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1. Introduction

According to the original proposal, this project is to perform moisture sensitivity and data assimilation studies with focus on the storm scale and quantitative precipitation. The project involves the following areas: 1) Develop and apply variational techniques for the analysis and assimilation of water and related diabatic fields; 2) Study the impact of high-resolution observations of water vapor and hydrometeor content on the forecasting of convective storm morphology and precipitation; 3) Develop and evaluate techniques for estimating error characteristics of numerical forecasts at the convective scale. 4) Apply single Doppler velocity and thermodynamic retrieval algorithms to mobile radar data collected during IHOP; 5) Provide real-time, high-resolution (2-3 km) analysis and forecasts to assist IHOP field operations.

Significant progresses have been made so far, despite significant delay in personnel hiring in this first year. Two graduate students, one master (Dan Dawson) and one Ph.D. (Haxia Liu), joined the project in August 2002, the start of fall semester. Visiting research scientist, Jinzhong Min, joined in May and a post-doctoral scientist, William Martin, will start in December. The late start of the last was partly due to the need to complete his Ph.D. dissertation first. In the fall semester of 2002, an additional Ph.D. student, Paul Nutter was also supported under this project. He is expected to complete his Ph.D. program at the end of the year. In the following we report progresses in several areas.

2. Real-time Forecast Support for IHOP 2002 and Forecast Evaluation

From May 13 through June 2002, the group successfully carried out real time forecast operations in support of IHOP field experiment. The effort leveraged on support from other related projects at CAPS. In addition to providing support for the real time operations of IHOP, we also had and successfully achieved the goals of obtaining an initial assessment of the forecast model performance during the period and of identifying specific data sets and cases for extensive retrospective studies. Some details of the real time forecast are given here.

The realtime forecasts were produced on three grids with 27, 9 and 3 km grid resolutions, respectively. The fine resolution grids were nested inside the coarser ones in one-way nested mode. These three grids cover the Continental US, the Central Great Plains, and the entire state of Okalahoma plus south-central Kansas and Texas panhandle, respectively (Fig. 1). These three grids are referred to as the US, SPmeso, and SPstorm grids, respectively.

The US and SPmeso forecast start from initial conditions (IC) at 12 UTC each day, and forecast for 42 and 24 hours, respectively (Fig. 2). Six-hour (06 UTC) NCEP Eta forecast fields were used as the analysis background, and the forecasts from the same Eta forecast cycle were used as the boundary conditions (BC) for the US grid. The SPmeso grid obtained its BC from the US grid. The 3 km SPstorm grid was run twice a day, starting at 15 UTC and 00 UTC. The 15 UTC SPstorm analysis used the 3-hour SPmeso forecast as the background, while the 00 UTC SPstorm forecast used 9-hour SPmeso forecast for its analysis background fields. Boundary conditions for both SPstorm forecasts were from the 12 UTC SPmeso forecast.

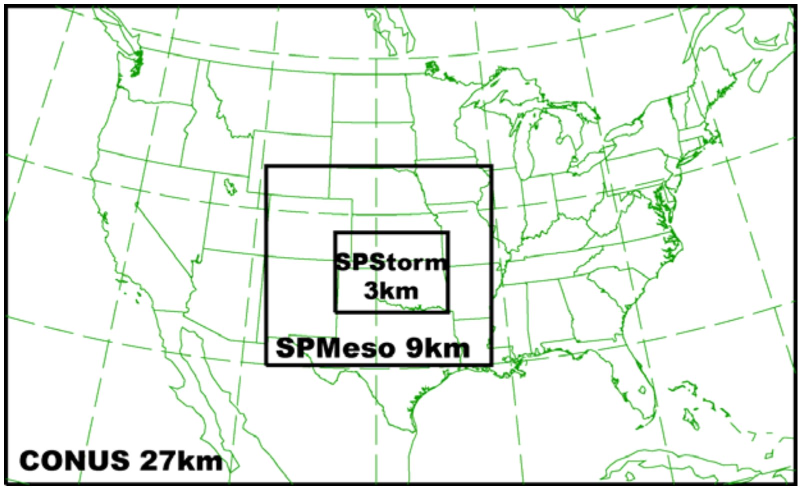


Figure 1. The 27, 9 and 3 km resolution ARPS forecast grids run during IHOP.

The initial conditions were produced using the ARPS Data Analysis System (ADAS, Brewster 1996). Data incorporated into the initial conditions included all available rawinsondes from the standard network and special launch soundings, wind profilers, standard surface observations, the Oklahoma and western Texas Mesonet data and DOE/ARM surface observations. A unique aspect of this work is the use of broadband, Level-II data from a network of radars through the Collaborative Radar Acquisition Field Test (CRAFT, Droegemeier *et al.* 2002) project.

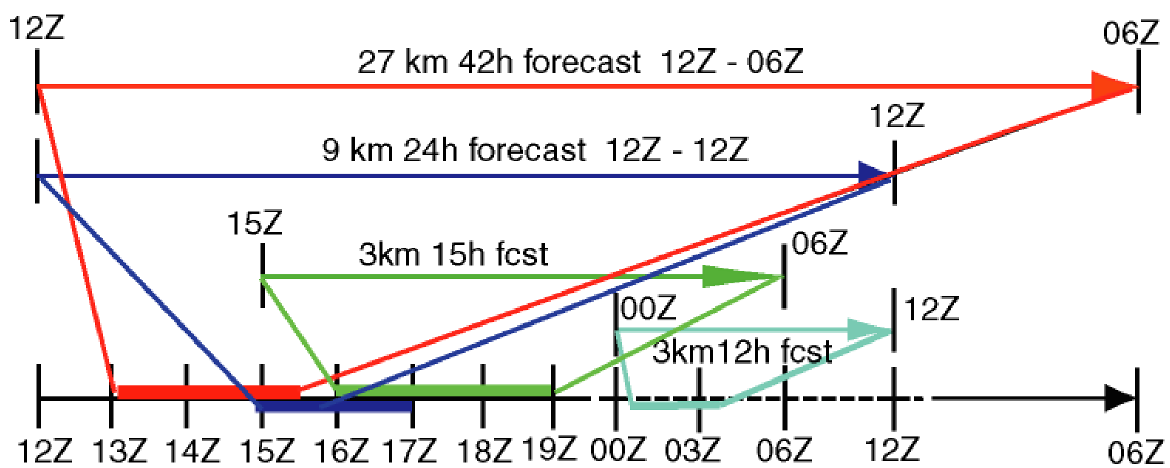


Figure 2. Forecast timeline, showing the start and end times of forecasts, and wall clock times of the operations.

Level-II data from 12 radars and Level-III (NIDS) data from 12 others in the Central Great Plains were ingested in real-time, remapped to the ARPS Cartesian grids, and used in a cloud analysis procedure (Zhang et al. 1998; Brewster 2002) to improve the representation of water vapor, cloud water and other microphysical variables. The IC analysis includes a diabatic adjustment to modify the temperature field in the presence of cloud and vertical motion in the initial condition. Furthermore, where Level-II data were not available, the radar data from Level-

III NIDS products were used. The cloud analysis also utilized visible and infrared channel data from GOES-8 satellite and surface observations of clouds. In addition to the forecasts performed at three resolutions, hourly analyses were produced on the SPmeso grid, making use of all of the data mentioned above.

To reduce the effect of imbalances in the initial condition, an incremental analysis update procedure (IAU, Bloom et al. 1996) was employed for the later part of the forecast period. This procedure is particularly effective for the 3 km forecast, where the analysis background was ARPS forecast. In this case, the analysis increment is introduced over a 10-minute period into the model, minimizing oscillations that can be introduced by imbalances in the analysis.

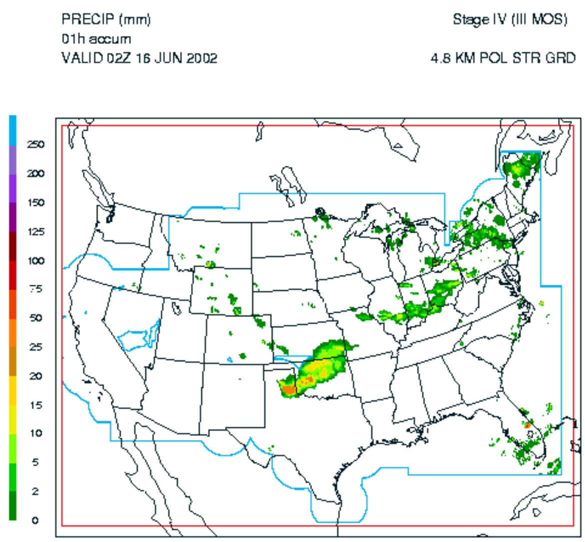
The number of horizontal grid points for the US, SPmeso and SPstorm grids were 213×131, 183×163 and 273×195, respectively, and all grids used 53 vertical levels with the model top being placed at 20 km above sea level. The full array of the ARPS physics package were employed. Recent improvements through validations against the Oklahoma Mesonet soil moisture measurements were incorporated into the soil model. A recently developed soil skin temperature initialization procedure that uses the Eta first guess field and the air temperature analysis was employed. The latest ARPS Version 5.0 was used.

The data ingest, preprocessing, analysis and boundary condition preparation were performed locally on three networked two-processor Pentium 4 Linux workstations. The model input data were then shipped to remote supercomputers at the Pittsburgh Supercomputing Center (PSC) or the National Center for Supercomputing Applications (NCSA). The three morning forecasts were run on one of the two Compaq Alpha-based clusters at PSC using 240 processors. The 00 UTC SPstorm forecast was run on NCSA's Intel Itanium-based Linux cluster, also using 240 processors. The model outputs were shipped back to local workstations and processed. Graphical products were posted on the Worldwide Web. The entire operation was automated by a sophisticated Perl-based control system. It is worth noting that both of the primary supercomputer systems used at NCSA and PSC were very new at the time of our forecast operations. Both systems were the first of their kind, so considerable system-wide tuning was still necessary. Our forecast operations required close interactions with the supporting staff of both centers, and such interactions significantly improved the overall timeliness of forecast during the period of operation.

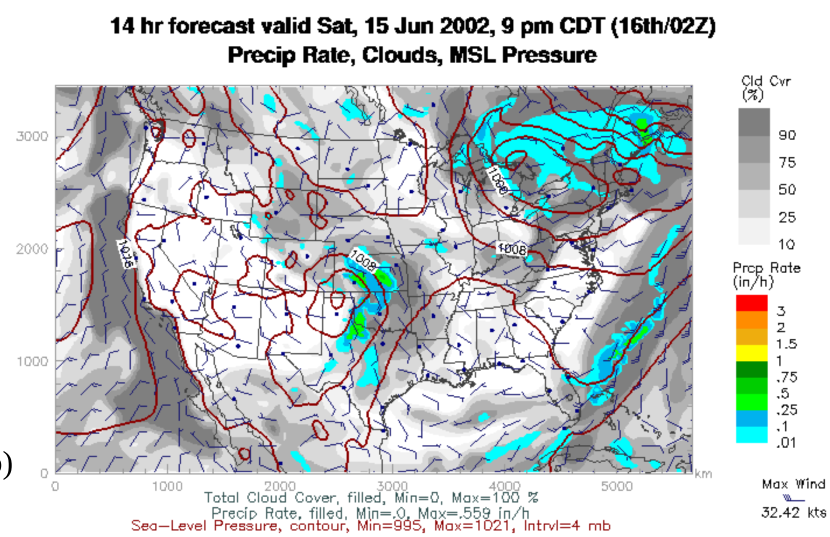
Graphical products, including fields and sounding animations, were generated and posted on the web as the hourly model outputs became available. A workstation dedicated to displaying forecast products was placed at the IHOP operation center. As part of the real time CAPS support for IHOP, a CAPS scientist was on duty daily to evaluate and assist in the interpretation of the forecast products. A web-based evaluation form was used to provide an archive of forecast evaluations and other related information. The forecast products were available at http://ihop.caps.ou.edu, and will remain online throughout the length of our project to facilitate forecast evaluation and case studies. Initial results of our IHOP forecast experiment were reported at the 15th NWP Conference in August 2002 (Xue et al 2002b).

As an example, we show in Fig. 3 a comparison of the ARPS predicted precipitation rate on three different grids valid at 02 UTC, 16 June 2002, with the corresponding NCEP stage IV analysis of one hour accumulated precipitation proceeding this time. In this day, convection initiated in northwest Nebraska at around 12 UTC, June 15 propagated south-southeastward. After entering Kansas, it linked up with an area of newly developed convection in western

Kansas (KS) and formed a WSW-ENE line that continued to propagate into Oklahoma (OK). This line had extended further west into Texas (TX) panhandle area by 02 UTC, June 16, due to new storms initiated in the TX-OK panhandle area (Fig. 3a). The 27 km forecast shows a general area of precipitation that covers SE KS, north-central OK through SW OK then into northwestern TX (Fig. 3b). The observed WSW-ENE oriented intense line of precipitation was not well captured by this coarse grid, however. In contrast, this line is reasonably well captured by the 9 km grid (Fig. 3c) except that its western end was not as strong as observed. Further improvement was provided by the 3 km grid, which predicted a few intensive convective cells near SW corner of OK that lead to a better match with the observed precipitation pattern at this end of line. This example clearly demonstrates the value of high resolutions that are capable of more explicit treatment of convection. The analysis of radar data on the high resolution grids in the initial conditions is likely to have had positive impacts. Reruns of this and other cases with and without radar and other high-resolution observations will provide the answer this question.

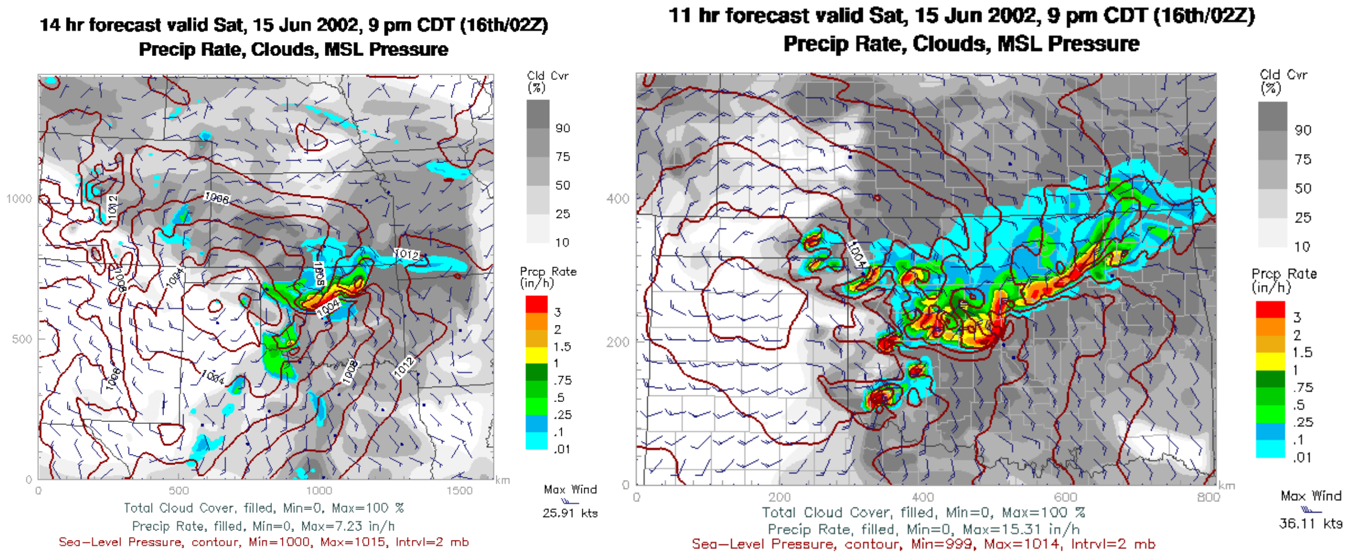


(a)



(b)

Figure 3. NCEP Stage IV hourly precipitation valid at 02 UTC, June 15, 2002 (a), and ARPS 14-hour forecast precipitation rate on 27 km (b), 9 km grid (c) and 11-hour forecast precipitation rate on 3 km grid (d), valid at the same time.



(c) (d)

Figure 3. Continued.

The forecast precipitation for the entire IHOP forecast period and for individual cases is being verified against the NCEP Stage IV gridded precipitation data as well as against the gauge station data. Equitable threat scores and biases are calculated for different periods and lengths of forecast for all three forecast grids and at different verifying resolutions. The scores are being carefully analyzed. In general, the high resolutions yield better precipitation scores. The precipitation bias is found to be rather large, however, especially at high threshold values. Further analysis is being performed to better understand the reason and cause. These verifications will guide us in designing reruns of these forecasts to test aspects of the model and assimilation system and to examine the impact of data on precipitation forecast.

3. Publications and other research accomplishments

During 2002, about 20 conference papers and journal articles that are within the score the current project were published by the project PIs, scientists and students (see list given at the end of this section). Most of the research was fully or partially supported by this grant. These papers include Shapiro, et al (2002) and Gao et al (2002a,b,c) on Doppler velocity retrievals and 3DVAR assimilation for small-scale hydrostatic flows; Brewster (2002a,b,c) on phase-correctiong data assimilation and application to storm-scale NWP, and diabatic initialization that includes the analysis of cloud hydrometeors; Xue et al (2002a) on further improvements to the ARPS model and storm-scale data assimilation; Hu and Xue (2002) on sensitivity of predicted tornadic storms to changes in environmental conditions; Nutter et al (2002) on the lack of lateral boundary condition perturbations on the dispersion of regional ensemble forecast and the proposed solutions; Bi et al (2002) on quality control of VAD winds and Level II radar data. Two more manuscripts on variational procedures for thermodynamic retrievals are also under preparation by the PI. Furthermore, a graduate student is working on the assimilation of slant-path GPS water using 3D variational method. Initial OSSE results have shown promises and limitations of the slant-path data from typical surface GPS networks. The best analysis is expected when these data are combined with other data sources, including especially those from surface stations. We will test the schemes with the Suomi Net data collected during the IHOP period and examine the impact of such data on the analysis of mesoscale moisture structures. Furthermore, several cases from the IHOP periods are being analyzed by the other graduate student to understand the convective initiation process.

To perform the proposed adjoint sensitivity experiments, we are developing a new version of the adjoint code based on Version 5.0 of the ARPS. This is being done with the help of an automatic adjoint code generator, TAF (Transformation of Algorithms in Fortran) which is the commercial version of the popular TAMC program (Tangent-linear and Adjoint Model Compiler). This effort leverages support from other related projects. Overall, we believe that our research has progressed satisfactorily, more or less following the proposed plan.

Finally, we point out that this project has provided education and training to three graduate students in the areas of data assimilation, numerical modeling and mesoscale convective dynamics. It also provided to training to two post-doctoral level scientists. The project PI taught a newly developed graduate course on data assimilation, which benefited for his research supported by this grant.

Referred publications:

Brewster, K.A., 2002a: Phase-correcting data assimilation and application to storm scale numerical weather prediction. Part I: Method description and simulation testing. *Mon. Wea. Rev*. In press.

Brewster, K.A., 2002b: Phase-correcting data assimilation and application to storm scale numerical weather prediction. Part II: Application to a Severe Storm Outbreak. *Mon. Wea. Rev*. In Press.

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Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2002a: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, DOI 10.1007/s00703-001-0595-6.

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