Final Report[1]

to the
National Oceanic and Atmospheric Administration
Collaborative Science, Technology & Applied Research (CSTAR) Program

Prediction of Heavy Banded Snowfall: Resolution Requirements, Microphysical Sensitivity, and Hydrometeor Lofting

NOAA Award: NA16NWS4680003
Award period: 5/1/2016 – 4/30/2020 (including 1-year no-cost extension)
Final Report

PIs: Gary M. Lackmann
Department of Marine, Earth, & Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina

Martin Baxter
Department of Earth and Atmospheric Sciences
Central Michigan University
Mount Pleasant, Michigan

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Contact Person:
Dr. Gary M. Lackmann
Department of Marine, Earth, & Atmospheric Sciences
Box 8208
North Carolina State University
Raleigh, North Carolina 27695-8208
Phone: (919) 513-4367
Fax: (919) 515-7802
gary@ncsu.edu

[1] This report format follows the OMB guidance on performance progress reporting.

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I. ACCOMPLISHMENTS

*1. What were the major proposed **goals, objectives, and tasks** of this project?*

A central hypothesis of the proposed research is that banded snowfall events are accompanied by regions, near or upwind of the bands, where *snow lofting* is taking place. This hypothesis is based on several observational and numerical studies that document examples of upward atmospheric vertical motion that exceeds the terminal fall velocity of snow. Further, we hypothesize that lofting, in conjunction with extended hydrometeor residence time, could substantially affect surface snowfall accumulations and distributions. This is in part due to horizontal transport of falling snow (advection) due to the significant time required for snow to fall to the surface in the presence of strong ascent. Previous studies documented lofting in generating cells and elevated convection. Here, we proposed an additional region of lofting in the lower and middle troposphere in close proximity to the bands. There are numerous implications, including the need for forecasters to account for a spatial offset between the location of strongest ascending air motion and surface snowfall, and the need for numerical weather prediction (NWP) models to represent accurately the terminal fall velocity and advection of snow.

Our second goal was to design an objective snowband detection algorithm, and use this in evaluation of high-resolution model performance in snowband forecasting. Although previous studies proposed quantitative definitions of snowbands, an objective, automated scheme for band detection was not yet available. Such an algorithm is of great potential utility both for use in real-time band detection, and in detecting bands in operational NWP model forecasts. However, our main objective in developing an automated band detection algorithm was to facilitate verification of operational NWP forecasts of snowbands, in particular the High-Resolution Rapid Refresh (HRRR) model. This allowed us to quantify model forecast skill in snowband prediction.

Operational forecasters utilize high-resolution forecasts during winter precipitation events, including banding cases. It is thus important that forecasters have information about the reliability of these high-resolution models for these events. The goals of this part of the project were to evaluate the accuracy of NCEP convection-allowing models for cases of heavy banded snowfall, and to communicate the results of this evaluation in a way that allows forecasters to better understand model strengths and limitations. HRRR forecasts and analysis/observational data for the 2016–2018 winter seasons were archived and analyzed, and form the basis of this evaluation. As the project progressed, this this component of the work essentially merged with the band detection task.

An additional goal was to document and understand the sensitivity of snowband forecasts to choice of model microphysics schemes.

2. What was accomplished under each task?

The accomplishments were detailed in each of the progress reports, and we will not repeat all of that material here. These results are presented in journal publications and online presentations, delivered at conferences, workshops, webinars, and seminars. Here, we present a condensed version of our accomplishments.

We tested the snow-lofting hypothesis directly by identifying regions of snow lofting in model simulations from the Weather Research and Forecasting (WRF) model. In collaboration with Greg Thompson of NCAR, we added the mass-weighted terminal snow fall velocity and the vertical snow flux as output variables from the Thompson microphysics scheme in the WRF model (which is the underlying model used as the operational HRRR model). Analysis of five high-resolution simulations of banded and non-banded snowfall events indicate the presence of upward snow flux (lofting) in the banded cases, but not in a non-banded case. A journal article manuscript on this topic was published in the AMS journal *Monthly Weather Review* (Lackmann and Thompson 2019).

As a part of this work, we recognized the utility of several customized diagnostics from the model microphysics scheme, for example, depositional snow growth and vertical snow flux. We continue to explore the utility of vertical snow flux as a diagnostic model output variable, along with other microphysical variables output from the Thompson scheme, for use in the prediction of heavy snowfall. Results were presented on several occasions to operational forecasters and at NCEP, as discussed below.

In modifying the Thompson microphysics scheme to output the vertical snow flux, we also realized that other potentially useful quantities could be output, including depositional and total snow growth rate (Fig. 1). These fields have the potential to aid forecasters in the identification and anticipation of heavy snowfall events. An additional note is in preparation for submission to the journal *Weather and Forecasting* on the topic of potentially useful predictive parameters that are not typically output from NWP models. PI Lackmann also delivered a presentation on this topic at the AMS Annual Meeting in Phoenix in the 9th Conference on Transition of Research to Operations on 10 January 2019.

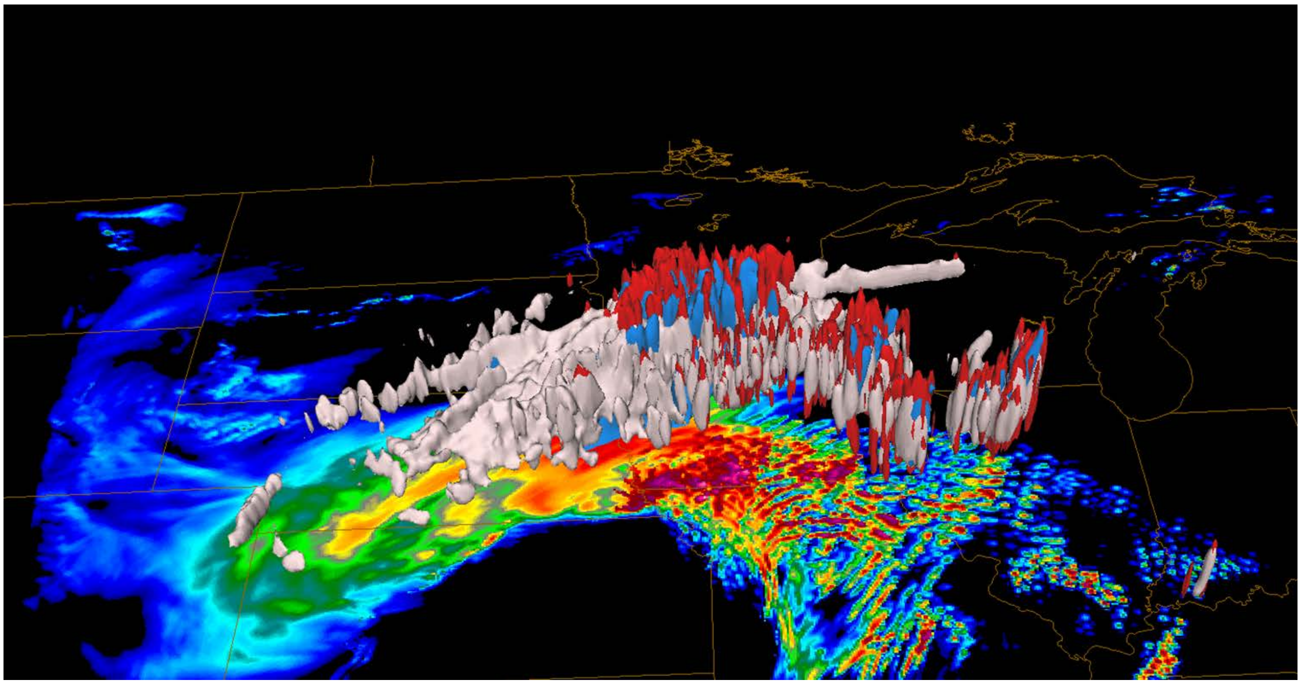

Figure 1. Non-traditional NWP output valid 14 UTC 2 Feb 2016 (hour 20 of 3-km grid length WRF simulation): Composite reflectivity (dBZ, color shaded), snow mixing ratio (blue isosurface, $1.5\text{x}10^{-3}$ kg kg^{-1}), upward vertical snow flux (red isosurface, small positive value), and depositional snow growth (white isosurface, $2.5\text{x}10^{-7}$ kg kg^{-1} s^{-1}).

Graduate student Jacob Radford developed and tested an automated snowband detection algorithm and applied it to winter storm events during the 2014-2018 winter seasons, using observed radar data and model output (HRRR). He optimized the detection algorithm and used it to evaluate the model performance in band prediction; a journal article on this topic was published in the AMS journal *Weather and Forecasting* (Radford et al. 2019).

Jacob Radford completed and defended his MS thesis, and was the lead author on the *Weather and Forecasting* article. The main accomplishments and findings presented in this paper are:

- An automated band-detection algorithm was developed and successfully applied to both observed and model-simulated (HRRR) radar fields.
- The climatology of observed banded snowfall (not including lake-effect bands) features two distinct maxima in the U.S. Northern Plains, and in New England (Fig. 2)

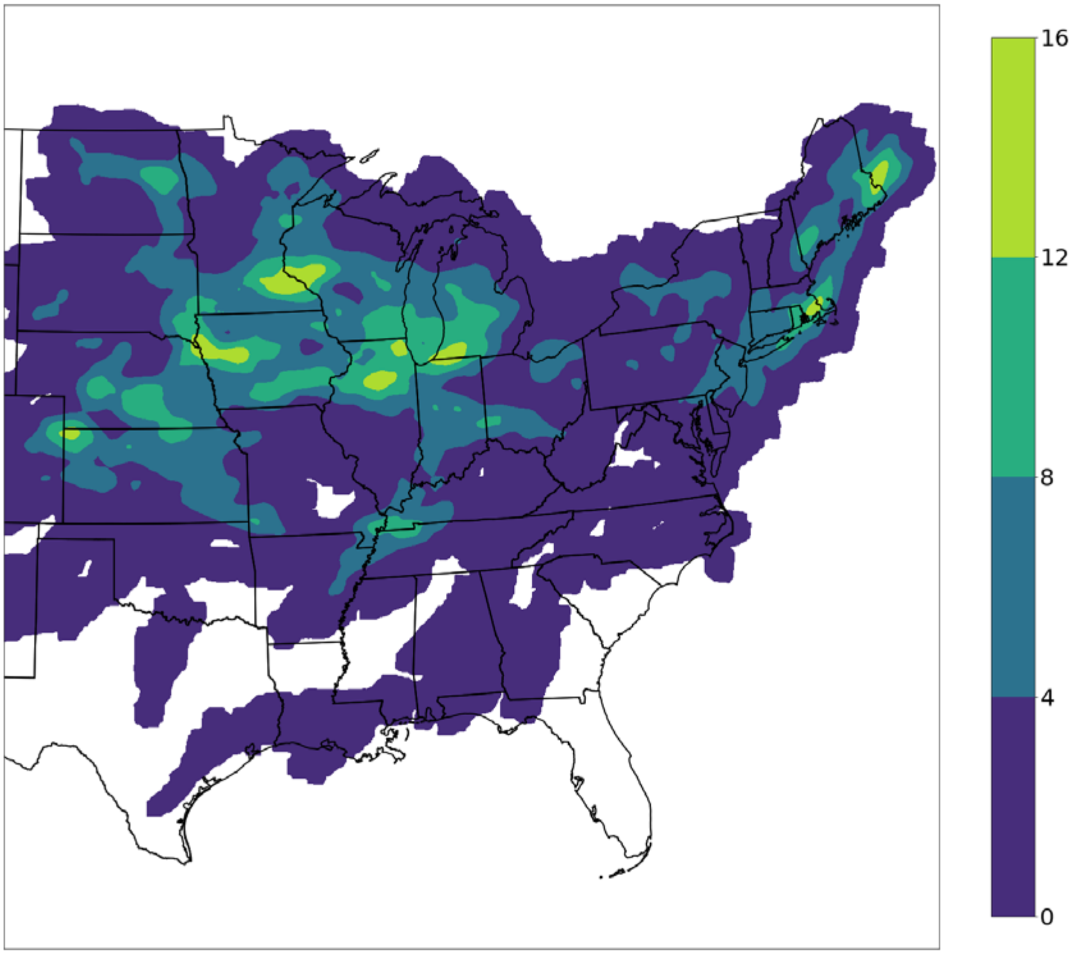

Figure 2: The total number of hours of banded snow for locations east of 104°W for the 2015–16, 2016–17, and 2017–18 winter seasons.

- The geospatial distribution of band frequency was similar between the observations and the HRRR forecasts, but with a significant positive bias in the forecasts.
- The positive frequency bias in the HRRR may be due, especially in parts of the U.S. upper Midwest, to limitations in observed radar coverage.
- Using traditional measures, snowband predictability in the HRRR is poor, but allowing fuzzy time verification (an offset up to 3 hours) significantly improved the results (Fig. 3). This suggests use of ensemble methods for band prediction.
- Object-oriented methods resulted in poor scores when applied in a deterministic sense, but in considering a variety of forecast lead times (time-lagged ensemble approach), results were more promising, with nearly 70% of cases exhibiting at least one forecast lead time demonstrating skill in an object-oriented verification metric.

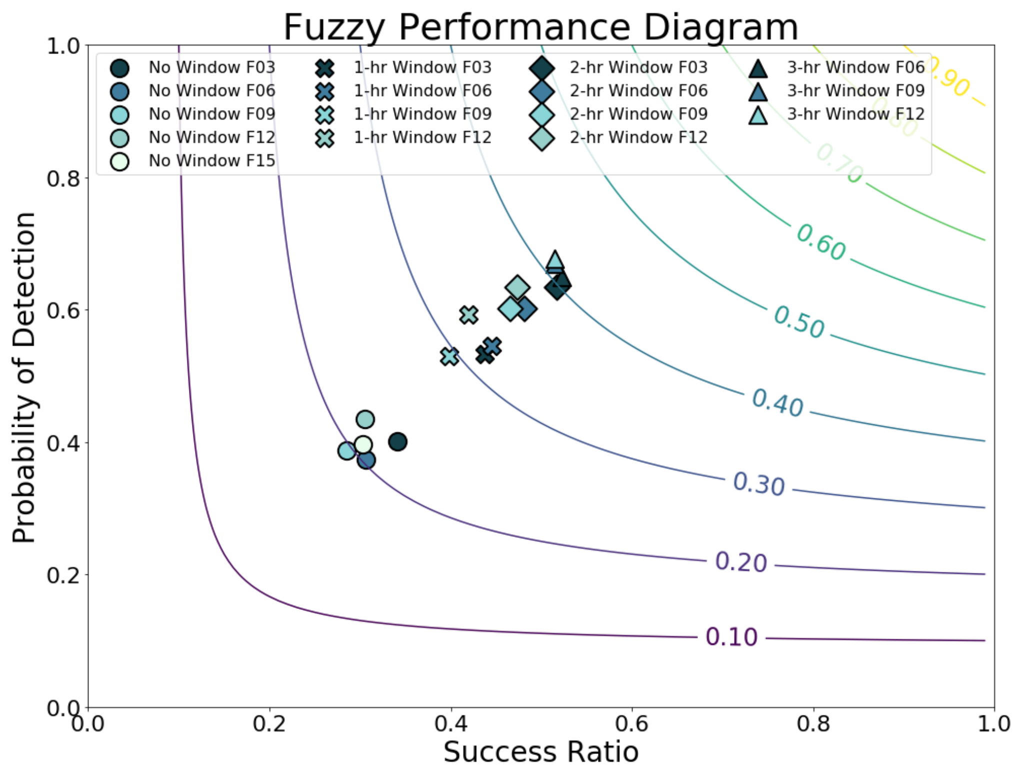

Figure 3: HRRR forecast performance evaluation using Roebber's (2009) performance diagram with fuzzy time windows. Contours indicate Critical Success Index values, with performance improving towards the top right of the diagram.

PI Baxter, working with NWS SOO Phil Schumacher and undergraduate students at CMU, undertook analysis of differences between cases that were well forecast versus poorly forecasted events. Using the 13-km RAP data as a proxy for the observations in order to analyze the 17 best and 17 worst forecasts, one of the largest differences was found to be the distance between the maximum frontogenesis and the location where equivalent potential vorticity equals zero (Fig. 4).

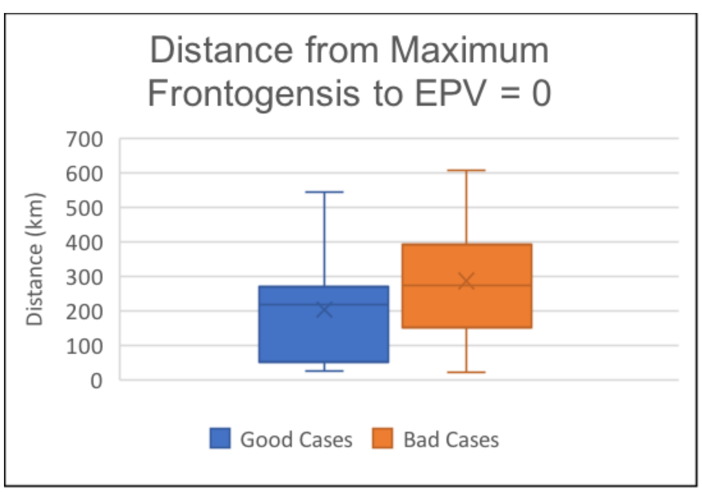

Figure 4. Boxplots demonstrating the distribution of distances between maximum frontogenesis and equivalent potential vorticity equal to zero, for 17 of the best forecast cases ("good", in blue) and 17 of the worst forecast cases ("bad", in orange).

In an effort to share our results with the operational forecasting community, we have delivered numerous presentations at conferences, and have attended and presented at the Weather Prediction Center's Winter Weather Experiment (WWE).

*3. Are the proposed project tasks **on schedule**? What is the cumulative percent toward completion of each task and the due dates?*

All proposed research has been completed. One or two additional journal articles may yet be prepared and submitted based on foundations originating in this work, but these are beyond the scope of the original proposal.

*4. What were the major completed **milestones** this period, and how do they compare to your proposed milestones?*

The primary milestones are listed below under the responses for professional development, dissemination, and (in Part II) products. These milestones are aligned with what we originally proposed.

5. What opportunities for training and professional development has the project provided?

NC State graduate student ***Jacob Radford*** obtained an M.S. degree via support from this project (December 2018). This project provided Jacob with opportunities to learn to use, and contribute to the development of the Model Evaluation Toolkit (MET) software package, including a visit to the Developmental Testbed Center (DTC) in June of 2018 to work with MET developers on snowband detection capabilities (see: https://dtcenter.org/news/2019/02/jacob-radford). Jacob has an exceptional technical skill set, and the foundation for his continuing work on ensemble data visualization for extreme weather, while under different support, was established with this project.

The Central Michigan University contribution to the project highlights the contributions and involvement of five undergraduate students. Though these students were involved for a sufficiently long time for authorship on a publication, two did present posters at the AMS student conference, and all five have gone onto either graduate school or to careers as forecasters. Two of the students enrolled in graduate school are continuing research on snow-related topics, with one poised to become a new leader in the use of GOES data to improve snowfall forecasting. It is clear that his involvement in the CSTAR project had a great influence on his decision to focus his research on snowfall. The unique pairing of a prominent researcher in Dr. Lackmann with Dr. Baxter's focus on undergraduate research has resulted in at least one student who looks to go on to a career with a focus on improving winter weather forecasts. Given that research on operational aspects of winter weather forecasting is somewhat limited in comparison to warm-season weather phenomena, our efforts in improving the pipeline of winter weather researchers have the potential to result in long-term benefits. The status of CMU students who were involved the project is detailed below.

- ***Sebastian Harkema*** – pursuing Ph.D., University of Alabama-Huntsville; published two papers in WAF on characteristics of thundersnow events. Awarded a NASA Future Investigators in Earth and Space Science and Technology grant to continue his research on thundersnow.

- ***Brandon Buckingham*** **–** forecaster at Accuweather
- ***Alex Smith*** **–** pursuing M.S. in Meteorology, Texas A&M University
- ***Adam Batz*** **–** NWS forecaster, Jackson, KY
- ***Jillian Goodin*** **–** pursuing M.S. in Meteorology, Northern Illinois University. Will be analyzing snowfall characteristics in future climate simulations

Each of these students gained experience in constructing and analyzing winter weather case studies, data analysis and visualization, and developing, writing, and delivering scientific presentations.

6. How were the results disseminated to communities of interest?

The results were disseminated via peer-reviewed journal articles (see Part II: Products), conference presentations (see Part II: Products), student theses and defense presentations (see Part II: Products), and via the Weather Prediction Center's Winter Weather Experiment (WPC WWE). Our WWE participation took place over several years, with two in-person visits during the experiment, and some remote participation. During the 2020 WWE, a remote presentation by PI Lackmann was followed by in-person participation by graduate student Radford. Radford's participation included a presentation and also a focus group that was designed to gain forecaster insights into ensemble data visualization for snowbands (related to a subsequent NOAA project).

Lackmann, Baxter, and Radford presented a progress update to NWS collaborators via online collaboration software on 15 November 2018; this discussion also involved WPC's Mike Erickson. Lackmann, Baxter, and Radford all presented at the AMS Annual Meeting in Phoenix, January 2019. PI Lackmann provided an update and seminar on 15 March 2019 via a webinar.

We presented examples of the vertical snow flux diagnostic both at the AMS Annual Meeting (Seattle, January 2017), and a regional NWS workshop held in Raleigh in late April 2017. An additional webinar will be presented on 13 December 2017 that features some of this work.

7. What do you plan to do during the next reporting period to accomplish the goals and objectives?

As discussed above, the goals and objectives of the project have been met and any subsequent work that is presented or published will be in addition to the original goals.

II. PRODUCTS

1. What were the major completed ***products or deliverables*** *this period, and how do they compare to your proposed deliverables?*

The products and deliverables align with those in the original research proposal.

a. The following publications resulted from this grant:

Lackmann, G. M., and G. Thompson, 2019: Hydrometeor lofting near mesoscale snow bands. *Mon. Wea. Rev.*, **147**, 3879–3899

Radford, J. T., G. M. Lackmann, and M. A. Baxter, 2019: An Evaluation of snowband predictability in the High-Resolution Rapid Refresh. *Wea. Forecasting*, **34**, 1477–1494.

b. The following conference presentations and seminars resulted from this grant:

2020 WPC WWE:

1) Lackmann, G. M. and J. T. Radford, Winter Weather NWP: Interpretations, Diagnostics, and HRRR Verification. WPC Winter Weather Experiment, 14 February 2020

2) Radford, J. T., Experimental Ensemble Visualization for Mesoscale Snowbands. WPC Winter Weather Experiment, 2 March 2020

AMS Annual Meeting, Boston, January 2020:

3) 19th Annual Student Conference Poster # S250 Evaluation of Convection-Allowing Ensemble Forecasts for Central U.S. Banded Snowfall Events **Jillian Rose Goodin**, Central Michigan Univ., Milan, MI; and M. A. Baxter

4) 30th Conference on Weather Analysis and Forecasting (WAF)/26th Conference on Numerical Weather Prediction (NWP) 6B.4 The Relationship between Simulated Reflectivity and Precipitation across Different Microphysics Schemes in a Banded Snowfall Event **Martin A. Baxter**, Central Michigan Univ., Mount Pleasant, MI

5) 30th Conference on Weather Analysis and Forecasting (WAF)/26th Conference on Numerical Weather Prediction (NWP) Poster 193, Verification and Visualization of Ensemble Snowband Forecasts **Jacob T. Radford**, North Carolina State Univ., Raleigh, NC; and G. M. Lackmann

AMS Annual Meeting, Phoenix, AZ, January 2019:

6) 14A.1 A Case for Operational Utility in Non-Traditional NWP Output Fields **Gary M. Lackmann**, North Carolina State Univ., Raleigh, NC

Northern Plains Weather Workshop, November 2018:

7) Expanding NWP output for analysis and forecasting of winter storms. St. Cloud, MN, 5 November 2018.

29th Conference on Weather Analysis and Forecasting (WAF)/25th Conference on Numerical Weather Prediction; AMS Denver, CO, June 4-8 2018:

8) The Impact of Microphysics Schemes in Convection-Allowing Simulations of Banded Snowfall. **Martin A. Baxter**, and P. N. Schumacher, J. T. Radford, and G. M. Lackmann

9) Investigation of Hydrometeor Lofting During Banded Snowfall Events. **Gary M. Lackmann**

10) Verification of High-Resolution Banded Snowfall Forecasts, **Jacob T. Radford**, G. M. Lackmann, and M. A. Baxter

11) *Winter Weather NWP, and Automated Detection of Mesoscale Snowbands*. (Lackmann and Radford), Webinar to NWS offices, 13 December 2017

AMS Annual Meeting in Seattle in January 2017:

12) Lackmann and Thompson, 2017; 28th Conference on Weather Analysis and Forecasting, 24th Conference on Numerical Weather Prediction). Recorded presentation available: https://ams.confex.com/ams/97Annual/videogateway.cgi/id/35861?recordingid=35861&uniqueid=Paper304563&entry_password=786921

NWS Raleigh Regional Workshop:

13) Lackmann and Radford, 28 April 2017: https://cimmse.wordpress.com/2017/05/01/2017-cstar-workshop-and-mid-atlantic-and-southeast-sub-regional-soo-meeting-held-in-raleigh/

c. The following graduate theses and dissertations resulted from this grant:

Radford, 2018: Verification of high-resolution banded snowfall forecasts. NC State University MS thesis, available from: https://repository.lib.ncsu.edu/handle/1840.20/36330

2. What has the project produced?

Results, presentations, and publications are described above. Other products include a case-study archive developed at CMU, a snowband detection algorithm developed by Jacob Radford, available to any who wish to use it, and versions of the WRF model with additional output from the Thompson microphysics scheme, developed by G. Lackmann and G. Thompson.

III. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

1. Which individuals have worked on this project?

Principal Investigators - North Carolina State University:
Dr. Gary Lackmann
Dr. Martin Baxter

Student Researchers – North Carolina State University:
Mr. Jacob Radford

Student Researchers – Central Michigan University:
Ms. Jillian Goodin
Mr. Sebastian Harkema
Mr. Brandon Buckingham

Mr. Alex Smith
Mr. Adam Batz

We have worked with Dr. Greg Thompson of NCAR on the modeling side of the project, and we have kept in touch with several individuals at the WPC, including Mike Erickson, Dave Novak, Mark Klein, and Jim Nelson. Previously, we also worked with Sara Sienkewicz until her departure from WPC. Jimmy Correia, Mike Bodner, and Kristin Harnos of WPC were also involved with discussions related to presentations and attendance at the WWE. Our original collaborators in the NWS were Phil Schumacher (SOO, NWS Sioux Falls) and Mike Evans (SOO, NWS Binghamton and Albany).

2. Has there been a change in the PD/PI(s) or senior/key personnel since the last reporting period?

No.

3. What other organizations have been involved as partners? Have other collaborators or contacts been involved?

In addition to the NOAA collaborators listed above, we have worked with the Developmental Testbed Center (DTC) at NCAR, and with collaborators such as Dr. Greg Thompson. See the following news item from DTC for example: https://dtcenter.org/news/2019/02/jacob-radford

IV. IMPACT

1. What was the impact on the development of the principal discipline(s) of the project?

The funding allowed Dr. Baxter to collaborate with NCSU on operationally relevant winter weather research, through providing some release from his teaching load, which is substantially higher than for those at more research-focused universities. The funding resulted in continued development of his research skill-set, including running WRF in a high-performance computing setting, maintaining and sharing a real-time data archive, and programming in Python, among others. In addition, his involvement in the project allowed him to make new connections in the winter weather forecasting community. Dr. Baxter's selection to chair the winter weather session in the weather and forecasting conference at the 100^{th} AMS Annual Meeting is evidence that the project has helped maintain his role in this community. Dr. Baxter is continuing work related to the project, in collaboration with Dr. Greg Thompson of NCAR, and plans to continue operationally focused winter weather research in the future.

Additional impacts include:

- We have identified hydrometeor lofting in numerical model simulations of snow bands, and we have demonstrated that this phenomenon has implications for the surface snowfall distribution.

- The results demonstrate a spatial offset between the regions of maximum upward air motion (which forecasters often focus upon) and the location where the snowfall reaches the surface.
- We have offered that upcoming field experiments seek to find observational evidence for these regions of lofting, should sufficient resources be available.
- We have identified a model output diagnostic of potential operational utility, the vertical snow flux. In fact, we have identified several microphysical quantities of potential operational value, and which are not typically output from models.
- We have developed an automated algorithm for the identification of banded snowfall, both in observed radar and model simulated radar.
- We have used the aforementioned algorithm to compute a HRRR model band climatology and an observed radar climatology, and we have compared the two.
- We have used both traditional skill scores, along with object-oriented methods, to evaluate the HRRR performance for banded snowfall cases.
- Using fuzzy verification in time, the HRRR shows some promise, but the lack of deterministic skill argues strongly for use of HRRR-based ensemble prediction systems such as the HRRRE.

2. What was the impact on other disciplines?

N/A

3. What was the impact on the development of human resources?

This was covered in item I.5, but is repeated here:

NC State graduate student ***Jacob Radford*** obtained an M.S. degree via support from this project (December 2018). This project provided Jacob with opportunities to learn to use, and contribute to the development of the Model Evaluation Toolkit (MET) software package, including a visit to the Developmental Testbed Center (DTC) in June of 2018 to work with MET developers on snowband detection capabilities (see: https://dtcenter.org/news/2019/02/jacob-radford). Jacob has an exceptional technical skill set, and the foundation for his continuing work on ensemble data visualization for extreme weather, while under different support, was established with this project.

The Central Michigan University contribution to the project highlights the contributions and involvement of five undergraduate students. Though these students were involved for a sufficiently long time for authorship on a publication, two did present posters at the AMS student conference, and all five have gone onto either graduate school or to careers as forecasters. Two of the students enrolled in graduate school are continuing research on snow-related topics, with one poised to become a new leader in the use of GOES data to improve snowfall forecasting. It is clear that his involvement in the CSTAR project had a great influence on his decision to focus his research on snowfall. The unique pairing of a prominent researcher in Dr. Lackmann with Dr. Baxter's focus on undergraduate research has resulted in at least one student who looks to go on to a career with a focus on improving winter weather forecasts. Given that research on operational aspects of winter weather forecasting is somewhat limited in comparison to warm-season weather phenomena, our efforts in improving the pipeline of winter weather researchers have the potential to result in long-term benefits. The status of CMU students who were involved the project is detailed below.

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Each of these students gained experience in constructing and analyzing winter weather case studies, data analysis and visualization, and developing, writing, and delivering scientific presentations.

It should also be mentioned that PIs Lackmann and Baxter also developed their skill sets and networks because of this project.

4. What was the impact on teaching and educational experiences?

The educational experiences of five undergraduate student at CMU have been discussed in the previous subsection, and are significant.

5. What was the impact on physical, institutional, and information resources that form infrastructure?

As detailed under Part II: Products, a number of online resources have been developed for the community

6. What was the impact on technology transfer?

We are happy to share the band-detection algorithm, or verification codes, with any who wish to use them. We have discussed this with the WPC. We are also pleased to share our output-enhanced version of the WRF model with any interested parties.

7. What was the impact on society beyond science and technology?

N/A

8. What percentage of the award's budget was spent in a foreign country(ies)?

None (0%).

V. CHANGES/PROBLEMS

Describe the following:

1. Changes in approach and reasons for the change.

None.

2. Actual or anticipated problems or delays and actions or plans to resolve them.

None.

3. Changes that had a significant impact on expenditures.

None.

4. Change of primary performance site location from that originally proposed.

None.

VI. SPECIAL REPORTING REQUIREMENTS

N/A

VII. BUDGETARY INFORMATION

The grant was spent to very near zero and has had final closeout.

VIII. PROJECT OUTCOMES

What are the outcomes of the award?

This material is largely repeated above. Some key outcomes of this award include:

- We have identified hydrometeor lofting in numerical model simulations of snow bands, and we have demonstrated that this phenomenon has implications for the surface snowfall distribution.
- The results demonstrate a spatial offset between the regions of maximum upward air motion (which forecasters often focus upon) and the location where the snowfall reaches the surface.
- We have offered that upcoming field experiments seek to find observational evidence for these regions of lofting, should sufficient resources be available.
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- Using fuzzy verification in time, the HRRR shows some promise, but the lack of deterministic skill argues strongly for use of HRRR-based ensemble prediction systems such as the HRRRE.

Are performance measures defined in the proposal being achieved and to what extent?

N/A