Final Report on

Evaluating the new Weather Research and Forecasting (WRF) model at the Storm Prediction Center

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SECTION 1: PROJECT OBJECTIVES AND ACCOMPLISHMENTS

Four primary objectives were addressed in this project: 1) to develop procedures for running, post-processing, and displaying output from the WRF model in an operational forecasting environment; 2) to increase forecaster awareness and usage of WRF model output, and to provide feedback from forecasters to WRF model developers; 3) to perform routine objective and subjective verification of WRF model output and to develop and refine new object based mesoscale verification strategies; and 4) to design and execute collaborative exercises involving both the research and operational communities during each spring's severe convective weather season, with an emphasis on quantitative subjective evaluation of numerical forecast guidance. Specific accomplishments related to these objectives are summarized below.

1.1 Develop procedures for running, post-processing, and displaying output from the WRF model in an operational forecasting environment

Initial efforts focused on developing procedures to run the WRF model locally and make the output available to SPC forecasters. During the first year of the project, we began to run the model daily on an 8 processor SGI Origin Series computer. In addition, we developed automated procedures to incorporate WRF precipitation forecasts from our local runs and from WRF forecasts generated at NCAR into precipitation verification database at OU/NSSL. In consultation with scientists from NCEP and NCAR, this database was used to generate web-based plots of equitable-threat and bias scores for all models, providing a valuable benchmark for WRF-beta performance compared to operational forecast models (especially the Eta model).

Although output from these forecasts was available to forecasters on the web and it influenced forecaster thinking on occasion, its day-to-day utility was limited because output was only available on the web – not within NAWIPS software (i.e., in GEMPAK format). Moreover, the WRF model was still at a relatively early stage of development and there were no remarkable WRF "success stories" that would motivate forecasters to routinely consult WRF output in the forecast preparation process. We solved the former problem by developing a WRF post-processing package that converts the model's native NETCDF output format to GRIB format. This package enables WRF output to be transformed into a format identical to that of the NCEP operational models, facilitating direct comparison with NCEP models (i.e., identical grids, computation of diagnostic quantities, etc.) This was a major step in enabling a side-by-side comparison of the WRF with operational models. Furthermore, it closed a gap that had previously precluded incorporation of the WRF (or WRF framework) into the NCEP operational suite.

During year 2, we leveraged our COMET support for WRF testing to procure funding for a 40-processor Pentium 4 Beowulf cluster. This cluster greatly increased our resources for realtime forecasts with WRF and we used it heavily during the 2003 SPC/NSSL Spring Program. Specifically, during this program, we initialized WRF every day using two different model configurations. The first used a CONUS domain with 12 km grid spacing and parameterized convection. The second used a small, re-locatable domain, 1200 km on all sides with 3 km grid spacing and no parameterized convection. This second domain was centered on the primary focus area for SPC forecasters every day. Output from both domains was infused into the SPC's operational data feed and it was examined closely during the Spring Program. This effort provided us with valuable experience in running the WRF model at high resolution and it provided many forecasters and modelers with a first-hand assessment of the capabilities of the WRF model in a convection-resolving configuration (see Kain et al. 2004a).

The 2003 Spring Program also revealed some deficiencies in our approach to high-resolution modeling. In particular, it became apparent that many of our high resolution forecasts were handicapped by problems associated with model "spin-up" and lateral boundary conditions (exacerbated by the relatively small domain size). In order to overcome these problems, we formed alliances with other WRF modeling centers for the 2004 Spring Program. In particular, we collaborated with scientists from NCAR, NCEP, and CAPS to produce relatively large domain, convection-resolving WRF forecasts for the 2004 program. Each center ran a different configuration of the WRF model, with all configurations covering at least 2/3 of the CONUS, using approximately 4 km grid spacing and explicit representation of convective clouds. A subset of the model-output dataset, centered on daily SPC focus areas, was processed at the remote centers then transferred to the SPC. This subsetting procedure allowed us to avoid the complications of transferring and managing the huge datasets that are generated by model runs with large domains, high resolution, and frequent output times, but still provided us with many output fields that have particular relevance for severe weather forecasting. Managing output files will clearly be a major challenge for future operational high-resolution modeling. Additional details about the SPC/NSSL Spring Program are provided in section 1.4.

1.2 Increase forecaster awareness and usage of WRF model output; provide feedback from forecasters to WRF model developers

During year 1 and the first part of year 2, daily map discussions provided an effective forum for increasing awareness of the WRF model among SPC forecasters. PIs on this project frequently led map discussions and made a concerted effort to display and consider WRF model forecasts in the context of the day's forecasting challenges. This approach appeared to be quite effective in introducing forecasters to the new model. Also, during the first year, a formal seminar on convective parameterization was presented during semi-annual SPC forecaster training exercises, focusing on the parameterizations used in the emerging WRF model. Forecaster feedback led model developers to consider several changes to both the Kain-Fritsch and Betts-Miller-Janjic convective parameterizations, ultimately leading to improved formulations of these schemes (see Baldwin et al. 2002; Ferrier 2004; Kain 2004).

During the second year, forecasters became actively involved in examining and evaluating WRF forecasts during the 2003 Spring Program. They were particularly intrigued by the convective-cloud-resolving forecasts that were being generated locally, as well as those that were running at NCAR in support of the BAMEX field program. Specific impressions of SPC forecasters were conveyed to model developers at NCAR and they significantly influenced qualitative assessments of WRF forecasts from BAMEX that will soon appear in scientific journals (i.e., Done et al. 2004). Furthermore, they provided important preliminary feedback regarding the potential severe convective weather forecasting utility of WRF model configurations in which convective clouds are marginally resolved.

During year 3, SPC forecasters became very aware of the evolving WRF model, including the alternative dynamic cores and the potential utility of high-resolution WRF forecasts. During the first half of the year, a segment of formal SPC training exercises was devoted to the WRF model. Specifically, forecasters were provided information about the history of the WRF model, the motivation for its development, and future plans for the model. Results from the 4-km BAMEX model runs were discussed in some detail, leading to some lively exchanges and varied opinions about the potential value of the forecasts. During the 2004 Spring Program, three different high resolution configurations ($\delta x \sim 4$ km) of the WRF model were examined and used to make severe weather forecasts every day. Selected SPC forecasters were involved at all times, and many of these forecasters continued to use the high-resolution forecasts when they returned to operational shifts. Through this process and forecaster testimonials, significant interest in the WRF model was generated, though not without a modicum of caution. Preliminary results from the 2004 Spring Program were presented at the 2004 WRF/MM5 workshop (Kain et al. 2004b) and more complete findings will be shared with WRF model developers. More detailed information about the 2004 Spring Program is provided in section 1.4.

1.3 Perform routine objective and subjective verification of WRF model output; develop and refine object based mesoscale verification strategies

As discussed in section 1.1, rainfall forecasts from the WRF model have been incorporated into PI Baldwin's precipitation verification database since the early days of this project. Analysis of this data was plotted on a web page, in the form of equitable-threat (ET) and bias scores, up until September 2003, when it was discontinued. These displays provided WRF development teams with valuable benchmarks for WRF performance compared to operational forecast models (especially the Eta model). They also revealed some of the shortcomings of ET and bias scores and motivated numerous investigators to devise alternative methods to verify mesoscale precipitation fields (e.g., Baldwin and Wandishin 2002; Bullock et al. 2004). Subjective assessments of WRF performance took place mainly within annual SPC/NSSL Spring Programs (detailed in section 1.4).

Development of an object oriented verification strategy has been a long-term goal of collaborative activities related to this project. A major milestone towards this goal has now been accomplished (Baldwin et al. 2004). Specifically, an automated procedure for classifying rainfall systems was developed using a national analysis of hourly precipitation estimates from radar and rain gauge data. The development process followed two main phases, a training phase and a testing phase. First, forty-eight hand-selected cases were used to create a training data set, from which a set of attributes related to morphological aspects of rainfall systems were extracted. A hierarchy of classes for rainfall systems was envisioned, in which rainfall systems are separated into general *convective* (heavy rain) and *non-convective* (light rain) classes. At the next level of classification hierarchy, convective events are divided into *linear* and *cellular* sub-classes, and non-convective events belong to the *stratiform* sub-class. Essential attributes of precipitating systems, related to the rainfall intensity and degree of linear organization, were determined during the training phase The attributes related to the rainfall intensity were chosen to be the parameters of the gamma probability distribution fit to observed rainfall amount frequency distributions using the generalized method of moments. Attributes related to the degree of linear organization of each rainfall system were obtained via geostatistical measures. Rainfall systems were categorized using hierarchical cluster analysis experiments with various combinations of these attributes. The combination of attributes that resulted in the best match between cluster analysis results and an expert classification were used as the basis for an automated classification procedure. The development process shifted into the testing phase, where automated procedures for identifying and classifying rainfall systems were used to analyze every rainfall system that occurred during 2002 in the contiguous 48 states. To allow for a feasible validation, a testing data set was extracted from the 2002 data. The testing data set consisted of 100 randomly selected rainfall systems larger than 40 000 km^2 as identified by an automated identification system. This subset was shown to be representative of the full 2002 data set. Finally, the automated classification procedure classified the testing data set into stratiform, linear, and cellular classes with 85% accuracy, as compared to an expert classification.

This classification strategy provides the fundamental elements of a generalized method for classification of rainfall systems. Further refinement of specific procedures may result in a variety of improvements. Moreover, this method could be used for purposes other than verification, such as predictability and climatology studies.

1.4 Design and execute collaborative exercises involving both the research and operational communities during each spring's severe convective weather season, with an emphasis on quantitative subjective evaluation of numerical forecast guidance

The SPC/NSSL Spring Program was held annually during peak severe convective weather season. The popularity of this program has grown each year, no doubt because of the interesting and relevant scientific issues that have been investigated. However, feedback from participants indicates that there is another equally compelling attraction - the rare opportunity for direct and interdependent interactions between operational forecasters and research scientists that this program provides (see Kain et al. 2003). COMET support has been critically important to the development and growth of this program.

The scientific objectives of the 2002 Spring Program were dictated by the IHOP field program. Forecasting for IHOP was the primary responsibility for participants. Mesoscale configurations of the WRF model were used to generate experimental forecasts, but output was available only on the web and subjective evaluation of the forecasts was limited. Nonetheless, numerous SPC Lead Forecasters participated in the program and interactions between the operational and research communities were quite rewarding.

The 2003 Spring Program had a dual focus. The primary emphasis was on the Day 2 convective forecast problem and the application of output from short-range ensembles therein. However, a second component involved the systematic subjective evaluation of deterministic models for the Day 1 time frame (See Kain et al. 2004a). Included in the group of deterministic models were two locally run WRF forecasts, one over a CONUS domain with parameterized convection and 12 km grid spacing, and one over a much smaller re-locatable domain, with a 3 km grid length and explicit representation of deep convective clouds. Subjective verification statistics suggested that the mesoscale configuration of WRF performed comparably to the operational models (i.e., Eta and RUC) in forecasting convective initiation and evolution. The convection resolving version received significantly lower ratings on average, an assessment that was ultimately attributed to very coarse initial conditions and lateral boundary effects exacerbated by the small domain size (1200 km^2). In spite of some obvious problems, the high-resolution forecasts generated a great deal of interest, particularly among forecasters. These forecasts occasionally produced very realistic-looking structures and viable indications of convective mode, especially during the historic tornado outbreaks in the first half of May 2003. These results provided motivation, enthusiasm, and focus for the next Spring Program.

The 2003 Spring Program had 37 participants, from the United States, Canada, and the United Kingdom, including numerous NOAA agencies/ forecast offices, 5 different universities, and other government agencies.

The 2004 Spring Program was the culmination of our WRF evaluation under this project. The primary objective of this program was to assess whether WRF configurations that marginally resolve deep convective clouds (i.e., configurations with grid spacing ~ 4 km) can help SPC forecasters make better predictions of severe convective weather. The program had an experimental forecasting component and a model evaluation component. Results from both elements suggested that severe weather forecasters benefit from the high-resolution guidance. For example, when forecasts prepared with and without examination of high-resolution output were evaluated separately the next day using a scale from 1 to 10, the former received a higher overall rating for 52% of the forecast periods, and a lower rating only 14% of the time. When the same type of rating procedure was used to evaluate model predictions of convective initiation, evolution, and mode, the high-resolution models were not significantly better or worse than the operational Eta model for initiation and evolution, but they were rated much better for convective mode. This is important because in recent years it has become evident that the type of severe weather that occurs (tornadoes, hail, or damaging winds) is often closely related to the convective mode (or morphology) that storms exhibit, such as forming in discrete cells, squall lines (or quasi-linear convective systems (QLCS)), and multicellular convective systems. In addition, some severe storms develop as dynamically unique classes of thunderstorms such as supercells and bow echoes, which are believed to produce a disproportionate number of tornado and widespread straight-line wind damage events, respectively. Thus, accurate severe weather forecasts are dependent on forecasters being able to properly predict not only where and when severe thunderstorms will develop and how they will evolve over the next 4 – 7 hours, but also the convective mode(s) that are most likely to occur.

The 2004 Spring Program had 54 participants from the United States, Canada, and Finland representing numerous NOAA agencies/ forecast offices, 12 different universities, and other government agencies. Three high-resolution model forecasts were produced daily, one from CAPS (WRF mass core), another from EMC (WRF NMM core), and the third from NCAR (WRF mass core). Results from this program are in a preliminary stage of evaluation and will be discussed and summarized in a forthcoming paper. Additional details about this Spring Program can be found here.

References

Baldwin, M. E., J. S. Kain, and M. P. Kay, 2002: Properties of the convection scheme in NCEP's Eta model that affect forecast sounding interpretation. *Wea. Forecasting*, 17, 1063-1079.

Baldwin, M. E., and M. S. Wandishin, 2002: Determining the resolved spatial scales of Eta Model precipitation forecasts. *Preprints, 15th Conf. on Numerical Weather Prediction*. San Antonio, TX, Amer. Meteor. Soc., 85-88.

Baldwin, M. E., S. Lakshmivarahan, and J. S. Kain, 2004: Development of an Automated Classification Procedure for Rainfall Systems, *Mon. Wea. Rev.* (Accepted for publication).

Bullock, R., B. G. Brown, C. A. Davis, M. Chapman, K. W. Manning and R. Morss, 2004: An Object-Oriented Approach to the Verification of Quantitative Precipitation Forecasts: Part I - Methodology, *Preprints, 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction*, Seattle, WA, Amer. Meteor. Soc., CD-ROM, J12.4

Done, J., C. Davis, and M. Weisman, 2004: The next generation of NWP: Explicit forecasts of convection using the Weather Research and Forecasting (WRF) model. Accepted for publication in *Atmospheric Science Letters*.

Ferrier, B. S., 2004: Modification of two convective schemes used in the NCEP Eta model. *Preprints, 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction*, Seattle, WA, Amer. Meteor. Soc., CD-ROM, J4.2

Kain, J. S., P. R. Janish, S. J. Weiss, M. E. Baldwin, R. S. Schneider, and H. E. Brooks, 2003: Collaboration between forecasters and research scientists at the NSSL and SPC: The Spring Program. *Bull. Amer. Meteor. Soc.*, **84**, 1797-1806.

Kain, J. S., 2004: The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteor.*, 43, 170-181.

Kain, J. S., S. J. Weiss, D. R. Bright, M. E. Baldwin, and J. J. Levit, 2004a: Subjective verification of deterministic models during the 2003 SPC/NSSL Spring Program. *Preprints, 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, 9.3

Kain, J. S., S. J. Weiss, J. J. Levit, M. E. Baldwin, and D. R. Bright, 2004b: Evaluating the utility of WRF as a severe weather forecasting tool. Presented by J. Kain at the WRF/MM5 User's Workshop, Boulder, CO, June 2004.

SECTION 2: SUMMARY OF UNIVERSITY/NWS EXCHANGES

This project has directly or indirectly supported numerous activities that have cultivated a strong working relationship between the university community and the NWS. Some examples:

- **Annual research/forecast experiments**. Collaborative experimental research and forecasting programs (*i.e.*, the NSSL/SPC Spring Program) have been conducted each spring in association with this project. They have involved a core group of forecasters and scientists from the University of Oklahoma (OU), SPC, and NSSL, with recent visiting scientists/forecasters from AFWA, COMET, NCEP/EMC, NCEP/HPC, NCAR, NOAA/FSL, NWS/OUN, NWS/DTX, NWS/NIFC, NWS/USWRP, UK Met. Office, Met. Services of Canada, Finnish Met. Institute, and over a dozen universities. Year by year lists of participants can be found here: 2002, 2003, 2004.
- **Daily map discussions**. These daily gatherings have become a focal point for informal exchanges between research scientists and forecasters and a breeding ground for collaborative research. They are organized by PIs Kain and Weiss and are frequently attended by personnel from OU, SPC, NSSL, and the Norman WFO.
- **Seminars**. SPC training seminars were conducted in years 1 and 3, as discussed in section 1.2 above. Bill Skamarock, a leading developer of the WRF model, presented a seminar on WRF in year 2. Most external visitors to the Spring Program presented SPC/NSSL seminars on their work.
- **COMET Symposia**. PIs Baldwin, Carr, and Kain have presented numerous talks at COMET symposia and workshops in Boulder, CO.
- **Verification web page**. The web pages created as part of this project (see section 1.3) provided a valuable resource for students. At OU, students frequently accessed this page as one way of assessing the reliability of various forecast models and it was used as a resource in the graduate level "Forecast Verification" course at OU.
- **Collaborative papers**. COMET funding has been a catalyst for collaborative research at SPC/CIMMS/NSSL. In addition to the studies highlighted in the list of papers in the next section, numerous unlisted collaborative projects have been inspired and promoted by the interactive environment that this funding has allowed us to create in Norman, OK.

SECTION 3: PRESENTATIONS AND PUBLICATIONS

3.1 Presentations/Conference Papers

Baldwin, M. E., and J. S. Kain: Model parameterizations: How do they affect NWP forecasts? Presented at *Heavy Precipitation COMET Symposia* October 16 2001, October 23, 2001, and *RFC/HPC Hydromet Course* November 28, 2001, UCAR/COMET, Boulder, CO.

Baldwin, M. E., 2001: Verification of small-scale details in WRF forecasts. Presented at *The Second WRF Users Workshop,* August 13-17, 2001, NCAR, Boulder, CO.

Baldwin, M. E., 2002: Forecast characterization and implications for verification. Invited presentation by M. Baldwin at the FAA/AWRP Workshop on Forecast Verification, Boulder, CO, 31 July 2002.

Baldwin, M. E., and M. S. Wandishin, 2002: Determining the resolved spatial scales of Eta Model precipitation forecasts. *Preprints, 15th Conf. on Numerical Weather Prediction.* San Antonio, TX, Amer. Meteor. Soc., 85-88.

Baldwin, M. E., S. Lakshmivarahan, and J. S. Kain, 2002: Development of an "events-oriented" approach to forecast verification. *Preprints, 15th Conf. on Numerical Weather Prediction*, San Antonio, TX, Amer. Meteor. Soc., 210-213.

Baldwin, M. E. and S. Lakshmivarahan, 2002: Rainfall classification using histogram analysis: An example of data mining in meteorology. Presented by M. Baldwin at Conference on Artificial Neural Networks In Engineering, St. Louis, MO,12 Nov 2002.

Baldwin, M. E., and S. Lakshmivarahan, 2003: Development of an events-oriented verification system using data mining and image processing algorithms. *Preprint CD, AMS 3rd Conf. Artificial Intelligence*, Long Beach, CA

Baldwin, M. E. and J. S. Kain, 2004: Examining the sensitivity of various performance measures. *Preprint CD, AMS 17th Conference on Probability and Statistics in the Atmospheric Sciences*, Seattle, WA, January 2004.

Kain, J. S., 2001: Convective parameterization in mesoscale models. Presented at *The Cumulus Parameterization Workshop*, December 3-5, 2001, NASA/Goddard Space Flight Center, Greenbelt, MD.

Kain, J. S., 2002: Simple but effective technology transfer in a collaborative research/operational environment. Presented at the *2002 NASA-NWS Joint Symposium on Short-Term Forecasting and Convective Weather Warning Process*, April 9, 2002, NASA/Marshall Space Flight Center, Huntsville, AL.

Kain, J. S., M. E. Baldwin, and S. J. Weiss, 2002: WRF model evaluation at the SPC and NSSL. *Preprints, 15th Conf. on Numerical Weather Prediction*, San Antonio, TX, Amer. Meteor. Soc., 256-259.

Kain, J. S., M. E. Baldwin, S. J. Weiss, P. R. Janish, J. A. Hart, and A. Just, 2002: Grassroots science and technology transfer in a collaborative research/operational environment. *Preprints, 15th Conf. on Numerical Weather Prediction*, San Antonio, TX, Amer. Meteor. Soc., J1-J6.

Kain, J. S., M. E. Baldwin, S. J. Weiss, P. R. Janish, G. W. Carbin, M. P. Kay, and L. Brown, 2002: Subjective verification of numerical models as a component of a broader interaction between research and operations. Presented by M. Baldwin at the AMS 15th conference on Numerical Weather Prediction, San Antonio, TX, 12-16 August 2002.

Kain, J. S., S. J. Weiss, D. R. Bright, M. E. Baldwin, and J. J. Levit, 2004: Subjective verification of deterministic models during the 2003 SPC/NSSL Spring Program. *Preprints, 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, 9.3

Kain, J. S., S. J. Weiss, J. J. Levit, M. E. Baldwin, and D. R. Bright, 2004: Evaluating the utility of WRF as a severe weather forecasting tool. Presented by J. Kain at the WRF/MM5 User's Workshop, Boulder, CO, June 2004.

Kay, M. P. and M. E. Baldwin, 2002: Combining objective and subjective information to improve forecast evaluation. *Preprints, 15th Conf. on Numerical Weather Prediction,* San Antonio, TX, Amer. Meteor. Soc., 411-414.

Weiss, S. J., P. R. Janish, R. S. Schneider, J. Cupo, E. Szoke, J. Brown, and C. Ziegler, 2002: Probabilistic Convective Initiation Forecasts in Support of IHOP During the 2002 SPC/NSSL Spring Program. Presented by S. Weiss at the National Weather Association Annual Meeting, Fort Worth, TX, October 2002.

Weiss, S. J., 2002: Storm Prediction Center Annual Highlights. Presented at the NCEP/Environmental Modeling Center Annual Review, Washington, DC, December 2002.

Weiss, S. J., D. Bright, J. Levit, D. Stensrud, J. Kain, and M. Dahmer, 2003: The SPC/NSSL Spring Program 2003: Exploration of Short-Range Ensemble Prediction Systems and High Resolution Deterministic Numerical Models for Use in Operational Severe Weather Forecasting. Presented by S. Weiss at the National Weather Association Annual Meeting, Jacksonville, FL, October 2003.

Weiss, S. J., 2003: Storm Prediction Center Annual Highlights. Presented at the NCEP/Environmental Modeling Center Annual Review, Washington, DC, December 2003.

Weiss, S. J., P. Janish, J. Kain, M. Baldwin, D. Bright, and J. Levit: 2004: Overview of Recent SPC/NSSL Spring Programs. Presented by S. Weiss at National Weather Association Severe Storms and Doppler Radar Conference, Des Moines, IA, March 2004.

Weiss, S. J. and J. T. Schaefer, 2004: A Historical Perspective on the Role of NWP Models in the Prediction of Severe Local Storms. Presented by S. Weiss at the Symposium on the 50th Anniversary of Operational Numerical Weather Prediction, College Park, MD, June 2004.

Weiss, S. J., J. S. Kain, J. J. Levit, M. E. Baldwin, and D. R. Bright, 2004: Examination of several different versions of the WRF model for the prediction of severe convective weather: The SPC/NSSL Spring Program 2004. To be presented at the AMS 22nd Conference on Severe Local Storms, Hyannis, MA, October 2004.

3.2 Refereed Publications

Baldwin, M. E. and S. Lakshmivarahan, 2002: Rainfall classification using histogram analysis: An example of data mining in meteorology. *Intelligent Engineering Systems Through Artificial Neural Networks*, Volume 12, C.H. Dagli, A.L. Buczak, J. Ghosh, M.J. Embrechts, O. Ersoy, S.W. Kercel, Eds., ASME Press, 429-434.

Baldwin, M. E., J. S. Kain, and M. P. Kay, 2002: Properties of the convection scheme in NCEP's Eta model that affect forecast sounding interpretation. *Wea. Forecasting*, 17, 1063-1079.

Baldwin, M. E., S. Lakshmivarahan, and J. S. Kain, 2004: Development of an Automated Classification Procedure for Rainfall Systems, *Mon. Wea. Rev.* (Accepted for publication).

Ebert, E. E., U. Damrath, W. Wergen, and M. E. Baldwin, 2003: The WGNE Assessment of Short-term Quantitative Precipitation Forecasts. *Bull. Amer. Meteor. Soc.*, **84**, 481-492.

Kain, J. S., M. E. Baldwin, and S. J. Weiss, 2003: Parameterized updraft mass flux as a predictor of convective intensity. *Wea. Forecasting*, **18**, 106-116.

Kain, J. S., M. E. Baldwin, and S. J. Weiss, P. R. Janish, M. P. Kay, and G. Carbin, 2003: Subjective verification of numerical models as a component of a broader interaction between research and operations. *Wea. Forecasting*, **18**, 847-860.

Kain, J. S., P. R. Janish, S. J. Weiss, M. E. Baldwin, R. S. Schneider, and H. E. Brooks, 2003: Collaboration between forecasters and research scientists at the NSSL and SPC: The Spring Program. *Bull. Amer. Meteor. Soc.*, **84**, 1797-1806.

Kain, J. S., 2004: The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170-181.

3.3 Theses

Baldwin, M. E., 2003: *Automated classification of rainfall systems using statistical characterization*. Univ. of Oklahoma, PhD dissertation, 195pp.

SECTION 4: SUMMARY OF BENEFITS AND PROBLEMS ENCOUNTERED

4.1 University of Oklahoma

a) *Benefits* - Through this project, the University has demonstrated its commitment to active involvement in WRF development and collaboration with the operational community. This is beneficial to students, helping them to appreciate the challenges involved with developing a new forecast model in a multi-agency collaboration. It also provides students with exposure to operational forecast problems, such as data overload, timeliness, reliability and stability of models, and visualization of model output. This exposure has helped students to understand model development procedures and interactions between research and operations, providing them with a perspective that will be useful for either operational or research careers.

   It is also important to note that educational benefits from this project spread beyond the University of Oklahoma. For example, several external participants in the 2004 Spring Program indicated that their experience in the program would have a direct impact on the content of courses that they teach at other major universities. The Spring Program provides participants with first-hand knowledge about operational forecasting of severe convective weather and research that is relevant to this challenge. In addition, it exposes them to implementation and testing strategies that facilitate the transition of science and technology from research to operations. This kind of experience is not available elsewhere and it inspires a potentially valuable addition to the traditional meteorological curriculum.

b) *Problems Encountered* – Computer resources were somewhat of a problem. A 40-processor Beowulf cluster was purchased specifically for realtime model forecasts early in the second year of the project. However, this cluster was handicapped by recurring instability and was not as dependable as we had hoped. We were able to minimize the impact of this problem by forging agreements with other modeling centers to produce high resolution WRF forecasts during the 2004 Spring Program. In particular, scientists from CAPS, EMC, and NCAR all agreed to run high-resolution configurations of WRF and provide us with the output on a daily basis. In retrospect, this was a very desirable solution since it provided us with much more model data than we could have hoped to produce locally and it strengthened our working relationships with these different modeling/research centers.

4.2 Storm Prediction Center

The initial WRF model experimental implementation is part of a continuing program that furthers SPC/NSSL interactions and collaboration. This critical process will help ensure that WRF model development will be partially guided by operational forecasting interests and requirements. This collaborative effort provides a direct benefit to SPC staff since they are among the first group of forecasters to have direct access to cutting edge WRF research and prediction.

This project has invigorated ongoing SPC/CIMMS/NSSL interactions and collaboration. Previous interactions between these organizations, partially funded by COMET, helped to form the foundation for a solid working relationship between operations and research at the Oklahoma Weather Center and this project has been critical for stimulating the collaboration. Many forecasters at the SPC have become very adept at interpreting numerical model output, due largely to this project and previous COMET support. These acquired skills have enabled SPC forecasters to provide valuable insight and guidance for WFOs and better forecasts for the public. Furthermore, SPC forecasters have provided valuable feedback to WRF model developers, from their unique and important perspective. This feedback has had a significant impact on development and implementation trends of the WRF model.