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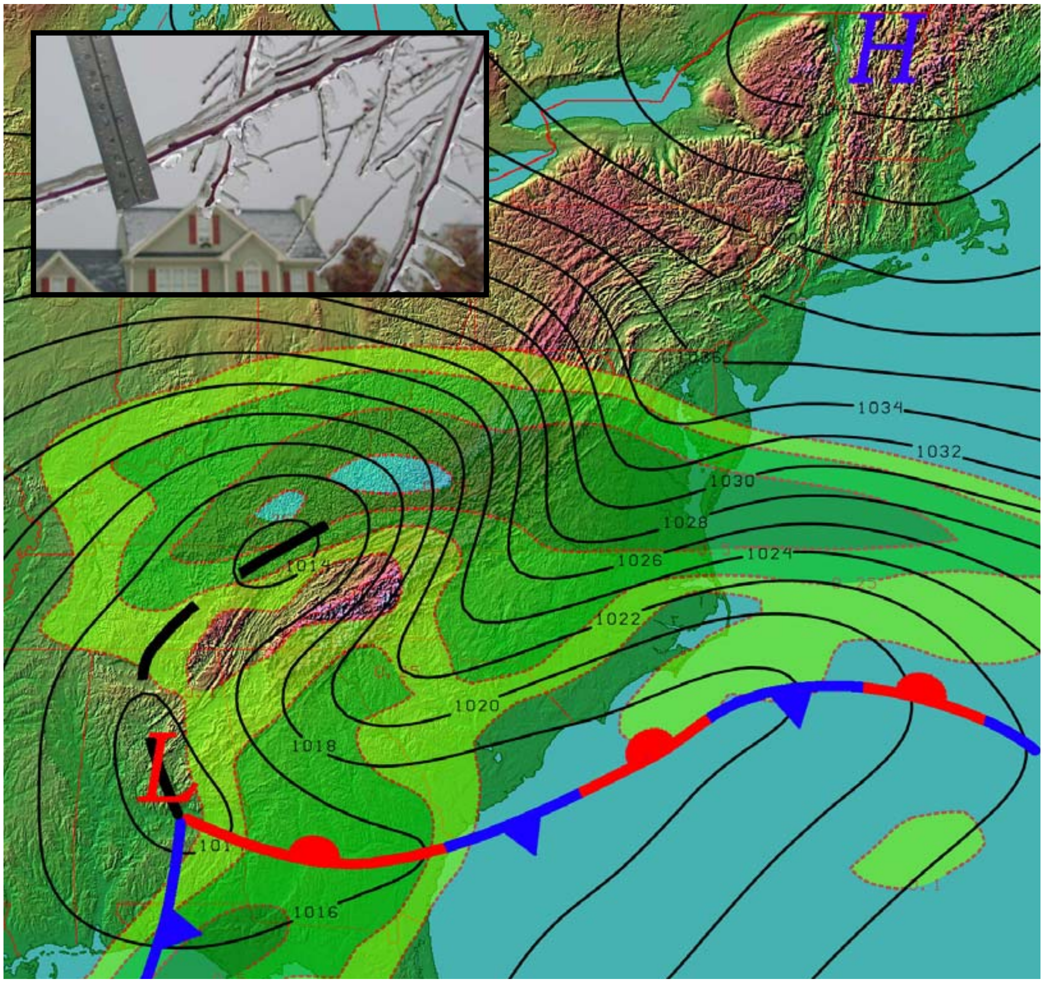

Improving Cold-Season Quantitative Precipitation Forecasting in the Southeastern United States

A Final Report on the Proposal to the
National Oceanic and Atmospheric Administration
in Support of the
Collaborative Science, Technology & Applied Research Program
(CSTAR)

Dept. of Marine, Earth, & Atmospheric Sciences
North Carolina State University

Final Report on

Improving Cold-Season Quantitative Precipitation Forecasting in the Southeastern United States

To the
National Oceanic and Atmospheric Administration
Collaborative Science, Technology & Applied Research Program (CSTAR)
Award Number NA03NWS4680007
For the period 1 June 2003 through 31 May 2006

Department of Marine, Earth, & Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina

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Contact Person: Gary M. Lackmann
Department of Marine, Earth, & Atmospheric Sciences
Box 8208
North Carolina State University
Raleigh, North Carolina 27695-8208
Phone: (919) 515-1439
Fax: (919) 515-7802
gary@ncsu.edu

List of Participants and Collaborators:

Principal Investigators - North Carolina State University:
- Gary M. Lackmann
- Allen J. Riordan
- Lian Xie

Student Researchers (contributing during project):
- Kelly Mahoney (Graduated August 2005, M.S.; currently Ph.D. candidate)
- Tom Green (Graduated December 2005, M.S.)
- Mike Brennan (Graduated August 2005, Ph.D.)
- Nicole Haglund (Current M.S. candidate)
- Joshua Palmer (Current M.S. candidate)
- Paul Suffern (Undergraduate researcher, currently non-CSTAR graduate student)

Collaborative Offices of the National Weather Service:
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I. Overall Summary of Accomplishments

This report summarizes the accomplishments under CSTAR grant NA03NWS4680007 for the funding period of this proposal: 1 June 2003 through 31 May 2006.

A.) Project Summaries

1.) Quantitative precipitation forecasting (QPF) and upstream convection (UC)

The challenges of QPF are well documented, and the difficulties are exacerbated when precipitation is convective in nature. Forecasters in the southeastern U.S. had brought to our attention a situation where model QPF has proven to be especially unreliable: when organized convection was taking place to the southwest of the region, typically over the Gulf of Mexico or the Gulf Coast states. Leading up to the development of this proposal, it was evident that conventional forecaster wisdom in these situations was to reduce model QPF when upstream convection was anticipated or underway.

Research by graduate student Kelly Mahoney was designed to address several aspects of this problem. Objectives included: (i) developing a physical understanding of precisely how UC impacts the *downstream* precipitation distribution; (ii) determining the extent to which the "convectional wisdom" mentioned above applied when many cases were considered, and (iii) isolating the causes behind numerical model failure in many of these UC situations.

The findings of this research indicate that UC impacts the downstream precipitation shield by reducing the northward moisture flux in the lower-troposphere to the east of the mesoscale convective system (MCS). This was found to be due to ***moisture consumption*** by the convective system as well as a ***turning of the lower tropospheric winds to a more westerly direction in the wake of the MCS***. A representative case study from 31 December 2001 – 1 January 2002 was analyzed to develop these conclusions.

Construction of an initial model (NAM-Eta) error climatology for the central North Carolina region for the years 2000 to 2003 allowed identification of many cases of large model QPF error. Of those that were accompanied by UC, it was found that ***in some of these cases the Eta (NAM) model QPF bias was negative, opposite to the conventional wisdom.*** Analysis of one of these events demonstrated that UC can, if moving slowly with an ana-cold front system, serve to enhance northward moisture flux and the low-level jet (LLJ) to the east, increasing precipitation. However, these events were not as prevalent as the fast-moving convection events. ***The speed of the upstream MCS appears to be a critical factor in determination of the character of the impact on downstream precipitation.***

Model experiments from the 31 December case study indicate that the inability of models to develop a rapidly moving upstream MCS was linked to the downstream QPF failures. Correction of these difficulties is the subject of ongoing research, but it is hypothesized that limitations in models with relatively coarse grid spacing, and employing convective parameterization (CP) schemes, are unable to account for realistic cold pool development with the MCS. As depicted in Fig. 1, even for the same grid spacing, a model run that explicitly represents convection generates a more realistic cold pool than does a run that utilizes a CP scheme. Further, the lack of momentum adjustment in CP schemes may preclude the development of a realistic rear-inflow jet, which is related to system motion.

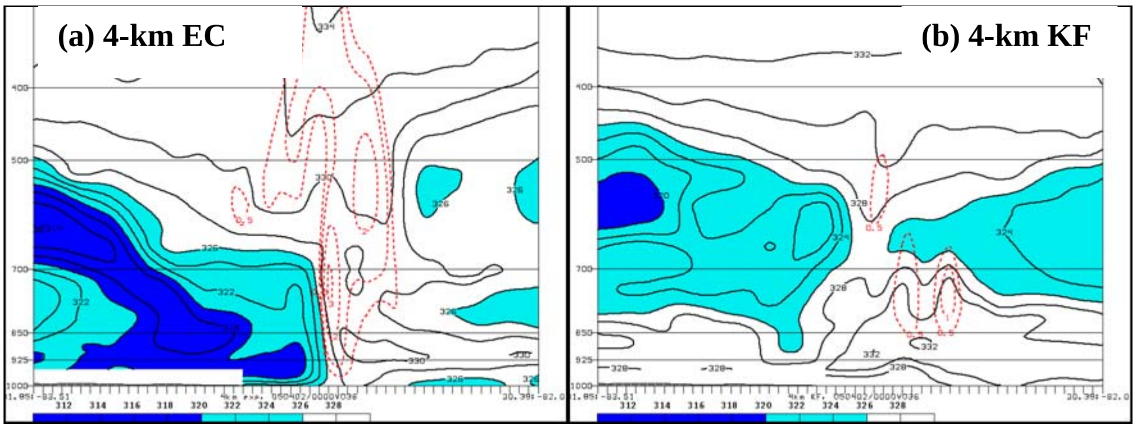

Fig. 1. WRF 36-h forecast cold pool comparison valid 00 UTC 2 April 2005 for cross section through a Southeastern US squall line. Theta-e (black contours, 2K interval, shaded as in legend at bottom of panels), and vertical velocity (red dashed contours 0.5 m/s interval): (a) 4-km explicit convection (EC) WRF run; (b) as in (a) except for 4-km WRF run using a CP scheme (Kain-Fritsch, KF). The differences suggest that CP schemes may sometimes preclude accurate cold pool representation.

These results have been shared with the regional NWS offices via VISIT sessions, presented at two major AMS conferences (the WAF/NWP conference in August 2005 and the Mesoscale conference in October 2005), at the Hydrometeorological Prediction Center (HPC) in August 2005, and in a refereed publication in the AMS journal *Weather and Forecasting*. Kelly Mahoney completed and successfully defended her M.S. thesis on this topic in July, 2005. Additional research based on this project is underway: (i) Kelly is working to solve the model deficiencies in the representation of MCS motion in NWP models, and (ii) a COMET Partner's project has been funded to develop real-time tools that will allow forecasters to better anticipate the impact that UC will have on downstream precipitation in a given event in order to best adjust model QPF guidance.

2.) Winter cyclonic storms

The forecasting challenges provided by wintry weather (e.g., freezing and frozen precipitation) are compounded by difficulties with model QPF; this was one of the reasons for emphasizing cold-season QPF in the initial proposal. Three different graduate students have worked on problems related to winter cyclones in the southeast. Doctoral student Michael Brennan undertook a detailed analysis of the 24-25 January 2000 East Coast snowstorm, master's student Kelly Mahoney took on a side project in which she examined the sensitivity of coastal cyclogenesis to different CP-scheme choices, and master's student Nicole Haglund investigated the role of model microphysics and sea-surface temperature representation in two East Coast winter weather events.

a.) January 2000 East Coast winter storm

The surprise snowstorm that impacted the southeast and mid-Atlantic states on 24-25 January 2000 has received considerable research attention. Our focus was on an area of incipient precipitation (IP) that developed over Mississippi, Alabama, and Georgia early on 24 January, more than 12 hours prior to the main cyclogenesis along the East Coast. Numerical predictions by the Eta and other operational models failed to capture this early precipitation (as well as the westward extension of the downstream precipitation shield); it was thus hypothesized that this area of incipient precipitation played a role in the subsequent downstream model forecast failures. Specifically, ***we hypothesized that latent heat release (and associated lower-tropospheric potential vorticity (PV) production) was linked to a westward shift (farther north and later in time) in the subsequent precipitation shield relative to what would have occurred if it had not developed (Fig. 2).***

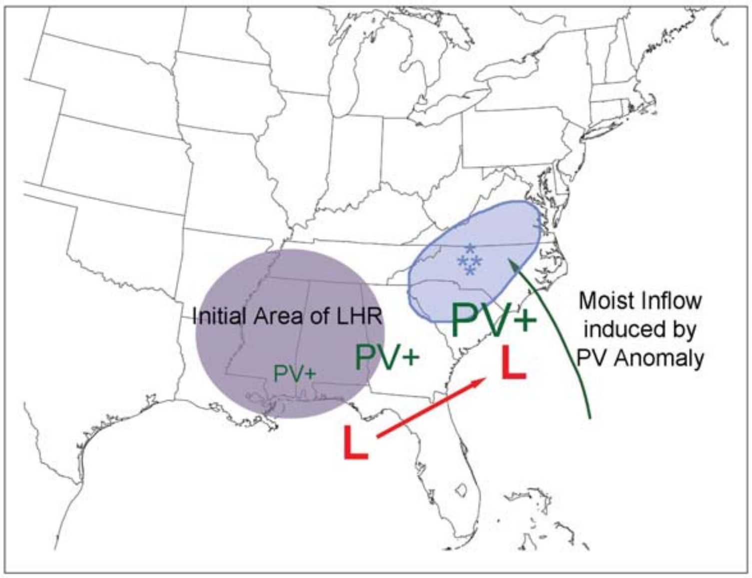

Fig. 2. Schematic diagram illustrating role of diabatically produced, lower-tropospheric PV maximum in moisture transport during 24-25 January 2000 East Coast cyclone event.

Piecewise PV inversion, along with numerous model experiments, ***confirmed the importance of the incipient precipitation to the westward extent of the precipitation shield*** (Brennan and Lackmann 2005). But perplexing questions remained concerning the IP feature and its predictability. For example, why were models unable to predict this feature given that it formed within the observational network ahead of a well-sampled upstream disturbance? A second journal publication (Brennan and Lackmann 2006a) explored the fundamental nature of the precipitation feature from an observational perspective. This analysis ***demonstrated that elevated upright and conditional symmetric instability were present in the region of IP development.*** Numerical models do not parameterize slantwise convection, and have difficulty representing elevated convection as well. A third journal manuscript (Brennan and Lackmann 2006b) addressing modeling aspects of this event has been completed and is ready for submission as of this writing. It was found that using the Weather Research and Forecasting model, run with grid spacing as small as 1 km, that elevated and perhaps slantwise convection was generated in a model forecast. However, sensitivity to choice of initial condition data, specifically the moisture analysis, appears to have played at least as large a role in the forecast failures as did the model physics.

Results of this research were presented on numerous occasions and to a variety of audiences, using several different means. It is our contention that analysis of observational data such as radar and satellite imagery, in conjunction with PV concepts, would aid forecasters in anticipation of model biases in future events of this type. Therefore, an additional manuscript along with VISITVIEW presentations, were developed in order to emphasize the utility of PV methodology in forecasting.

b.) February 2004 winter weather threat and coastal cyclone event

A particularly challenging winter storm QPF scenario developed over the southeastern U.S. and mid-Atlantic region during the period from 15–17 February, 2004. During this complex event, model guidance proved inconsistent. Sub-freezing air in place across the region, in conjunction with a strong upper disturbance, indicated the potential for a major snowstorm. However, the heaviest precipitation remained offshore and the major population centers avoided winter storm conditions. However, model forecasts had indicated sufficient inland QPF to create headaches for forecasters, and the inconsistent model performance for this event warranted further investigation.

Although tangential to her M.S. thesis work, master's student Kelly Mahoney examined the sensitivity of the model QPF and cyclogenesis forecasts to the choice of model convective parameterization scheme (Mahoney and Lackmann 2006b). It was found that not only was the character and strength of the coastal cyclogenesis strongly affected by the CP scheme choice, but also that ***the coastal front location and strength were impacted simply by changing the Betts-Miller-Janjić scheme to the Kain-Fritsch option.*** A journal article discussing this work appeared in the journal *Weather and Forecasting* in August, 2006.

As with the January 2000 cyclone event, PV diagnosis proved valuable in identifying features of the numerical forecast that were dictated by CP scheme activity. Owing to the lower predictability of such features (due, in part, to the inherent limitations of CP schemes), it is advantageous for forecasters to identify those aspects of the model forecast. A VISIT presentation and journal article in *Weather and Forecasting* (Brennan et al. 2006) were thus prepared ***to introduce the PV methodology to the operational forecasting community***.

c.) The impact of model representation of microphysical processes on QPF;

In some notable winter weather events, as well as some cases in which numerical guidance indicated a threat of winter weather that did not materialize, it was noted that precipitation was being generated by numerical models that took place in environments that were thermodynamically unfavorable for precipitation growth by the Bergeron process. In some cases, the forecasted cloud-top temperatures were as warm as 0°C with several tenths of inches of grid-scale precipitation falling, whereas little or no precipitation was observed. The goal of a research project undertaken by master's student Nicole Haglund was to determine to what extent model QPF sensitivity in these "warm cloud" scenarios is attributable to the ice nucleation temperature and other aspects of the model microphysics scheme.

As discussed in the original CSTAR proposal, several cases have been documented in which the NCEP Eta model produced precipitation in "warm cloud" situations. Correspondence with Dr. Brad Ferrier at NCEP encouraged us to further investigate this phenomenon, and when new graduate student Nicole Haglund arrived from the University of Oklahoma in January 2005, this research began. Owing to the timing of her start, Nicole has had to complete this research under funding from a different source. Nevertheless, she is scheduled to defend her M.S. thesis in October, 2006. During the period in which she received CSTAR support, Nicole learned how to run the WRF model and has selected two case studies for detailed analysis: (i) the 2–3 December 2000 North Carolina snow event, and (ii) a 21-22 January 2003 "warm cloud" event. She has successfully completed WRF experiments using different model microphysics options and is well underway with the analysis of the model output.

A test of the warm-cloud QPF error hypothesis was conducted by running control and experimental WRF simulations, first for the 21-22 January 2003 event. In the control simulation, the Ferrier microphysics scheme (as used in the operational NAM) was run unmodified. In the experimental simulation, the ice nucleation threshold for the scheme was lowered from -5°C to -10°C. ***Consistent with the hypothesis, model QPF was lighter in the experimental run, more in line with observed totals.*** Nicole has presented these results at a regional CSTAR workshop.

In addition, Nicole has been running model simulations of the 2-3 December 2000 North Carolina snowstorm. This event was characterized by a massive positive bias in model QPF over central NC, with several Eta runs predicting over 2" of liquid equivalent precipitation for central NC, with less than 0.1" observed. Examination of model forecast sounding for this event indicated the presence of fairly warm cloud top temperatures, approaching -10°C during the peak of the event. Here, we tested the hypothesis that the QPF overestimate was due to the microphysics scheme being overactive in this thermodynamic regime. However, ***results indicate that the model microphysics scheme was not the cause of the model failure in this case***, as similar QPF values were obtained in WRF simulations with various microphysics schemes, as well as different ice nucleation and glaciation thresholds set in the Ferrier scheme.

Documentation from NCEP for storms during the winter of 2000-2001 suggested that problems with sea-surface temperature (SST) representation in the models may have been to blame for some of the forecasting difficulties. Therefore, Nicole has experimented with SST conditions (Fig. 3) for the 2-3 December 2000 event as well, finding considerable sensitivity to this choice. However, perhaps the most important result of all this research is that the WRF-ARW model used here provided excellent QPF guidance regardless of microphysics or SST settings.

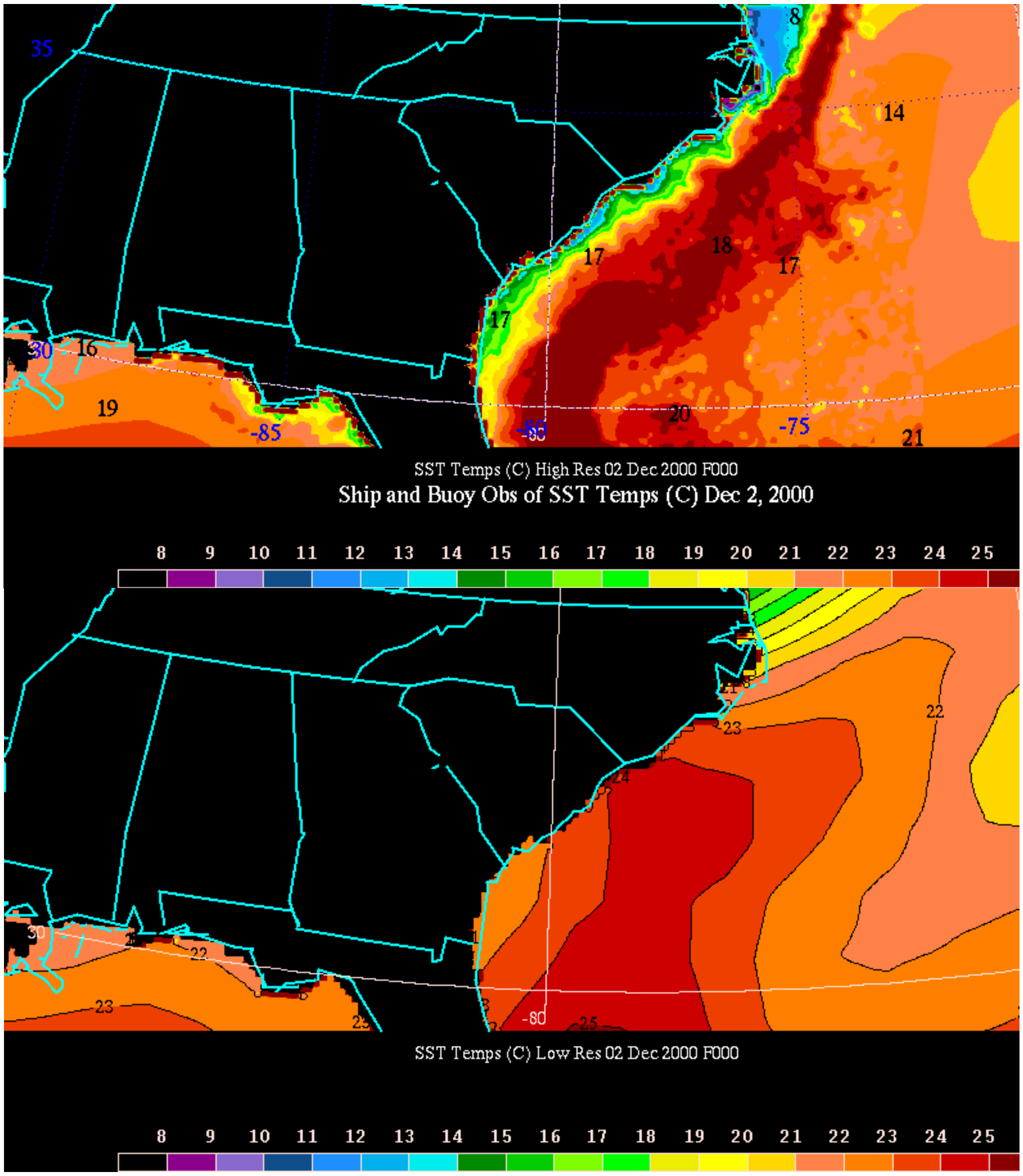

Fig. 3. Sea-surface temperature comparison from 12-km WRF model output: (a) SST field enhanced by high-resolution AVHRR data used in WRF initial condition; (b) Reynolds 1° analysis used in control model run.

3.) Tool and technique development

During the sharing and presentation of the research described above in subsections 1.) and 2.), several NWS forecasters and science officers indicated that it would be useful to describe the PV techniques used in Brennan and Lackmann (2005, 2006) and Mahoney and Lackmann (2006a, b) in a way that was useful to operational forecasters. So, Mike Brennan took the lead on writing a new paper aimed at the operational community advocating the use of lower-tropospheric PV diagnosis to identify the signature of latent heat release in an operationally useful fashion. This manuscript, Brennan et al. (2006), has been submitted to *Weather and Forecasting*. In addition to this manuscript, Mike Brennan developed PV-based AWIPS procedures for use on the forecast floor, and a VISIT session for the southeastern NWS offices was conducted as well. This work was also presented at the AMS WAF/NWP conference as well as at a regional CSTAR meeting in October, 2005.

Another research tool that was often utilized in our work was the WRF model. In response to forecaster inquiries and requests, Mike Brennan also spent time during the summer of 2005 working with Jonathan Blaes of the Raleigh NWSFO to set up a version of the WRF to run on a local workstation in that office. Additional technology transfer activities will be discussed later in this report. VISIT sessions conducted by Gary Lackmann on 3 and 7 June 2004 presented general NWP information and WRF model background to a large audience of operational forecasters.

4.) Climatological baseline studies

a.) Quantitative precipitation estimation (QPE) and precipitation mapping.

During all of the previous studies dealing with QPF, it was apparent that an observational precipitation baseline analysis would be useful for high-impact precipitation case studies. The focus of M.S. student Josh Palmer (working with Lian Xie) was to utilize results obtained via multivariate linear regression to produce gridded, multi-resolution precipitation maps for various high-impact precipitation events. As an example, such an analysis was developed for 15 September 1999, the day of heaviest precipitation associated with Hurricane Floyd. Josh and collaborators described the technique above as kriging with external drift (KED). The encompassing objective in doing the above geostatistical modeling was to formalize an algorithm that would combine all of the piecemeal programming required to create accurate observational precipitation analyses. As a result of successfully reaching these objectives, a beta build of this algorithm was completed in April, 2005; this is now called the Multi-Predictor Precipitation Mapping Model (M2P2M).

The beta M2P2M was developed using data from 15 September 1999 and as such was initially ill-suited to run on additional cases. Therefore, the first universal, semi-automated M2P2M was created in May 2005, along with documentation, numerous enhancements that, for example, improve model efficiency and allow us to produce event precipitation maps (i.e., maps of multi-day precipitation accumulations), and added features that allow us to perform statistically based sensitivity tests on the output. To test and verify these improvements, we commenced our second case study: 8 September 2004 (Hurricane Frances; day of heaviest North Carolina precipitation) and also updated the NCSU in-house rain gauge database to include 2004 data for GA, KY, NC, SC, TN, VA, and WV. The final period of research utilized this model version in 2-4 additional cases: one tropical and the remainder cool-season events and will investigate and interpret model performance and related sensitivity experiments as well as compare model performance at event and daily time scales.

b.) Precipitation patterns accompanying different cold-air damming (CAD) scenarios;

Based upon the earlier work of Wendy Stanton (Stanton, 2003), graduate student Tom Green studied CAD erosion patterns, and the accompanying precipitation distributions associated with each. Tom completed and successfully defended his M.S. thesis, under the advisement of Al Riordan, in December 2005.

Earlier studies had produced very coarse-resolution composites of CAD and CAD-erosion scenarios based on NCAR/NCEP global reanalysis 2.5 degree data. Here, *higher-resolution* versions of these composites have been constructed, with emphasis on documentation of the patterns of precipitation accompanying the different CAD patterns. Tom Green adapted compositing software to work with higher-resolution Rapid Update Cycle (RUC) and North American Regional Reanalysis (NARR) gridded datasets, checked these data sources against manual analyses, and evaluated three different gridded precipitation datasets for use in defining the precipitation patterns. For example, a comparison of sea level pressure for 12 UTC 16 February 2003 between the NCAR/NCEP global analysis and the RUC analysis is shown in Fig. 4. Note the additional level of detail in the RUC analysis, particularly the inverted trough extending northward to the east of the Delmarva region.

Tom completed his evaluation of three precipitation datasets to use as ground truth to characterize mesoscale spatial and temporal patterns associated with CAD in the Southeast United States. In this evaluation, Tom compared the precipitation fields with regional surface gage reports and snow-cover maps for a variety of CAD events. He determined that the NARR dataset was comparable to the other two and that it was an appropriate choice to complement the RUC analyses, since the NARR 32-km grid spacing is comparable with a RUC 40-km grid. Thus, the NARR dataset is the choice for representing the precipitation fields.

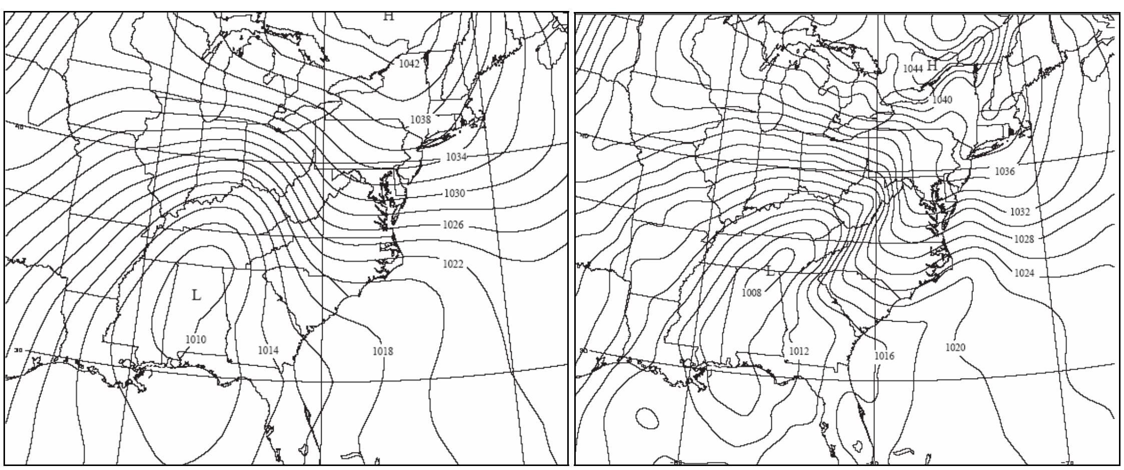

Fig. 4. Comparison of CAD event representation with NCEP/NCAR global reanalysis (a) with RUC 40-km analysis (b), for sea level pressure (contour interval 2 hPa) at 12 UTC 16 February 2003.

Tom downloaded the RUC and NARR grids for each of the 124 CAD cases detected by the CSTAR CAD-detection algorithm developed by Bailey et al. (2003) for the period January 2000-December 2004. Tom classified each case by the CAD erosion scenario defined by Stanton (2003) and created composites based on the different erosion scenarios. The five erosion scenarios include Northwest Low, Northwest Low with Cold Front, Southwest Low, Coastal Low, and Residual Cold Pool.

The RUC composite grids include variables such as mean sea level pressure, temperature, relative humidity, and geopotential height. Figure 5 gives an example of one of these composites, showing a 4-panel plot of the Northwest Low scenario, including times starting 24 hr before and ending 6 hr after CAD demise. These panels show much greater detail than was possible with the previous 2.5 degree data.

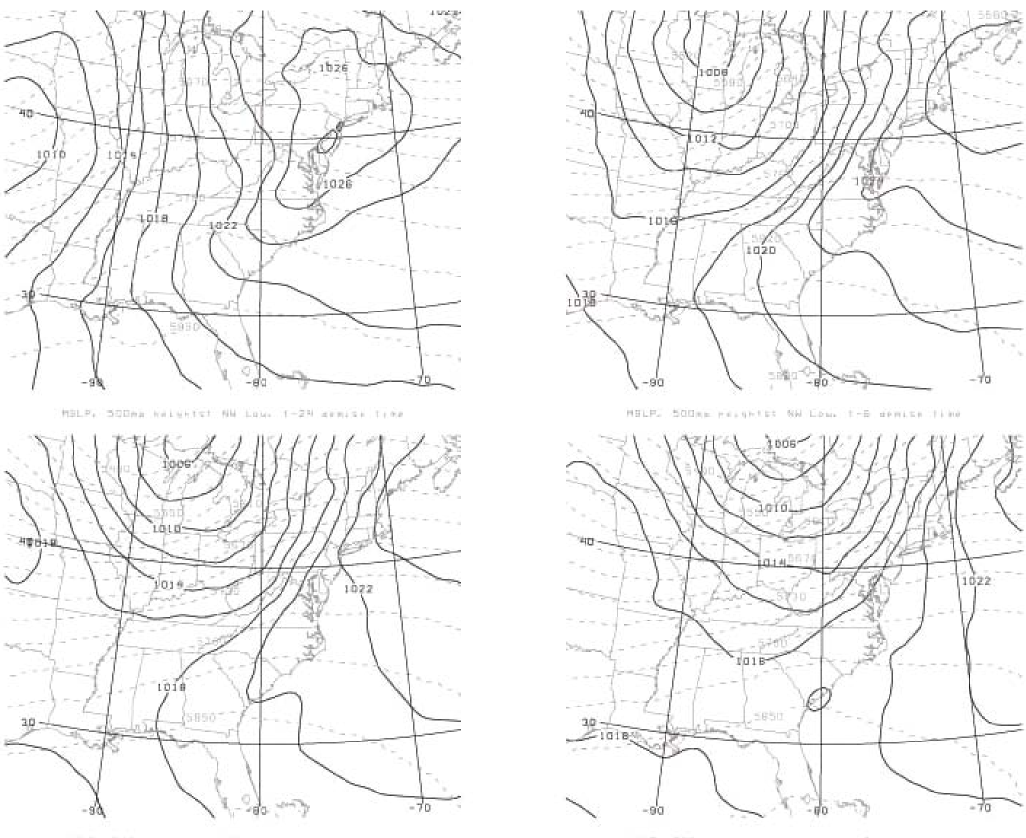

Fig. 5. Composite for NW Low CAD events using RUC 40-km grid spacing. Sea level pressure (solid; contour interval, 2 mb) and 500-mb height (dashed; contour interval, 30 dam). Top-left panel is 24 hours before demise, top-right panel is 6 hours before demise, lower-left panel is at demise time, and lower-right panel is 6 hours after demise.

Once the major datasets were obtained, Tom's focus was to determine differences between “wet” cases and “dry” cases among different erosion scenarios. The first candidates for analysis were the NW Lows, SW Lows, and Coastal Lows, since Residual Cold Pool cases are defined by their lack of synoptic features, and NW Lows with Cold Fronts made up a very small percentage of the cases.

One question forecasters face at the outset of a CAD event is how the given synoptic or mesoscale precipitation regime will evolve. For example, some NW lows produce abundant precipitation in the Carolinas, while others do not. Furthermore, one might wonder if some cases initially classified as SW lows could later better be classified as NW lows. To help address these types of questions, Tom designed an objective method to identify similar maps by computing the correlation coefficient, r, based on grid-point values. In one application, the composite MSLP sequence for each erosion scenario was compared to that of every MSLP map of every case from 6 hours before formation to 12 hours after CAD demise. The top r value from each case was averaged for 6-hour intervals from 24 hours before demise to 6 hours after demise to obtain an average r value for the entire case.

The cases most similar to that of the composite for each scenario were then examined. For each erosion scenario, the four "best" cases each included at least one "wet" case and one "dry" case, so differences between these groupings were again considered. Trends that were noted during these four cases were then expanded to all cases from a given erosion scenario. Different thresholds of values for quantities such as relative humidity, wind speed, and vorticity were tested to see if certain "critical values" could be determined to distinguish between "wet" and "dry" storms. One quantity that can be used to distinguish between "wet" and "dry" SW Lows is temperature advection at 850 mb. For example, in a particular part of the CAD region, when warm advection is greater than 5×10^{-5} K/s over a majority of the gridpoints, the case is typically "wet."

To summarize, some highlights of Tom Green's CAD climatology research include:

- Data from the RUC model were used to create updated CAD erosion composites, increasing the spatial and temporal resolution from that presented by Stanton (2003).
- Differences in areal coverage of precipitation were noted between erosion scenarios, with SW Low events showing greater coverage than Coastal and NW Low type CAD events.
- This research was presented at a regional CSTAR meeting in October 2005.
- During early December, 2005, Tom Green completed and defended his M.S. thesis, and has since taken a job with the NWS as a forecaster in Marquette, Michigan.

B.) Publications, Presentations, and Technology Transfer Activities

Areas of focus included **technology transfer and information sharing** designed to increase the relevance of this work to operational forecasters. These activities included: (i) presentation of research and educational materials via the VISITview software; topics included the use of potential vorticity (PV) in operations, the Weather Research and Forecasting (WRF) model, and coastal cyclogenesis issues; (ii) publications and conference presentations; (iii) development of training materials and reference guides, and (iv) meetings, workshops, and site visits.

1.) Refereed publications

Appel, W. K., A. J. Riordan, and T. A. Holley, 2006: An objective climatology of Carolina coastal fronts. *Weather and Forecasting*, in press.

Bailey, C. M., G. Hartfield, G. M. Lackmann, K. Keeter, and S. Sharp, 2003: An objective climatology, classification scheme, and assessment of sensible weather impacts for Appalachian cold-air damming. *Wea. Forecasting*, **18**, 641–661.

Brennan, M. J., and G. M. Lackmann, 2005: The impact of incipient precipitation on the precipitation distribution of the 24–25 January 2000 snowstorm. *Mon. Wea. Rev.,* **133,** 1913–1937.

Brennan, M. J., K. Keeter, A. J. Riordan, and G. M. Lackmann, 2005: Expanding horizons with an NWS intern course. *Bull. Amer. Meteor. Soc.,* **86**, 1407–1409.

Brennan, M. J., G. M. Lackmann, and S. E. Koch, 2004: THE MAP ROOM: The Impact of a Split-Front Rainband on Appalachian Cold-Air Damming Erosion. *Bull. Amer. Meteor. Soc.,* **85**, No. 7, 935–939.

Brennan, M. J., and G. M. Lackmann, 2006: Observational diagnosis and model forecast evaluation of unforecasted incipient precipitation during the 24–25 January 2000 East Coast cyclone. *Mon. Wea. Rev.,* **134,** 2033–2054.

Brennan, M. J., G. M. Lackmann, and K. M. Mahoney, 2006: Potential vorticity (PV) thinking in operations: Diagnosing the dynamical impact of latent heat release in numerical model output. *Wea. Forecasting, in review*.

Mahoney, K. M., and G. M. Lackmann 2006a: The Sensitivity of Numerical Forecasts to Convective Parameterization: A Case Study of the 17 February 2004 East Coast Cyclone. *Weather and Forecasting*, 465–488.

Mahoney, K. M., and G. M. Lackmann 2006b: The effect of upstream convection on downstream precipitation. *Weather and Forecasting, in press*.

2.) Theses and Dissertations

Brennan, M. J., 2005: The Formation and Impact of an Incipient Cold-Air Precipitation Feature on the 24-25 January 2000 East Coast Cyclone. Ph.D. Dissertation, Dept. of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 401 pp. (Available online at: http://www.lib.ncsu.edu/theses/available/etd-06272005-152529/unrestricted/etd.pdf).

Green, T. A., 2005: Cold Air Damming Erosion and Associated Precipitation in the Southeastern United States. M.S. thesis, Dept. of Marine, Earth, and Atmospheric

Sciences, North Carolina State University, 270pp. (Available online at: http://www.lib.ncsu.edu/theses/available/etd-01022006-235238/unrestricted/etd.pdf).

Mahoney, K. M., 2005: The effect of upstream convection on downstream precipitation. M.S. thesis, Dept. of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 204 pp. (Available online at: http://www.lib.ncsu.edu/theses/available/etd-07212005-101546/unrestricted/etd.pdf).

3.) Conference preprints and presentations

Brennan, M. J., and G. M. Lackmann, 2004: The role of antecedent precipitation in the development of the 24–25 January 2000 U.S. East Coast snowstorm. Preprints, *20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction*, Seattle, WA, Amer. Meteor. Soc.

Brennan, M. J., and G. M. Lackmann, 2005: Analysis of a cold-air precipitation event: Observational diagnosis and numerical model sensitivity. Preprints, *21st Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc.

Brennan, M. J., and G. M. Lackmann, and K. M. Mahoney, 2005: Potential vorticity (PV) thinking in operational weather forecasting: Diagnosing the dynamical impact of latent heat release in model output. Preprints, *21st Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc.

Lackmann, G. M., and W. M. Stanton, 2004: Cold-Air Damming: Physical Erosion Mechanisms and Model Representation. Preprints, *20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction*, Seattle, WA, Amer. Meteor. Soc.

Mahoney, K. M., and G. M. Lackmann, 2005a: The effects of organized upstream convection on downstream precipitation. Preprints, *21st Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc.

Mahoney, K. M., and G. M. Lackmann, 2005b: The sensitivity of numerical forecasts to convective parameterization: A case study of the 17 February 2004 East Coast cyclone. Preprints, *21st Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc.

Mahoney, K. M. and G. M. Lackmann, 2005c: The effects of organized upstream convection on downstream precipitation: Physical processes and model representation. Preprints, *32nd* ***Conference*** *on Radar Meteorology/11th Conference on Mesoscale Processes*, Albuquerque, NM, Amer. Meteor. Soc.

4.) Other presentations

- The NCSU CSTAR group attended a CSTAR workshop at NWS Headquarters from 9–10 July 2003. We presented findings from CAD climatological research, CAD erosion research, and split front-CAD interaction research to other CSTAR participants and NWS personnel. The meeting also included fruitful discussion of technology transfer issues, metrics by which to gauge the impact of research on operations.

- Ms. Wendy Stanton completed and defended her M.S. thesis entitled "*An Analysis of the Physical Processes and Model Representation of Cold Air Damming Erosion*". Her successful defense took place on Tuesday 29 July 2003. Although most of her research was supported by a previous award, this presentation came within the funding period for this project.

- On 3 June, and twice on 7 June, 2004, Gary Lackmann conducted VISIT presentations related to NWP materials as it related to specific forecasting problems in the southeastern U.S. These sessions lasted 60-90 minutes, and a survey conducted by Kermit Keeter of NWS Raleigh indicated that 76 NWS personnel participated in the sessions.

- During September 2004: Kelly Mahoney gave her graduate student seminar on upstream convection project.

- WRF model training VISIT sessions were given by Gary Lackmann in November 2004.

- A VISIT session entitled "The Impact of Latent Heating on Extratropical Cyclones: Using the PV Framework in Operations" was prepared and delivered to NWS CSTAR offices and other Eastern Region offices on 7 December 2004 and again on 16 December 2004.

- Kelly Mahoney delivered her M.S. thesis defense concerning upstream convection on July 7th 2005; two detailed case study analyses completed.

- Mike Brennan completed and defended Ph.D. dissertation entitled: "The Formation and Impact of an Incipient Cold-Air Precipitation Feature on the 24–25 January 2000 East Coast Cyclone" on 15 June 2005.

- A presentation on upstream convection was given by Kelly Mahoney and Gary Lackmann at the NOAA/NWS Hydrometeorological Prediction Center (HPC) on August 3rd 2005.

5.) Site visits and workshops

- The Raleigh NWSFO convened a regional CSTAR conference held in Raleigh October 16-17, 2003. At this conference, major findings were presented from all earlier CSTAR works.

- A regional CSTAR meeting was held at NC State's Centennial Campus on October 6th and 7th 2005. This meeting featured research presentations by NC State graduate students and faculty, and was attended by SOOs from 9 regional offices, along with several lead forecasters and representatives from NWS Eastern Region HQ and NWS HQ.

- Joshua Palmer and Michael Brennan attended the Columbia, SC training day on 26 August 2004 to provide input and perspective on CSTAR related research for representatives of numerous CSTAR offices.

6.) Web pages and other CSTAR communication

- Jonathan Blaes (NWS RAH) set up a new CSTAR mailing list (nws.er.mid.atlantic.cstar@noaa.gov) which allows members to communicate with the group as a whole via one email address but it also allows the group to go back and view previous messages and discussions, view imagery and other attachments.

- A web page containing numerous CSTAR-related collaborative research results, case summaries, and powerpoint and VISITVIEW presentations is located at the following URL:

C.) Personnel

Student researchers who were supported 50% or more by CSTAR funds:
Kelly Mahoney (Graduate student, M.S. completed, Ph.D. candidate)
Tom Green (Graduated December 2005, M.S.)
Mike Brennan (Graduated August 2005, Ph.D.)
Nicole Haglund (Graduate student, M.S. candidate)
Joshua Palmer (Graduate student, M.S. candidate)
Paul Suffern (Undergraduate student)

This project has supported, so far, one completed Ph.D. (Brennan), and 2 completed M.S. degrees (Mahoney and Green). Palmer and Haglund are very close to completing their degrees as well, with Haglund scheduled to defend her thesis in October 2006.

Where are these students now?
Tom Green is now working with the NWS as a forecaster in Marquette, MI
Mike Brennan is working as a postdoc at the Tropical Prediction Center (TPC)
Palmer is working for the Southeast River Forecast Center
Kelly Mahoney is working towards her doctoral degree
Nicole Haglund is scheduled to graduate in December, 2006
Paul Suffern recently completed his M.S. thesis on a non-CSTAR research project.

D.) Tangential and Collaborative Developments

In addition to these primary research areas, an outcome of the CSTAR group meeting of October 2005 was the extension of research into northwest-flow snow events along the windward slopes of the Appalachians. Steve Keighton of NWSFO Blacksburg initiated this effort, which continues as of this writing. This is research not directly supported by this CSTAR award, but the coordination of this project began under the auspices of CSTAR collaboration.

Kelly Mahoney, Mike Brennan, and Gary Lackmann attended WRF Tutorial at NCAR in Boulder, CO from 28 June to 4 July 2004 to learn about WRF model for use in CSTAR related research activity.

An NWS internship course was developed, in part to strengthen the NWS-NCSU collaboration, beginning in the spring of 2004. See Brennan et al. (2005) for details.

E. Reference:

Most of the references are included in the "refereed publications" section above, with the following exception:

Stanton, W., 2003: An analysis of the physical processes and model representation of cold air damming erosion. M.S. thesis, Dept. of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 207 pp. [Available from NCSU Libraries].