5 (a-c) illustrates the comparison of snow depths from the RUC Control and RUC CDAS cycles against the NOHRSC (National Operational Hydrologic Remote Sensing Center) NSA (National Snow Analysis). The NOHRSC product combines the snow model assimilation with all available snow observations and provides one of the most reliable datasets of this variable (Cline et al. 2002). Although RUC CDAS improves the cycled snow state, at the same time certain deficiencies still exist in the amounts of the precipitation in RUC CDAS, causing most often underestimation of cycled snow depth. This also has a delayed effect on the soil moisture climate and surface physics in the warm season.

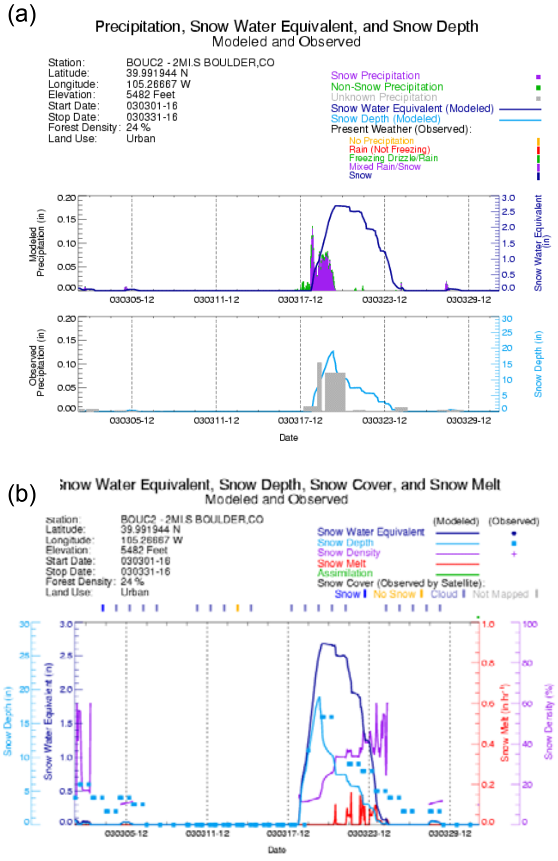

Figure 6. The precipitation forcing from RUC 1-hour forecasts (a, top panel) for March 2003 snow storm compared to the observed precipitation (a, bottom panel), and the NSA snow depth (b) comparison to observations for Boulder, CO.

Further improvements of the cycled snow depth could be achieved by updating the snow state fields from existing observations. This approach has been implemented at the NOHRSC NSA. Snow data used to update the model include observations from the NOHRSC's Airborne Snow Survey Program, NWS and FAA field offices, NWS Cooperative Observers, the NRCS SNOTEL and snow course networks, the California Department of Water Resources snow pillow networks, and snow cover observations from NOAA's GOES and AVHRR satellites.

The first step in this direction is to compare RUC CDAS snow state variables to the NOHRSC NSA and identify the areas with the largest deficiencies. Then the technique should be developed and applied to make corrections of RUC

CDAS snow variables for these areas. Improvements of the snow climate in the RUC CDAS will also be beneficial for NOHRSC NSA, because the NOHRSC snow model is driven by the RUC precipitation and atmospheric forcing. An example of time series products from NSA showing the verification of the RUC precipitation forcing as well as NSA snow depth verification for the March 2003 snow storm in Boulder, CO is presented on Figure 6 (a,b). In this particular case the RUC model was able to provide sufficiently accurate forcing for the NOHRSC snow model, and corrections of the snow analysis from observations were not needed. Similar verification of RUC precipitation and atmospheric forcing is performed at NOHRSC for different stations on the regular basis, and it demonstrates that in some cases the improvements to the RUC precipitation forcing are necessary. More detailed comparisons between RUC CDAS snow state variables and the NOHRSC NSA will be presented at the meeting.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Benjamin, S.G., D. Kim, and J.M. Brown, 2002: Cloud/hydrometeor initialization in the 20-km RUC with GOES and radar data. Preprints, *10th Conf. on Aviation, Range, and Aerospace Meteorology*, Portland, OR, Amer. Meteor. Soc., 232-235.

Benjamin, S.G., D. Devenyi, S.S. Weygandt, K.J. Brundage, J.M. Brown, G.A. Grell, D. Kim, B.E. Schwartz, T.G. Smirnova, T.L. Smith, and G.S. Manikin, 2003a: An hourly assimilation/forecast cycle: The RUC. *Mon. Wea. Rev.* ,**131**, in press.

Benjamin, S.G., G.A. Grell, J.M. Brown, T.G. Smirnova, and R. Bleck, 2003b: Mesoscale weather prediction with the RUC hybrid isentropic / terrain-following coordinate model. *Mon. Wea. Rev.* ,**131** , in press.

Brown, J.M., T.G. Smirnova, S.G. Benjamin, R. Rasmussen, G. Thompson, and K. Manning, 2000: Use of a mixed-phase microphysics scheme in the operational NCEP Rapid Update Cycle. Preprints, *9th Conf. On Avia. Meteor.*, AMS, Orlando, 100-101.

Cline, D., Carroll, T., Li, L., Fall, G. and Nilsson, A., 2002: Demonstration of the NOHRSC Operational Snow Mass/Energy Balance Model for the Continental U.S. Preprints, *Second Federal Interagency Hydrologic Modeling Conference*, Las Vegas, Nevada.

Devenyi, D., and S.G. Benjamin, 2003: A variational assimilation technique in a hybrid isentropic-sigma coordinate. *Meteor. and Atmospheric Physics*, **82**, 245-257.

Etchevers, P., E. Martin, R. Brown, C. Fierz, Y. Lejeune, E. Bazile, A. Boone, Y.-J. Dai, R. Essery, A. Fernandez, Y. Gusev, R. Jordan, V. Koren, E. Kowalczyk, N.O. Nasonova, R.D. Pyles, A. Schlosser, A.B. Shmakin, T.G. Smirnova, U. Strasser, D. Verseghy, T. Yamazaki, Z.-L. Yang, 2003: Validation of the surface energy budget simulated by several snow models (project SNOWMIP), *IGS symposium*, 2-6 June, Davos, Switzerland.

Grell, G.A., and D. Devenyi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29**, 38-1-4.

Grell, G.A., S. Emeis, W.R. Stockwell, T. Schoenemeyer, R. Forkel, J. Michalakes, R. Knoche, and W. Seidl, 2000a: Application of a multiscale, coupled MM5/chemistry model to the complex terrain of the VOTALP valley campaign. *Atmos. Env.*, **34**, 1435-1453.

Grell, G.A., L. Schade, R. Knoche, A. Pfeiffer, and J. Egger, 2000b: Nonhydrostatic climate simulations of precipitation over complex terrain. *J. Geophys. Res.,* **105**, 29595-29608.

Gutman, S.I., and S.G. Benjamin, 2001: The role of ground-based GPS meteorological observations in numerical weather prediction. *GPS Solutions*, **4**, 16-24.

Higgins. R.W., J.E. Janowiak and Y.Yao, 1996: A gridded hourly precipitation data base for the United States (1963-1993). *NCEP/Climate Prediction Center Atlas No. 1*, 47 pp.

Houser, P.R., B.A. Cosgrove, and J.K. Entin, 2000: Short-term retrospective Land Data Assimilation Schemes, *15th AMS Conference on Hydrology*, 7-9.

Kim, D., S.G. Benjamin, and J.M. Brown, 2002: Cloud/hydrometeor initialization in the 20-km RUC using radar and GOES data. *19th Conf. on Wea. Analysis and Forecasting (WAF)*, San Antonio, TX, Amer. Meteor. Soc., 335-338.

Koren, V., J. Schaake, K, Mitchell, Q.-Y. Duan, F. Chen, and J. M. Baker, 1999: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, *J. Geophys. Res.*, **104**, 19569-19585.

Mitchell K., C Marshall, D. Lohmann, M. Ek, Y. Lin, P. Grunmann, P. Houser, E. Wood, J. Shaake, D. Lettenmaier, D. Tarpley, W. Higgins, R. Pinker, A. Robock, B. Cosgrove, J. Entin, Q. Duan, 2000: The collaborative GCIP Land Data Assimilation (LDAS) project and supportive NCEP uncoupled land-surface modeling initiative. *15th AMS Conference on Hydrology*, 1-4.

Reisner, J., R.M. Rasmussen, and R.T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Roy. Meteor. Soc.*, **142**, 1071-1107.

Schlosser, C.A., A. Slater, A. Robock, A.J. Pitman, K.Ya. Vinnikov, A. Henderson-Sellers, N.A. Speranskaya, K. Mitchell, A. Boone, H. Braden, P. Cox, P. DeRosney, C.E. Desborough, Y.-J. Dal, Q. Duan, J. Entin, P. Etchevers, N. Gedney, Y.M. Gusev, F. Habets, J. Kim, E. Kowalczyk, O. Nasonova, J. Noilhan, J. Polcher, A. Shmakin, T. Smirnova, D. Verseghy, P. Wetzel, Y. Xue, and Z.-L. Yang, 1999. Simulations of a boreal grassland hydrology at Valdai, Russia: PILPS Phase 2(d), *Mon. Wea. Rev.*, **128**, No. 2, 301-321.

Schreiner, A.J., T.J. Schmit, W.P. Menzel, 2001: Clouds based on GOES sounder data. *J. Geophys. Res.*, **106 (D17)**, 20349-20363.

Smirnova, T.G., J.M. Brown, S.G. Benjamin, and D. Kim, 2000: Parameterization of cold-season processes in the MAPS land-surface scheme. *J. Geophys. Res.*, **105**, D3, 4077-4086.

Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1998: Impact of a snow physics parameterization on short-range forecasts of skin temperature in MAPS/RUC. Preprints, *12th Conf. on Numerical Weather Prediction*, Phoenix, AZ, Amer. Meteor. Soc., 161-164.

Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1997: Performance of different soil model configurations in simulating ground surface temperature and surface fluxes. *Mon. Wea. Rev.*, **125**, 1870-1884.

Thompson, G., R. M. Rasmussen, and K. Manning, 2003: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. Mon. Wea. Rev., **131**, accepted.