Extension of the Great Smoky Mountain rain gauge mesonet and exploration of the origins of extreme precipitation events in the southern Appalachian Mountains and their signatures as observed by GOES-R

Overview

The Duke University Great Smoky Mountains National Park Rain Gauge Network (Duke GSMRGN), funded by NASA to measure rainfall accumulation at 32 mid (~3400 feet) and high (~6600 feet) elevation locations in the Pigeon River basin (Figure 1 of Duan et al. 2015), has been collecting observations since the first gauges were installed in June 2007. One of the overarching goals of the NASA-funded study (Barros et al. 2014) was to advance the understanding of physical processes responsible for precipitation production in a temperate mountain range and to incorporate knowledge of these processes in NASA-derived rainrate retrieval algorithms. Although analysis of the nine-year record of precipitation observations continues, significant findings have emerged and been publicized (e.g., Wilson and Barros 2014, Duan et al. 2015, Miller et al. 2017). Noteworthy findings based in-part on the tipping bucket rain gauge observations of the Duke GSMRGN,

- significant rainfall accumulation occurs at mid and high elevation locations in the mountains of the southern Appalachians (Duan et al. 2015),
- a significant fraction of the annual rainfall accumulation (30 - 50%) at mid and high elevation locations in the mountains comes from light rainfall events (Wilson and Barros 2014) and is difficult to detect using GPM/TRMM microwave algorithms (Prat and Barros 2010, Duan et al. 2015),
- much of this light rainfall is produced via the 'seeder-feeder' mechanism with low-level fog and/or stratus clouds serving as an abundant source of cloud water droplets needed for precipitation production (Wilson and Barros 2014),
- the efficacy of the seeder-feeder mechanism is dependent on the local relief of the adjacent ridges and valleys; contributing a greater amount of rainfall at high elevation locations in an 'inner mountain region' (Wilson and Barros 2014), and
- high elevation extreme rain events during a five year period are associated with long-lived events in which the primary synoptic pattern sets up strong, humid 1000-700 hPa layer flow from the Gulf of Mexico (210 – 230^{o}) or a secondary pattern sets up strong, humid flow from the Atlantic Ocean (110^{o}) as indicated in Figure 2. These extreme events are associated with moderate- to heavy-flooding events observed at a low elevation river gauge located near Knoxville, TN and analysis indicates that half the events are associated with atmospheric rivers (Miller et al. 2017).

As the designated public liberal arts university in North Carolina, UNC Asheville (UNCA) focuses primarily on educating undergraduate students in the classroom and through research projects. The Atmospheric Sciences (ATMS) Department at UNCA is extraordinarily fortunate to have the opportunity to provide a unique learning experience for UNCA students majoring in the atmospheric sciences in field work associated with the Duke GSMRGN, made possible by the NASA-funded research collaboration with Dr. Ana Barros and her graduate and post-doc students at Duke University. The foundational objective of the proposed project, to

provide needed infrastructure support of the Duke GSMRGN over a three year period, allows the execution of the specific objective of our project, to increase the breadth and variability of the types of precipitation events observed in the southern Appalachians (e.g., precipitation events associated with the remnants of tropical cyclones are absent from 12 of the 32 observation locations available during the warm seasons of 2007-2015), which will allow us to:

(1) evaluate the utility of GOES-R and blended GOES-R/microwave algorithms to observe and detect signatures that may forewarn of conditions leading to heavy flooding and/or flash-flooding events in the mountains of the southeastern U.S.,
(2) formulate a robust climatology of the frequency and intensity of atmospheric rivers (ARs) impacting the southern Appalachians,
(3) continue to characterize the linkage between precipitation production and local topographic features, and
(4) support field research learning opportunities for undergraduate students of UNCA and graduate students of Duke University.

NASA funding for the Duke GSMRGN ended with calendar year 2014 and has been supported in an *ad hoc* fashion since then via internal research grants at Duke University that ended in calendar year 2015. This proposal represents a collaborative research effort to extend the period of observations of the Duke GSMRGN for three years beyond 1 July 2016, with funding provided by UNC Asheville, the Center for Western Weather and Water Extremes located at the Scripps Institution of Oceanography, and NOAA-NESDIS.

Science

a) Research

A follow-on precipitation science mission to TRMM, the Global Precipitation Mission (GPM), was launched by NASA in February 2014 and a field experiment closely tied to validation of its rainrate algorithm (IPHEx, Barros et al. 2014) was run from 1 May – 15 June 2014 over the central and western Carolinas. A natural follow-on to previous TRMM-related work is to investigate if GPM has similar tendencies as TRMM in severely underestimating production during stable precipitation events in the mountains as a result of the inability of the instrument to observe signals of low-level seeder-feeder precipitation production. Validation of GPM algorithms utilizing observations from the Duke GSMRGN is underway as part of the post-IPHEx case study analysis (Barros et al. 2014). Current COMET GOES-R Project Partners Miller and Hotz (Morristown, TN NWSFO) envision the potential of testing actual GOES-R (to be launched in October 2016) observations in detecting the influence of ARs over the southern Appalachians. Continued support of the Duke GSMRGN allows the possibility of a long enough period to test the utility of GOES-R observations in providing advanced warnings of potential flooding events in the Knoxville, TN region. The continued investigation beyond the COMET Project is consistent with several FY 2014 GOES-R new start risk reduction proposals (e.g., J. Li and P. Xie et al. [http://www.goes-r.gov/users/risk-reduce/2014.html]) and would utilize new GOES-R TPW sounding capabilities that may effectively resolve high vapor transport events within the 1000-700 hPa layer.

Given the unique high elevation nature of the Duke GSMRGN, it is possible to re-visit a quantification of the relationship between long-term rainfall observations at each gauge site to

local topographic relief characteristics (e.g., exposure, slope) as was done in the 1950s by the Tennessee Valley Authority (Smallshaw 1953) and, more recently, by Konrad (1995). The older studies found relief characteristics quite important in explaining annual precipitation differences in the mountains. These studies utilized gauge observations at a markedly lower elevation than those of the Duke GSMRGN. A confirmation of the link between the topographic relief characteristics and observed high-elevation annual precipitation could prove useful to our operational colleagues as it could lead to new hypotheses linking flood-prone areas to locations having unique orographic characteristics.

b) Education

Support of the proposal foundational objective [provide needed infrastructure funding of the Duke GSMRGN over a three year period] will make possible extra-curricular learning opportunities for UNCA students enrolled in two ATMS Department courses "Understanding the Atmosphere Laboratory" (ATMS 111, one credit hour) and "Meteorological Instruments" (ATMS 320, three credit hours) as they learn about rain gauge calibration and rudimentary rainrate algorithm development in remote sensing applications. Each course fulfills a graduation requirement for non-ATMS majors (ATMS 111; natural sciences laboratory course) and for ATMS majors (ATMS 320; core course in the major).

The Duke GSMRGN was listed as a cornerstone of the funded NSF S-STEM ACES project description as an opportunity to participate in field research under one of the categories of extracurricular triad options (teaching, research, operations). Funding of the proposal will maintain field research opportunities for ACES scholars that lead to a greater awareness of the overall scientific method and an opportunity for making professional connections beyond the academic hydrologic and atmospheric science communities. Although a rigorous assessment methodology has not been applied, it is hypothesized that ATMS undergraduate student involvement in the Duke GSMRGN-oriented field research (Appendix A) makes it more likely that the student will pursue post-baccalaureate education by attending graduate school (12/26 = 46.2%) compared to the general ATMS undergraduate student population (27.8%).

Mentoring activities for ACES scholars were also listed in the funded NSF S-STEM ACES project description and focused on offerings of a summer research experience entitled 'Research Experience for Nearly Undergraduates' (RENU) designed to provide high school students of the Eastern Band of the Cherokee Indians with opportunities for research activities in the natural sciences. One of the activities would focus on a visit to the multi-instrumented Duke GSMRGN site at Purchase Knob (location of gauge #100 in Fig. 1). A prototype of the hydrology activity at Purchase Knob has already been developed and was demonstrated as part of the MYLES of Science program (Montreat College) for North Carolina high school students in June and July 2015. Should the proposed study be funded, the hydrology activity at Purchase Knob will be incorporated into the RENU as well as into the recently-funded Gaining Early Awareness and Readiness to Undergraduate Programs (GEAR UP) project at UNCA. Through the GEAR UP project, 6^{th} – 8^{th} grade students of eight counties in western North Carolina, designated as having a large segment of underserved students, are offered summer precollege awareness experiences in the natural sciences (UNC Asheville 2016).

Work Plan

This will be a collaborative project with University of North Carolina Asheville (UNCA), Duke University and the University of California San Diego's (USCD's) Scripps Institution of Oceanography (SIO). SIO and UNCA will provide matching funds to that requested from NOAA's GOES-R Program Science Office to accomplish the proposed work.

The Principal Investigator will serve as field manager for field campaigns to maintain (and extend the observation record for) the Duke University Great Smoky Mountains National Park Rain Gauge Network (Duke GSMRGN) for the next three years. Based on past campaigns since the inception of the Duke GSMRGN project in 2007, 10 hours per day will be devoted to a trek (defined as travel by vehicle and by foot to visit the planned rain gauges on a given day), 14 treks will occur each campaign, and three campaigns will occur per calendar year (spring, summer, and autumn). For safety reasons there will be two students assisting the field manager during each trek. Students will participate in data collection and gauge maintenance and upgrades.

As has been done in the past, raw observations of the Duke GSMRGN will be submitted to colleagues at Duke University from each gauge location during the three gauge visitation campaigns completed during a calendar year (spring, summer, autumn) to be run through a quality control procedure. The tipping bucket gauges have no means of communicating remotely and require data to be downloaded to a field laptop by a technician to assess the health of each rain gauge. Also, multiple visits are needed to insure that vegetation has not overgrown the rain gauge, resulting in severe undercatch of local rainfall. On occasion, wildlife has caused damage to the rain gauge exterior that required repair in the field. Field calibration at the 32 gauge sites will take place once per calendar year.

a) UNC Asheville – Doug Miller and Keith Krumpe

PI Doug Miller, Professor of Atmospheric Sciences, will serve as the overall project manager, insuring that project goals are being addressed during the study period. Miller will also serve as the primary field manager to insure that maintenance and calibration procedures are consistent during the study period and continue the highest quality rainfall observations possible for the scientific applications of the project partners at Scripps and NOAA/NESDIS. He will promote personal student research projects that support new directions in seeking to understand the interaction of ARs with the southern Appalachians and finding new applications of operational GOES-R remote sensing products that could forewarn of pending high impact hydrological events.

Keith Krumpe, Dean of Natural Sciences, is committing up to □ of matching funds over the 3-year project period to to continue providing field-based learning experiences of undergraduate students at UNCA (ATMS 111 and ATMS 320), continue field research opportunities for ATMS students, and provide a source of personal research projects whose hypotheses can be addressed utilizing a longer record of the Duke GSMRGN. A by-product of the continued network operation will be the opening of educational opportunities for K-12 students enrolled at underserved STEM schools of western North Carolina.

b) Duke University – Ana Barros

Co-PI Ana Barros, Professor of Civil and Environmental Engineering, as owner of the rain gauge hardware, will continue to take the lead in producing the highest quality rainfall observations through the acquisition of hardware needed for gauge upgrades and quality control of the observations after their collection in the field. Once the quality-control procedure has been completed, data will be posted in a location accessible to the proposal partners (e.g., DropBox). Dr. Barros will encourage new graduate student research endeavors at Duke University investigating the linkage of cloud microphysics and hydrological processes to local aspects of topography in the southern Appalachians.

c) Scripps Institute of Oceanography – F. Martin Ralph

Dr. F. Martin Ralph, Director of the Center for Western Weather and Water Extremes (CW3E) based at the Scripps Institution of Oceanography, is committing up to □ of matching funds over the three-year project period to leverage the major investment already made in establishing the network and maintaining it since 2007, and to open the door for broader scientific collaborations. CW3E support will also support the development of an understanding of the role of ARs in extreme precipitation events documented by the GSMRGN observations over the last decade, as well as a climatology of ARs in the southern Appalachians. The wealth of Duke GSMRGN observations available since 2007 is important to this type of study, and open access to quality-controlled observations of rainfall made by the Duke GSMRGN will be provided to partnering institutions. CW3E is committing up to an additional □ to support travel of CW3E investigators during the three-year period for collaborative meetings, including in Asheville, NC.

Duke GSMRGN observations and data availability

Observations from each of the remote 32 tipping bucket gauges associated with the Duke GSMRGN (Table 1) are accessed during field visits three times a year and consist of the date/times of bucket tips recorded on the gauge data logger and are downloaded in text and CSV format files. The 32 CSV format files are run through a QC process at Duke University and currently stored in numerous locations (e.g., DropBox), accessible by research partners. Gauge tip observations are assigned one of eight quality flags (e.g., time drift noted and fixed, or datum is reliable) based on notes recorded in field notebooks during site visits. On occasion, rain gauges are calibrated in the field and adjustments made to algorithms converting bucket tips to rainfall accumulation. Individual bucket tip observation formats in each CSV file,

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consist of the Hydrological Services of America accumulation estimate (mm), date and time (EDT) of the bucket tip, and the quality control flag (‘O’ indicates ‘datum is reliable’).

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Non-budget Tables and Figures

Table 1 of Duan et al. (2015). Region of rain gauge network in the Pigeon River basin. Note RG0XX, RG1XX, and RG3XX were installed in summer 2007, 2008, and 2009, respectively.

Table 1. Inventory of long-term raingauges in the Pigeon River basin including the Great Smoky Mountains National Park (GSMNP) in the southern Appalachians used in this study.

Raingauge	Latitude	Longitude	Elevation (m)	Series
RG001	35.4	−82.91	1156	
RG002	35.43	−82.97	1731	
RG003	35.38	−82.92	1609	
RG004	35.37	−82.99	1922	RG0XX eastern ridge
RG005	35.41	−82.96	1520	
RG008	35.38	−82.97	1737	
RG010	35.46	−82.95	1478	
RG100	35.59	−83.07	1495	
RG101	35.58	−83.09	1520	
RG102	35.56	−83.1	1635	
RG103	35.55	−83.12	1688	
RG104	35.55	−83.09	1587	
RG105	35.63	−83.04	1345	
RG106	35.43	−83.03	1210	RG1XX inner ridge
RG107	35.57	−82.91	1359	
RG108	35.55	−82.99	1277	
RG109	35.5	−83.04	1500	
RG110	35.55	−83.15	1563	
RG111	35.73	−82.95	1394	
RG112	35.75	−82.96	1184	
RG300	35.73	−83.22	1558	
RG301	35.71	−83.26	2003	
RG302	35.72	−83.25	1860	
RG303	35.76	−83.16	1490	
RG304	35.67	−83.18	1820	
RG305	35.69	−83.13	1630	RG3XX western ridge
RG306	35.75	−83.17	1536	
RG307	35.65	−83.2	1624	
RG308	35.73	−83.18	1471	
RG309	35.68	−83.15	1604	
RG310	35.7	−83.12	1756	
RG311	35.77	−83.14	1036	

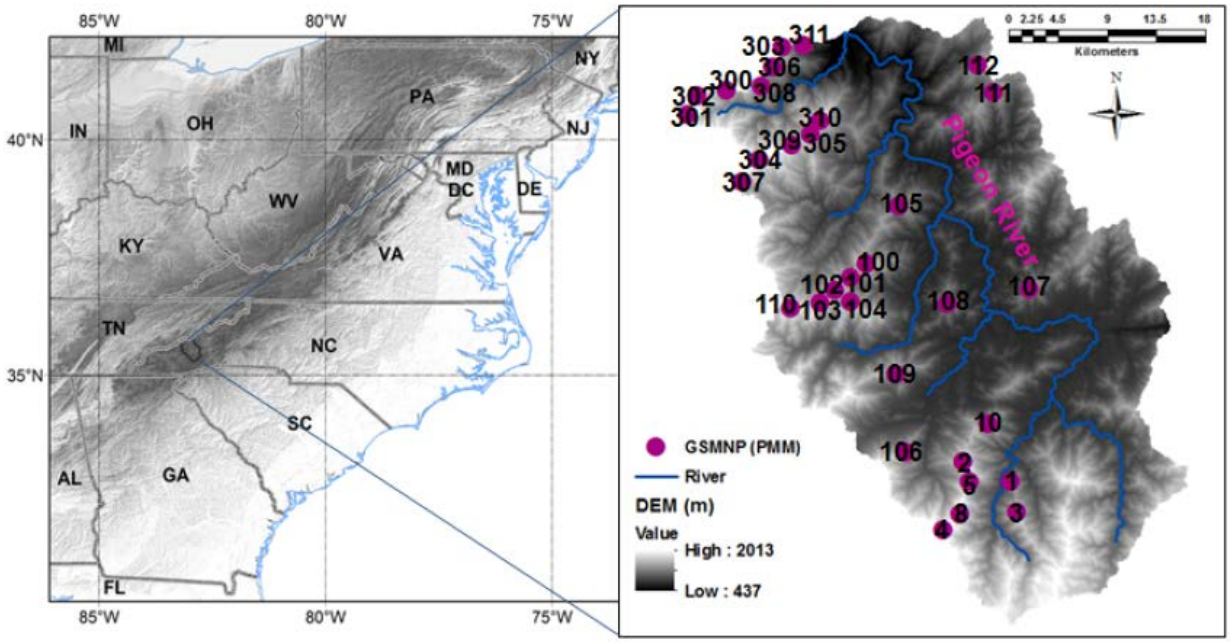

Figure 1 of Duan et al. (2015). Region of rain gauge network in the Pigeon River basin. Note RG0XX, RG1XX, and RG3XX were installed in summer 2007, 2008, and 2009, respectively.

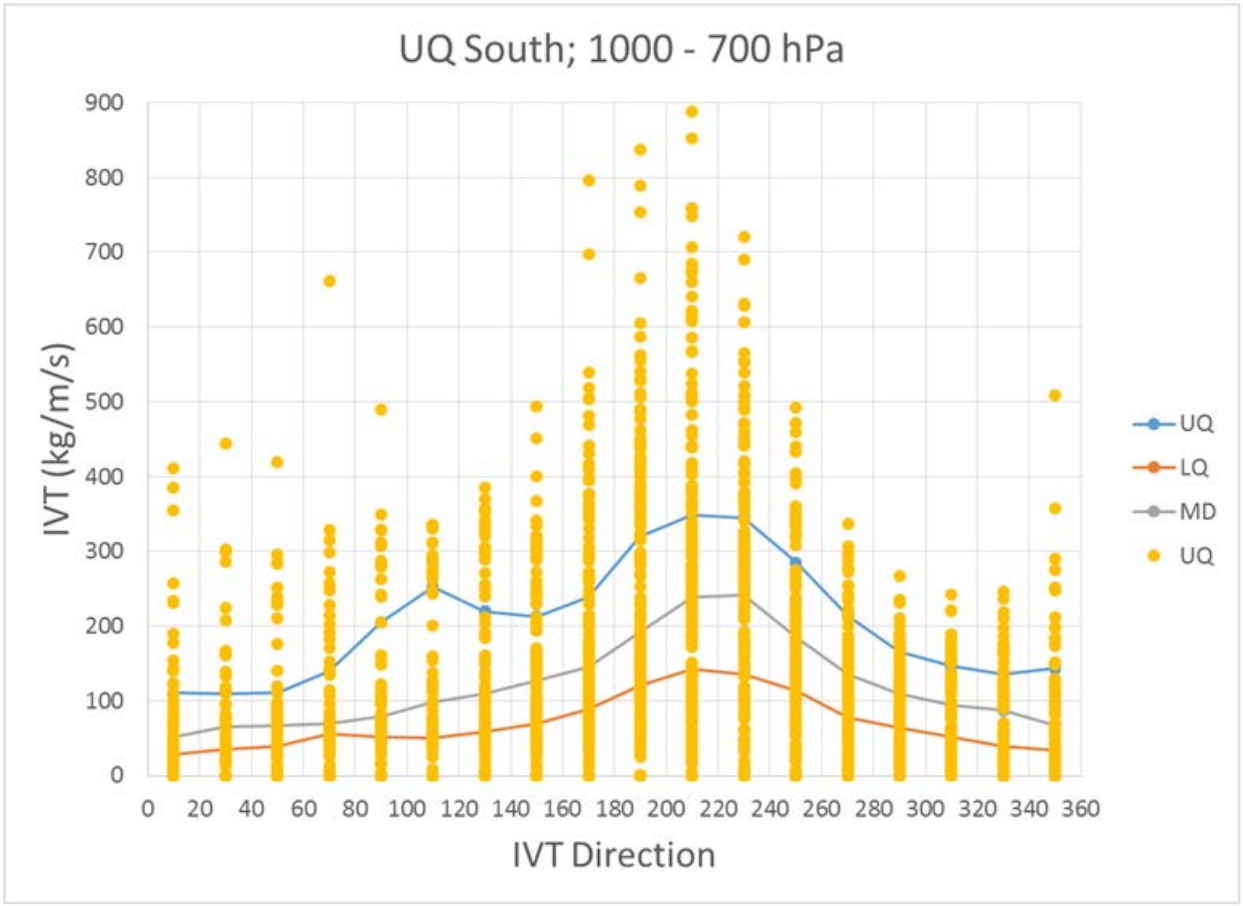

Figure 2. Layer (1000 – 700 hPa) integrated vapor transport (IVT) based on GFS 0.5º x0.5º gridded analyses of extreme rain events categorized using observations of the Duke GSMRGN from 1 July 2009 – 30 June 2014. Solid blue, red, and gray curves represent the upper- and lower-quartiles and median of analyzed layer IVT, respectively, as a function of IVT direction for grid points located within 5º south of the center point of the Duke GSMRGN and within 5º longitude centered on the gauge network. Orientation of the large-scale ridgeline of the southern Appalachian Mountains is 230º – 50º (southwest to northeast).

Appendix A - UNC Asheville students involved in the high elevation Duke University Great Smoky Mountain Rain Gauge Network – May 2016

The following student field researchers are or were under my supervision while at UNCA since the spring 2007 semester and contributed to field work associated with the Duke GSMRGN:

John A (BS-Atmospheric Sciences), Meridian Energy and Environment, LLC
Massey B (BS-Atmospheric Sciences), graduate school at SUNY - Albany
Duncan B (BS-Atmospheric Sciences), graduate student at University of New Orleans
William C (current UNCA student)
Samantha C (BS-Atmospheric Sciences), graduate student at Univ. of North Dakota
Greg C (BS-Atmospheric Sciences), graduate school at Univ. of Nebraska-Lincoln, LimoTech
Robert D (BS-Atmospheric Sciences), Ph.D. candidate at ETH Zürich
Kelly D (BS-Atmospheric Sciences), TV meteorologist, Augusta, GA
Ashley F (BS-Atmospheric Sciences), Berglund Credit Line
Michael G (BS-Atmospheric Sciences), graduate school at UNC Charlotte, Emergency Management Associates, IEM, LLC
Wes G (BS-Atmospheric Sciences), Genesis Aviation
Kurt H (BS-Atmospheric Sciences), graduate student at Univ. of North Dakota
Doug H (BS-Atmospheric Sciences), USGS
Ben H (current UNCA student)
Chris L (BS-Atmospheric Sciences), current activities; unknown
Will L (current UNCA student)
Daniel M (BS-Atmospheric Sciences), graduate school at Appalachian St. Univ., meteorologist at GBE Fund
Zachery M (BS-Atmospheric Sciences), NWS forecaster
Jeremy M (BS-Atmospheric Sciences), NWS forecaster
Robbie M (BS-Atmospheric Sciences), Ph.D. at ECU, NWS forecaster
Ryan S (BS-Atmospheric Sciences), meteorologist at 14th Weather Squadron
Nick S (BS-Atmospheric Sciences), current activities; unknown
Melissa T (BS-Atmospheric Sciences), current activities; 6-8 grade math teacher
Bobby T (BS-Atmospheric Sciences), Vaisala
Sky T (current UNCA student)
Daniel T (BS-Atmospheric Sciences), current activities; unknown
Bonnie T (current UNCA student)
Kenneth W (former UNCA student), TV meteorologist, Bozeman, MT
Anna W (BS-Atmospheric Sciences), Ph.D. at Duke University, post-doctoral research at Scripps Institute
Thomas W (BS-Atmospheric Sciences), graduate school at UNC Charlotte, NWS forecaster
Aaron W (BS-Atmospheric Sciences), current activities; unknown
Ethan W (current UNCA student)
Christopher Z (BS-Atmospheric Sciences), Ph.D. at Mississippi State Univ.

graduates attending (or attended) graduate school = 12
graduates = 26