FINAL REPORT

University: The University of Georgia Research Foundation, Inc.
Name of University Researcher Preparing Report: Dr. John A. Knox
NWS Office: The Aviation Weather Center (AWC)
Name of NWS Researcher Preparing Report: Dr. Steven R. Silberberg
Type of Project (Partners or Cooperative): Cooperative
Project Title: Improving Clear Air Turbulence (CAT) Forecasts at the NOAA/NWS/NCEP/AWC with State-of-the-Art Research Diagnostics
UCAR Award No.: S09-75795
Date: July 30, 2012

SECTION 1: SUMMARY OF PROJECT OBJECTIVES

1. Collaborate with AWC scientists to optimize the Knox et al. and Ellrod-Knox indices for use at AWC, based on the research insights of the proposers and the operational and research experience of AWC scientists;

2. Collaborate with AWC scientists and operational forecasters on evaluating the new methods in the NAM, RUC, GFS models and (in year 2) the SREF, GEFS, and ultra-high resolution NAM and Rapid Refresh models under development at EMC and GSD;

3. Collaborate with AWC scientists on the evaluation of the new methods in the NAM, RUC, GFS models over two winter seasons, and the SREF, GEFS, and ultra-high resolution NAM and Rapid Refresh models over one winter season;

4. Collaborate with AWC scientists on the operational implementation of the new methods, should the criteria for operational implementation be satisfied; and

5. Disseminate the results of the implementation and evaluation process to the operational forecasting community via conferences, workshops, and collaboration with COMET for the enhancement of existing turbulence forecasting modules.

SECTION 2: PROJECT ACCOMPLISHMENTS AND FINDINGS

Major Accomplishments:

1. Using two winter seasons of PIREP data (2009-10 and 2010-11 winters), we established that the Ellrod-Knox index is superior to the previous Ellrod-Knapp "Turbulence Index" for all three models examined and for a variety of verification times: GFS (24-hour forecasts), NAM (12-hour), and RUC2 (6-hour and 12-hour). The probability of detection of turbulence is greater for Ellrod-Knox than Ellrod-Knapp, which more than offsets a slight decrease in probability of detection of null turbulence for Ellrod-Knox vs. Ellrod-Knapp. Integrated indices of turbulence forecasting, such as the True Skill

Statistic, confirm that Ellrod-Knox is superior for all models at all verification times, and particularly for higher threshold values for the indices, as is usual practice.

Results not included in previous reports are shown below:

Verification of TI1 and Ellrod-Knox (EK) Indices
Dec'09 - Jan '10

6-hour NAM forecasts, VT 18Z (916 pilot reports – 473 null, 443 yes):

	Ellrod Turbulence Index (TI1)			New Ellrod-Knox (EK) Index		
Threshold	PODy	PODn	TSS	PODy	PODn	TSS
4	.622	**.738**	**.360**	**.785**	.560	.345
6	.403	**.896**	.299	**.550**	.803	**.353**
8	.283	**.937**	.219	**.414**	.871	**.285**
10	.181	**.977**	.158	**.224**	.968	**.192**
12	.165	**.979**	.144	**.204**	.975	**.178**

6-hour RUC forecasts, VT 18Z (916 pilot reports – 473 null, 443 yes):

	Ellrod Turbulence Index (TI1)			New Ellrod-Knox (EK) Index		
Threshold	PODy	PODn	TSS	PODy	PODn	TSS
4	.686	**.615**	**.301**	**.831**	.448	.279
6	.480	**.796**	.276	**.662**	.713	**.375**
8	.428	**.842**	.270	**.527**	.819	**.346**
10	.299	.881	.180	**.340**	**.898**	**.238**
12	.252	.890	.142	**.257**	**.913**	**.170**

12-hour NAM forecasts, VT 00Z (828 pilot reports – 465 null, 363 yes):

	Ellrod Turbulence Index (TI1)			New Ellrod-Knox (EK) Index		
Threshold	PODy	PODn	TSS	PODy	PODn	TSS
4	.579	**.744**	.323	**.791**	.542	**.333**
6	.361	**.903**	.264	**.570**	.800	**.370**
8	.259	**.927**	.186	**.408**	.888	**.296**
10	.143	**.968**	.111	**.193**	.957	**.150**
12	.113	**.972**	.085	**.165**	.959	**.124**

12-hour RUC forecasts, VT 00Z (828 pilot reports – 465 null, 363 yes):

	Ellrod Turbulence Index (TI1)			New Ellrod-Knox (EK) Index		
Threshold	PODy	PODn	TSS	PODy	PODn	TSS
4	.642	**.684**	**.326**	**.815**	.452	.267
6	.421	**.845**	.266	**.554**	.761	**.315**
8	.339	**.888**	.227	**.460**	.819	**.279**
10	.201	**.948**	.149	**.314**	.929	**.243**
12	.171	**.959**	.130	**.267**	.946	**.213**

NAM	WINTER 2010-2011 ALL PIREPS (3998)							
	PODy		PODn		TSS		CSI	
THRES	TI	EKI	TI	EKI	TI	EKI	TI	EKI
4	0.511791	**0.743149**	**0.803623**	0.622478	0.315414	**0.365627**	0.392473	**0.469027**
6	0.304653	**0.476099**	**0.91725**	0.846851	0.221903	**0.32295**	0.270056	**0.384853**
8	0.214786	**0.340344**	**0.950597**	0.91231	0.165383	**0.252654**	0.199526	**0.299663**
10	0.138305	**0.208413**	**0.97818**	0.962948	0.116485	**0.171361**	0.133785	**0.197107**
12	0.089866	**0.142129**	**0.988061**	0.979827	0.077927	**0.121956**	0.088235	**0.137824**
16	0.055449	**0.078394**	**0.99506**	0.990943	0.050509	**0.069337**	0.055028	**0.07731**

2. The Ellrod-Knox index was implemented at the Aviation Weather Center with the Rapid Refresh model on May 1, 2012. Implementation of the Ellrod-Knox index for the GFS and NAM models is scheduled to occur on August 22, 2012. This delay resulted from forecaster suggestions during initial operational use of the RAP Ellrod-Knox during: a) the AWC Aviation Weather Testbed Summer Experiment, and b) preliminary investigations of RAP Ellrod-Knox performance during two recent severe turbulence incidents in the periphery of thunderstorm anvils that are associated with gravity waves.

Dissemination:

The results of the evaluation process have been disseminated at national conferences, including two AMS Aviation, Range and Aerospace Meteorology (ARAM) conferences (January 2010 and August 2011), two National Weather Association Annual Meetings (2010 and 2011), a workshop held at AWC in February 2012, a presentation at North Carolina State University in April 2010, and a presentation at Delta Air Lines in December 2011. This research was published in the NWA Newsletter, and a publication is in preparation for *Meteorological Applications*.

Synergistic activities:

Activities related to the project include a completed M.S. thesis on clear-air turbulence forecasting (including analysis of both the Ellrod-Knox and Knox et al. methods) by UGA student Emily Wilson, entitled "Case Studies of Clear-Air Turbulence: Evaluation and Verification of New Forecasting Techniques." Travel funds for her research at NCAR with Dr. Robert Sharman, and for her conference attendance at ARAM, was supplied by this grant. This thesis is leading to a publication in preparation for the *Journal of Applied Meteorology and Climatology*. UCAR/COMET funding also supported one UGA undergraduate, Jared Rackley, during Summer 2012, as he assisted in analysis of the turbulence verification effort.

Other synergistic activities include two courses taught at UGA: GEOG 4911/6911, Collaborative Research in the Atmospheric Sciences (on clear-air turbulence forecasting research) and GEOG 4180/6180, Special Topics in Atmospheric Sciences: Aviation Weather Hazards. A total of 20 students were enrolled in these two classes. Operational aviation turbulence forecasters from

Delta Air Lines spoke to the Aviation Weather Hazards class, some members of which also visited Delta headquarters in Atlanta (see photos).

SECTION 3: BENEFITS AND LESSONS LEARNED: OPERATIONAL PARTNER PERSPECTIVE

AWC's operational benefits from this project include:

1. Operational implementation of the Ellrod-Knox turbulence diagnostic, which is an improvement over the currently operational Ellrod-Knapp and Ellrod TI1 indices, in the GFS, NAM, and RAP models;

2. Development of close collaboration between AWC forecasters and scientists with Gary Ellrod, Dr. Knox, and students at the University of Georgia through the AWC's Aviation Weather Testbed. This close collaboration resulted in:

A. Optimization of the Ellrod-Knox index for AWC operational use in the GFS, NAM, RAP and RUC models,

B. Led to an improved evaluation of the RAP model for turbulence diagnostic performance which was a critical factor in AWC's approving operational implementation of the RAP model,

C. Led to improvements in Ellrod-Knox formulation for the GFS, NAM, and RAP models, and

D. Led to preliminary case studies of aircraft turbulence incidents occurring this summer in the vicinity of thunderstorm anvils;

3. Increased interest from AWC forecast staff to participate in evaluations of Knox et. al. turbulence diagnostic to be conducted during the 2012-13 winter season and further refinement of Ellrod-Knox.

AWC operational lessons learned from this project include:

1. Better estimate project resources such as personnel (time and resources), computing resources (bandwidth, storage), and computing resource changes.

Although we had planned to examine high resolution deterministic models and the Short Range Ensemble Forecast (SREF), we learned after beginning the project that computing resource changes and limitations would limit the number of models we could evaluate for Ellrod-Knox and Knox et al methods. In addition, we learned that calculations with high resolution models

(i.e., 4 km NAM Nest) were found to take up to 10-50 times longer than originally anticipated and would overwhelm AWC's computer storage capacity.

SECTION 4: BENEFITS AND LESSONS LEARNED: UNIVERSITY PARTNER PERSPECTIVE

The benefits to the University of Georgia exceeded expectations, and include:

1. Expansion of a research and teaching program in clear-air turbulence forecasting, including undergraduate/graduate courses and summer support for an undergraduate researcher. This work is leading to publication in a leading journal.

2. Synergistic activity with one M.S. student, whose thesis work will further extend #1 via publication in a leading journal.

3. Expanded connections with Delta Air Lines and its turbulence forecasters.

The main lesson learned was the scope and time required for rigorous intermodel evaluation and verification for turbulence diagnostics in the context of the demands of operational meteorology and academic schedules. Both time and computing requirements exceeded our best prior estimates.

SECTION 5: PUBLICATIONS AND PRESENTATIONS

Wilson, E. N., and J. A. Knox, 2012: Case studies of clear-air turbulence and evaluation of new CAT forecasting techniques. In preparation for *Journal of Applied Meteorology and Climatology*. (synergistic)

Knox, J. A., S. Silberberg, G. P. Ellrod, and co-authors, 2012: Evaluation of the Ellrod-Knox turbulence forecast method: An intermodel comparison. In preparation for *Meteorological Applications*.

Wilson, E. N., 2012: *Case Studies of Clear-Air Turbulence: Evaluation and Verification of New Forecasting Techniques.* M.S. thesis, University of Georgia, 127 pp. [Available from University Microfilms, Inc., P.O. Box 1346, Ann Arbor, MI 48106.] (synergistic)

Ellrod, G. P. and Knox, J. A., 2011: Evaluation of Improved Clear-air Turbulence Forecast Techniques at the NWS' Aviation Weather Center. *NWA Newsletter*, **11**(9), 2-3. http://www.nwas.org/newsletters/pdf/news_sep2011.pdf

Knox, J. A., G. P. Ellrod, S. R. Silberberg, E. Wilson, A. Black, E. Galicki, J. Rackley, C. Dunn, P. Malone, S. Phelps, M. Augutis, and J. Grant, 2011: Verification of clear air turbulence (CAT) forecast indices during two winters. Poster presentation at the 36th National Weather Association annual meeting, Birmingham, AL, October 2011.

Ellrod, G. P., J. A. Knox, S. R. Silberberg, and E. Wilson, 2011: Evaluation of a Modified Clear Air Turbulence (CAT) Forecast Index During Major Turbulence Outbreaks of Winter 2010-11. Poster presentation at the 36th National Weather Association annual meeting, Birmingham, AL, October 2011.

Ellrod, G. P., J. A. Knox, S. Silberberg, and E. Wilson, 2011: Evaluation of a modified clear air turbulence (CAT) index based on horizontal deformation, vertical shear and divergence tendency. Poster presentation at the 15th Aviation, Range and Aerospace Meteorology meeting, Los Angeles, CA, August 2011.

Silberberg, S. R., Knox, J. A., and Ellrod, G. P., 2010: "AWC Progress in 2010." NCEP Production Suite Review, December 2010.

Silberberg, S. R., Knox, J. A., and Ellrod, G. P., 2010: "R2O of New Turb Diagnostics in the AWC Aviation Weather Testbed: A COMET Funded Grant," Aviation Weather Center, November 2010.

Ellrod, G. P., Knox, J. A. and Silberberg S. R., 2010: Evaluation of State-of-the-Art Research Diagnostics to Improve Clear Air Turbulence Forecasts at NOAA's Aviation Weather Center. National Weather Association Annual Meeting, 7 October 2010.

Ellrod, G. P., and J. A. Knox, 2010: Improvements to an operational clear-air turbulence diagnostic index. Abstracts, *14th Conference on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA.

Knox, J. A., G. P. Ellrod, and S. R. Silberberg, 2010: Improving forecasts of clear-air turbulence at NOAA's Aviation Weather Center with state-of-the-art diagnostics. Abstracts, *14th Conference on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA.

Knox, J. A., 2010: New directions in clear-air turbulence forecasting. Invited colloquium, North Carolina State University Department of Marine, Earth and Atmospheric Sciences, Raleigh, NC, April 30.

Knox, J. A., 2010: Clear-air turbulence forecasting research at UGA. Invited talk, UGA Aviation Club, Athens, GA, January 13.

SECTION 6: SUMMARY OF UNIVERSITY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

As the author lists for publications and presentations indicates, there was considerable interaction between the university (Knox, UGA) and operational (Silberberg, AWC) partners, and also with consultant Gary Ellrod, who provided invaluable expertise and service. As was originally proposed, Knox served as Project Director and coordinated the various research tasks. Knox and Ellrod collaborated with Silberberg on development, implementation and verification of the new

CAT forecasting method, and disseminating the results. These interactions went smoothly, even with the demands of operational forecasting and academic schedules.

The major result is implementation of a new turbulence forecasting method that will improve CAT forecasting and reduce costs and injuries due to in-flight turbulence encounters.