FINAL REPORT

University: University of North Carolina Asheville

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NWS Office: Morristown, TN

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Type of Project (Partners or Cooperative): Partners

Project Title: ***The Influence of Atmospheric Rivers on Extreme Precipitation Events Observed in the Southern Appalachians***

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Section 1: Summary of Project Objectives

The objectives of Partners Project #Z16-20569 are to determine the frequency that Atmospheric Rivers (ARs) impact the southern Appalachian Mountains and the severity of the flooding problems encountered in eastern Tennessee when ARs are impacting the region. By examining observations of remote sensing (GOES IR and passive microwave) systems and gridded model analyses (GFS), it is hoped that signatures can be detected that will give ample lead time for the dissemination of flood watches. As part of the methodology for meeting the broad objectives, the study proposal included the assembly of a storm atlas for documenting heavy rainfall events in the southern Appalachians over the 1 July 2009 – 30 June 2014 study period (identified using the high elevation Duke University Great Smoky Mountains Rain Gauge Network [GSMRGN] located in the Pigeon River Basin [PRB] of North Carolina and Tennessee) and the identification of commonalities and variations between case studies to define synoptic and/or mesoscale atmospheric conditions favorable for producing intense rainfall.

Section 2: Project Accomplishments and Findings

There were several project accomplishments that related to the focus of our research. The main emphasis was to determine if ARs have an impact on episodes of southern Appalachian flooding (they do) and explore if ARs are detectable using GOES sounder total precipitable water (TPW) observations (see below). We found that a majority of our Upper-Quartile (UQ) events involve an AR and had significant societal impacts identified by river flooding at the USGS gauge in the Pigeon River at Newport, Tennessee and by flooding reports in eastern Tennessee and western North Carolina documented in NOAA's Storm Data publication (columns 8 and 9 of Table 1). Based on our results, ARs can have an impact on rain events any time of the year, but extreme AR-related events are most likely to occur during the non-summer months (outside of June, July, and August).

GOES sounder observations were helpful in determining the location of ARs, but IR cloud contamination was a significant problem and will likely to be a limitation for GOES-R. The blended Integrated Water Vapor (IWV) approach will continue to be needed for the remote detection of ARs, although the improved resolution and cloud detection algorithm of GOES-R may significantly reduce the masked cloud contamination zone, thereby making GOES-R TPW observations more useful in diagnosing ARs in operations. Investigation of blended IWV observations over a domain covering the Gulf of Mexico, Caribbean Sea, and southwest Atlantic Ocean (Figure 1) found a promising link between evolving IWV upper and lowest quartile differences as the UQ storm matured (Figure 2), perhaps reflecting the close proximity of strong poleward moisture-excess and equatorward moisture-deficit transport as the mid-latitude storm intensified. An increase in the difference of the upper- and lower-quartile IWV values of 10 mm over a period of 24-h or less might be an indicator of a significant precipitation event associated with an AR.

Current methods of AR detection are moving away from using IWV or TPW fields and focusing, instead, on Integrated Vapor Transport (IVT) calculated from global model gridded analyses (e.g., GFS). Examination of IVT values for ARs in the southeastern U.S. by Mahoney et al. (2016) suggested the identification of a strong AR occurs when the IVT zone exceeding 500 kg m^{-1} s^{-1} is less than 1500 km in width and at least 1500 km in length. Analysis of GFS-based IVT analyses for periods corresponding to our AM and UQ case studies (Table 1) over an area just south of the PRB (Figure 3) indicates two peaks in the IVT upper-quartile when IVT values are binned by IVT direction (blue curve of Figure 4), 110^o and 210^o, each having a cross-mountain component and upslope flow. Points indicate individual GFS grid point IVT magnitudes corresponding to UQ case studies only and are included for comparison with the quartile and median curves. A summation of GFS grid point IVT values in the south-of-PRB domain (Figure 3) having cross-mountain components over the duration of each event (UQ03 example displayed in Figure 5) shows that large summed IVT values (exceeding 300,000 kg m^{-1} s^{-1}) typical of UQ events are a result of high individual IVT grid values coupled with their long duration (Table 1). A re-examination of the possible AR events (final column of Table 1) using Mahoney et al.'s criteria for strong AR events (defined above) indicates that nine of 12 possible UQ AR events (UQ01, UQ03-UQ06, UQ09, UQ12, UQ14, and UQ15) are strong, while only one of the seven possible AM AR events was found to be strong.

Several atmospheric fields beyond satellite observations were found useful in identifying the potential presence of ARs while examining the moderate and intense PRB rainfall events (final column of Table 1). A deep and positively tilted (slow-moving) trough, surrounded by a strong polar jet stream at the 500 hPa level (UQ03 example displayed in Figure 6) provides the necessary conditions at lower levels to produce an AR. A deep trough or cut-off low at the 850 hPa level (UQ03 example displayed in Figure 7) upstream of the southeastern U.S. provides conditions drawing air parcels at low levels from the Gulf of Mexico and/or the Atlantic Ocean. Strong low-level southerly flow also implies (through QG theory) strong ascent associated with warm air advection, creating clouds and precipitation. High climatology IWV values along with favorable HYSPLIT-derived trajectory flow from over the Gulf of Mexico and/or Atlantic Ocean (UQ03 example displayed in Figure 8), with clockwise-oriented directional shear at the PRB endpoint, indicates warm air advection and the potential for QG-generated lift and cloud/precipitation production. High IVT values and the orientation of the IVT from SSW to SE correlated the best with AR associated flooding events (UQ03 example in Figure 9). Besides moisture availability and transport, strong upper level forcing and large scale ascent are necessary.

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

The collaborated project with UNC Asheville has greatly improved NWS Morristown, Tennessee understanding of ARs and flooding across the southern Appalachians Mountains. The much closer investigation of ARs, synoptic map overview, and societal impacts have given forecasters a greater awareness of patterns that are more conducive to flooding.

The closer look at ARs and synoptic overview of each flood event has been very enlightening, and given NWS forecasters a much greater understanding of the patterns that produce heavy rainfall. The pattern recognition will aid forecasters with predicting flash flood events in the future, and maintaining a greater situational awareness of the societal impacts of the heavy precipitation.

The following distinguishing factors were found that contribute to flooding across the southern Appalachians:

1) A clear connection between AR presence and low-level southerly air flow (highlighted using HYSPLIT-derived trajectories) and high IWV values.
2) The stronger the IVT plume the greater the likelihood of flooding.
3) The more significant impact events associated with AR had greater cross-mountain flow.
4) Direction of IVT can be used to help determine the potential of flooding.
5) Duration of the IVT. The greater the duration of the event, the greater likelihood of flooding.
6) Besides an AR connection, the strength of the upper level forcing/large scale ascent must be determined. The most devastating synoptic scenario is one with a deep positively-tilted trough at the 500 hPa level that propagates slowly with an initial surface cyclone drawing moisture northward from the Gulf of Mexico (Figures 6-8), and secondary surface cyclogenesis that acts to nearly anchor the mid-tropospheric flow and maximize the exposure of the southern Appalachian Mountains to the AR.
7) There were several climatology related results that have a clear importance to operational forecasting across the southern Appalachians. ARs do impact the southern Appalachians during all seasons. However, their impacts are most severe, and have the greatest societal impact during the non-summer months (Table 1).
8) Strong correlation between climatologically high IWV values and AR presence.

These factors will be communicated to the staff through presentations and one-on-one simulation training. No significant problems were encountered during our research.

Section 4: Benefits and Lessons Learned: University Partner Perspective

The extra-curricular learning experience of Mr. Lukas Stewart, an undergraduate at UNCA, has been an invaluable benefit of the project. From his first-ever tour of the NWS Morristown facility to the coding (Python) and presentation experience associated with the project, Mr. Stewart has gained knowledge and skills that will benefit him in his future career and will pay dividends in the field of meteorology based on his future contributions. Specifically, as part of the project, Mr. Stewart,

1) Learned the important processes before, during, and after quality research is started and completed.

2) Learned how much time and effort were needed for a research project.

3) Learned how to create the poster and to determine the most important points of our research to be displayed on the poster.

4) Learned how to balance schoolwork with research in time management skills.

5) Learned the frustration of coding and debugging a program in order for it to finally run properly.

6) Learned the importance behind data collection and the discussions with multiple individuals for specific datasets.

7) Determined that the GOES Sounder Observations of TPW were not a good indicator of AR presence or flooding. This was most likely due to the GOES Sounder’s inability to measure the TPW values if clouds were present, which can cause large biases in statistical products created with these TPW values.

8) Traveled to his first weather-related conference (NWA 41st Annual Meeting) and learned how a conference functioned.

9) Learned how to create an oral presentation, to determine the key points to highlight, to present our research to many people, and to be able to intelligently answer questions people might have.

10) Visited a National Weather Service (NWS) office in Morristown, Tennessee both to discuss our research with our partners and to learn about the different jobs in the NWS building.

11) Had amazing experiences and worked with incredible people that he will have lifelong connections with.

Utilization of netCDF, ncl, and IDL libraries and routines has opened new analysis and data display opportunities for undergraduate research and atmospheric sciences (ATMS) courses that were previously either unfamiliar or unknown. Results of the COMET project will add material related to ARs in the Synoptic Meteorology I course (ATMS 410) of PI Miller in which, until recently, only focused on research relevant to the west coast of the U.S. The project has opened a direct research avenue between partner institutions that have formed the basis of a three-year follow-on study (1 July 2016 – 30 June 2019) related to the Duke University GSMRGN for our region of intersection; the southern Appalachians. At least one manuscript based on the COMET Partners collaboration is anticipated (see below) and will provide an excellent learning opportunity for all project participants.

No major problems were encountered during the project. There were gaps in some of the blended IWV and GOES TPW archives that could not be overcome in our analysis of the 15 AM and 17 UQ events over the 1 July 2009 – 30 June 2014 study period. Current archiving practices of remote sensing data at the institutions will make data gaps less frequent as newer heavy precipitation events are studied (Mr. John Forsythe and Dr. Arastoo Biazar, personal communication).

Section 5: Publications and Presentations

Stewart, L., D. Miller, D. Hotz, and J. Winton, 2016: The Influence of Atmospheric Rivers on Extreme Precipitation Events Observed in the Southern Appalachians. Poster presentation given at the *41st Annual Meeting of the National Weather Association*, Norfolk, VA (12 September).

Miller, D., L. Stewart, D. Hotz, J. Winton, A. Barros, J. Forsythe, A. P. Biazar, and G. Wick, 2016: Investigation of Atmospheric Rivers Impacting the Pigeon River Basin of the Southern Appalachians. Oral presentation given at the *2016 International Atmospheric Rivers Conference*, San Diego, CA (11 August).

Stewart, L.M., D.K. Miller, D. Hotz, J. Winton, 2016: The Influence of Atmospheric Rivers on Extreme Precipitation Events Observed in the Southern Appalachians. Oral presentation given at the *National Conference of Undergraduate Research 2016*, Asheville, NC (7 April).

Miller, D.K., L.M. Stewart, D. Hotz, J. Winton, 2016: The Influence of Atmospheric Rivers on Extreme Precipitation Events Observed in the Southern Appalachians. Oral presentation given at the *2016 Great Smoky Mountains National Park Science Colloquium*, Gatlinburg, TN (17 March).

Planned future presentations and publications…

Miller, D.K., D. Hotz, L. Stewart, and J. Winton, manuscript to be submitted to *Weather and Forecasting* of the American Meteorological Society (February 2017).

D. Hotz, J. Winton, D.K. Miller, and L. Stewart – local office seminar to the staff on the Atmospheric River Grant Results & Cool-Season Flood Forecasting Techniques (January 2017).

J. Winton, Hotz, D., D.K. Miller, and L. Stewart – annual meeting of the American Meteorological Society, Weather and Forecasting and/or Hydrology Conference, Seattle, WA (January 2017, abstract submitted August 2016).

D. Hotz, J. Winton, D.K. Miller, and L. Stewart, Oral presentation at the Smoky Mountain AMS Chapter, Morristown, Tennessee. Atmospheric River Grant Results & Cool-Season Flood Forecasting Techniques (November 2016).

Section 6: Summary of University/Operational Partner Interactions and Roles

The division of labor has been split primarily between two general categories; those tasks requiring the acquisition of textual and graphical data [MRX] and those tasks requiring the acquisition, manipulation, and display of numerical data [UNCA]. The project partners have worked together on the examination and interpretation of the significance of patterns emerging from the various sources of data.

NWS Morristown, TN reviewed the societal impacts for each “above median and upper quartile” rainfall event. The societal impacts were recorded using NCDC’s Storm Events Database. Societal impacts were road closures, property damage, and evacuations necessary during the entirety of each event (column #9 of Table 1). This part of research was to determine how significant the rainfall event was to disrupting people’s lives and property.

Looking closer at the rainfall impacts on river levels, the river gauge at the Pigeon River in Newport, TN was analyzed. This rain gauge was chosen due to the close proximity to the area of study in western North Carolina. Discharge graphs were recorded from the USGS. These graphs were used to determine societal impacts from river levels. The Action Stage, Minor Flooding, Moderate Flooding, and Major Flooding levels were recorded for any rainfall events that reached one of the four levels, as well as the flood impacts from each rainfall event (column #8 of Table 1).

Synoptic charts were copied and recorded for the Synoptic Map Overview. The 500 mb, 700 mb, and 850 mb maps were recorded beginning with the synoptic time (0000 or 1200 UTC) closest to at or before the rainfall start time and ending with the synoptic closest to or after the rainfall end time. The maps were used to determine synoptic patterns during each rainfall event. Our findings showed that during most rainfall events, a deep trough set up over the Great Plains with low level 850 mb flow from the south and southwest over several periods (Figure 7).

Two in-person meetings were conducted over the course of the research project. One meeting took place in UNCA Asheville, NC on November 13, 2015, and another at the NWS office in Morristown, TN on March 4, 2016. These meetings were to discuss current research and findings, as well as plan the upcoming components of the project. The latter meeting was the first opportunity for the undergraduate research student from UNCA (Lukas Stewart) to have a tour of a NWS office.

Several phone calls and conference calls (e.g., 9 September 2016) were conducted to clarify analysis methodologies and discuss ‘next steps’ in the research project. Completion of research milestones and conference discussions related to the research were shared via email nine times between 20 May 2016 and 23 September 2016 as the project approached its conclusion. Electronic files were shared between the research partners via Google Drive,

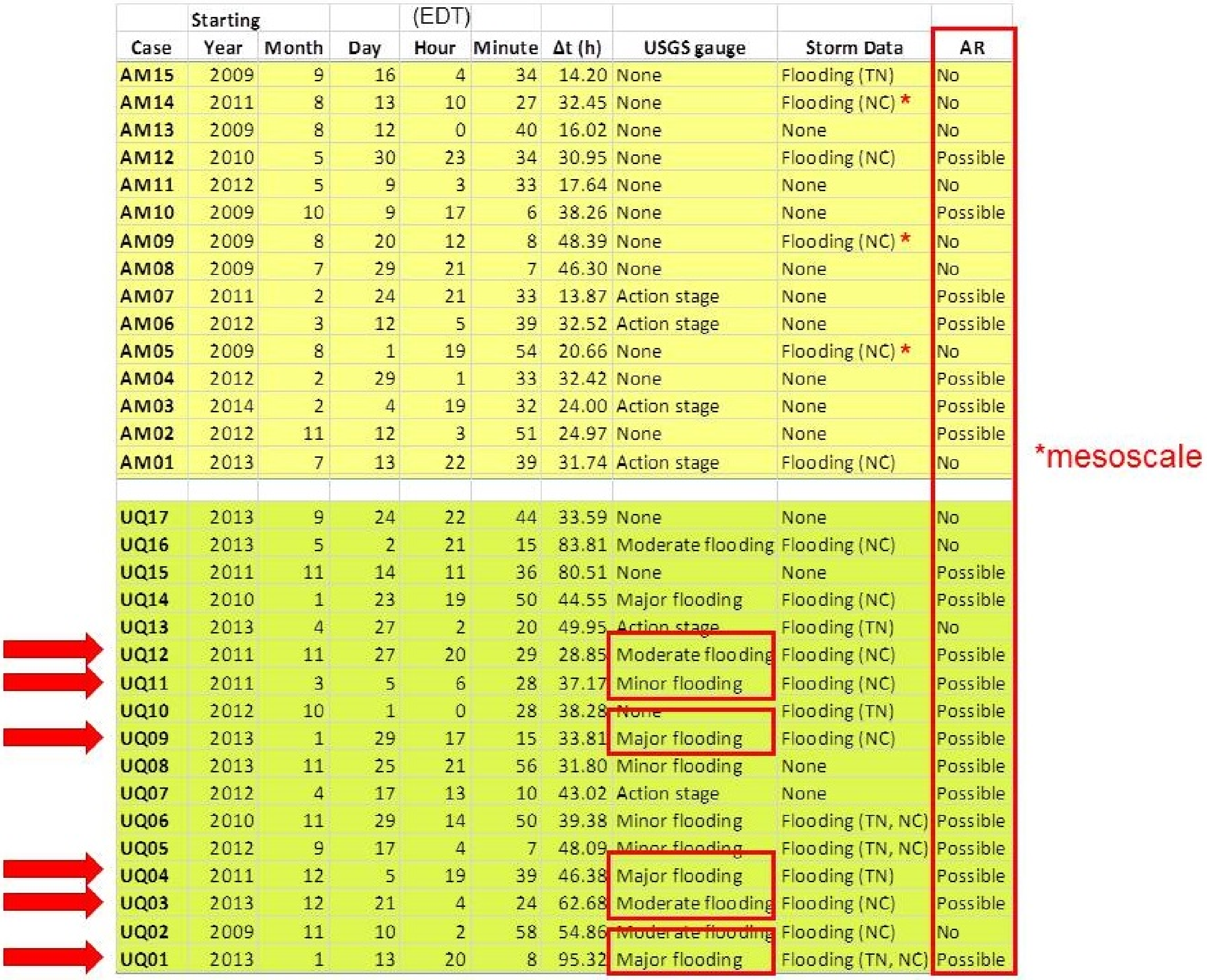
https://drive.google.com/drive/folders/0B9P8oUaRiBOwbVlDWHFUUlJnOVE

References

Mahoney, K.M., D. L. Jackson, P. Neiman, M. Hughes, L. Darby, G. Wick, A. White, E. Sukovich, R. Cifelli, 2016: Understanding the role of atmospheric rivers in heavy precipitation in the southeast United States. *Mon. Wea. Rev.*, **144**, 1617-1632.

Tables and Figures

Table 1. Above-median (AM, but not upper-quartile) and upper-quartile (UQ) events as gleaned from observations of the Duke University Great Smoky Mountains Rain Gauge Network. The heaviest precipitation events are found toward the lower portion of the table (denoted '01' in the case name). Six red arrows indicate UQ events having similar synoptic patterns, an example of one (UQ03) is provided in Figures 5-9 below. Duration of each event is located in the column labeled 'Δt (h)'. Possibility of the presence of an AR defined using synoptic maps and HYSPLIT trajectories is indicated in the final column of the table.



	Starting			(EDT)					
Case	Year	Month	Day	Hour	Minute	Δt (h)	USGS gauge	Storm Data	AR
AM15	2009	9	16	4	34	14.20	None	Flooding (TN)	No
AM14	2011	8	13	10	27	32.45	None	Flooding (NC) *	No
AM13	2009	8	12	0	40	16.02	None	None	No
AM12	2010	5	30	23	34	30.95	None	Flooding (NC)	Possible
AM11	2012	5	9	3	33	17.64	None	None	No
AM10	2009	10	9	17	6	38.26	None	None	Possible
AM09	2009	8	20	12	8	48.39	None	Flooding (NC) *	No
AM08	2009	7	29	21	7	46.30	None	None	No
AM07	2011	2	24	21	33	13.87	Action stage	None	Possible
AM06	2012	3	12	5	39	32.52	Action stage	None	Possible
AM05	2009	8	1	19	54	20.66	None	Flooding (NC) *	No
AM04	2012	2	29	1	33	32.42	None	None	Possible
AM03	2014	2	4	19	32	24.00	Action stage	None	Possible
AM02	2012	11	12	3	51	24.97	None	None	Possible
AM01	2013	7	13	22	39	31.74	Action stage	Flooding (NC)	No
UQ17	2013	9	24	22	44	33.59	None	None	No
UQ16	2013	5	2	21	15	83.81	Moderate flooding	Flooding (NC)	No
UQ15	2011	11	14	11	36	80.51	None	None	Possible
UQ14	2010	1	23	19	50	44.55	Major flooding	Flooding (NC)	Possible
UQ13	2013	4	27	2	20	49.95	Action stage	Flooding (TN)	No
UQ12	2011	11	27	20	29	28.85	Moderate flooding	Flooding (NC)	Possible
UQ11	2011	3	5	6	28	37.17	Minor flooding	Flooding (NC)	Possible
UQ10	2012	10	1	0	28	38.28	None	Flooding (TN)	Possible
UQ09	2013	1	29	17	15	33.81	Major flooding	Flooding (NC)	Possible
UQ08	2013	11	25	21	56	31.80	Minor flooding	None	Possible
UQ07	2012	4	17	13	10	43.02	Action stage	None	Possible
UQ06	2010	11	29	14	50	39.38	Minor flooding	Flooding (TN, NC)	Possible
UQ05	2012	9	17	4	7	48.09	Minor flooding	Flooding (TN, NC)	Possible
UQ04	2011	12	5	19	39	46.38	Major flooding	Flooding (TN)	Possible
UQ03	2013	12	21	4	24	62.68	Moderate flooding	Flooding (NC)	Possible
UQ02	2009	11	10	2	58	54.86	Moderate flooding	Flooding (NC)	No
UQ01	2013	1	13	20	8	95.32	Major flooding	Flooding (TN, NC)	Possible

*mesoscale

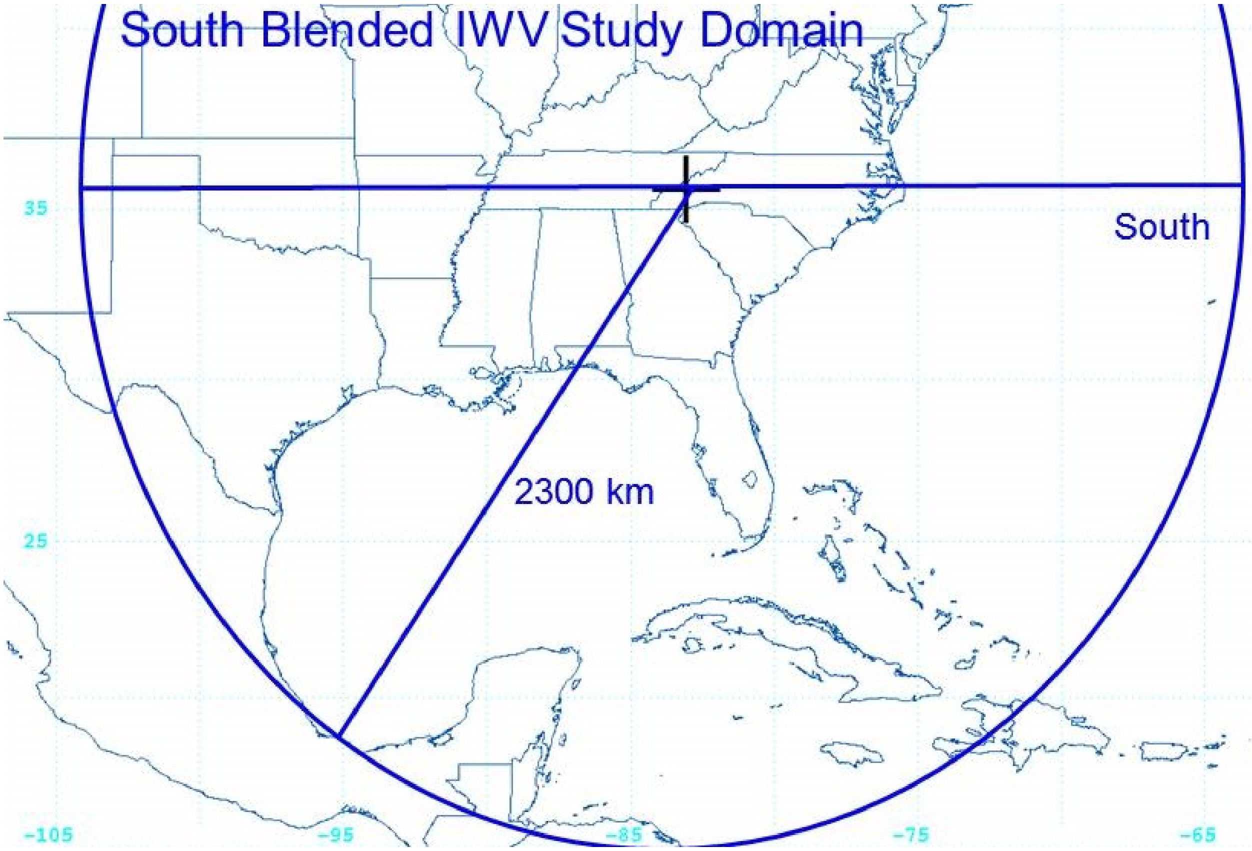


Figure 1. Domain for investigating pixels of the blended IWV patterns observed during the selected AM and UQ case studies.

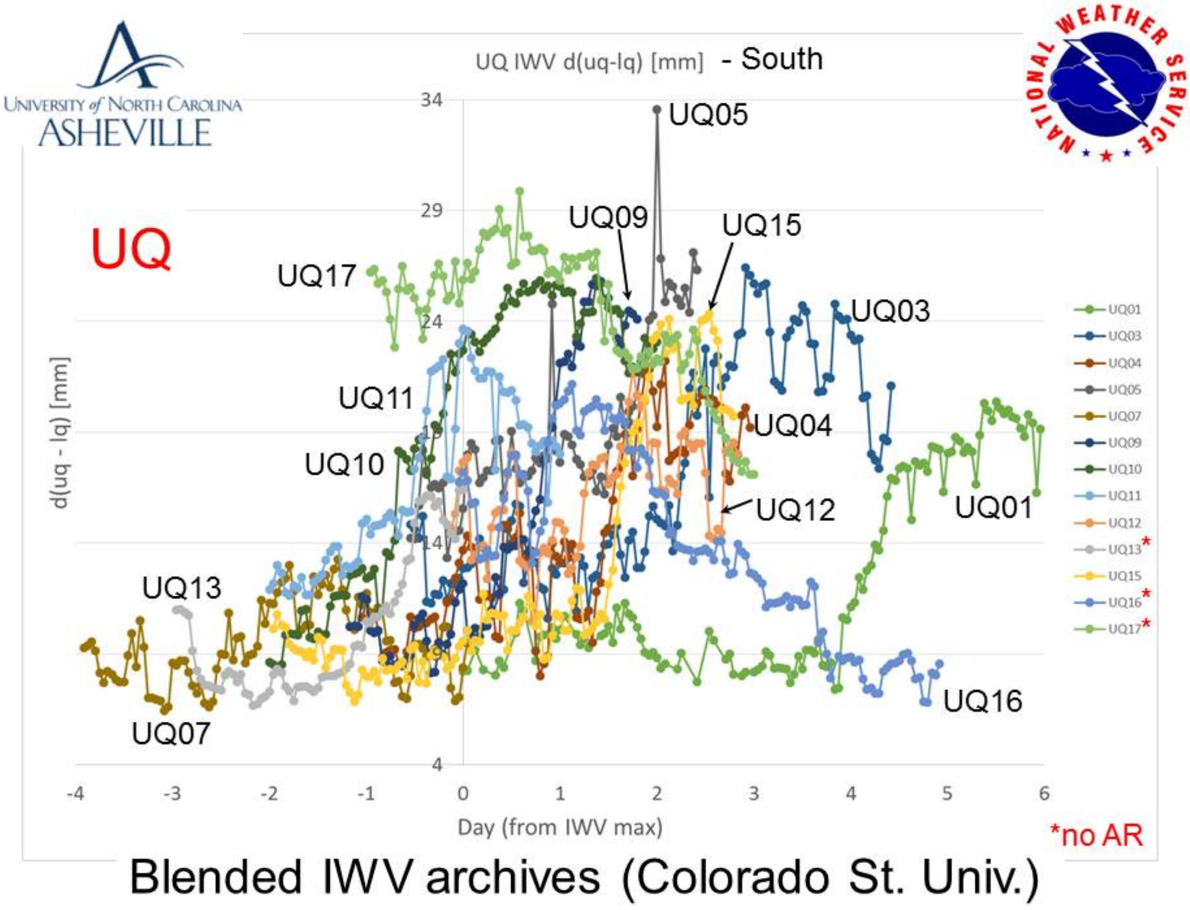


Figure 2. Time series of upper-quartile minus lower-quartile blended IWV observations for satellite pixels falling within the southern half of the 2300 km IWV search radius (Figure 1). Day "0" corresponds to the time when maximum IWV value of a case study was observed within the IWV search domain. Series are restricted to UQ precipitation events only. Red asterisk indicates event occurred without an AR (UQ13, UQ16, UQ17). Blended IWV observations were missing from the archives for events UQ02, UQ06, UQ08, and UQ14.

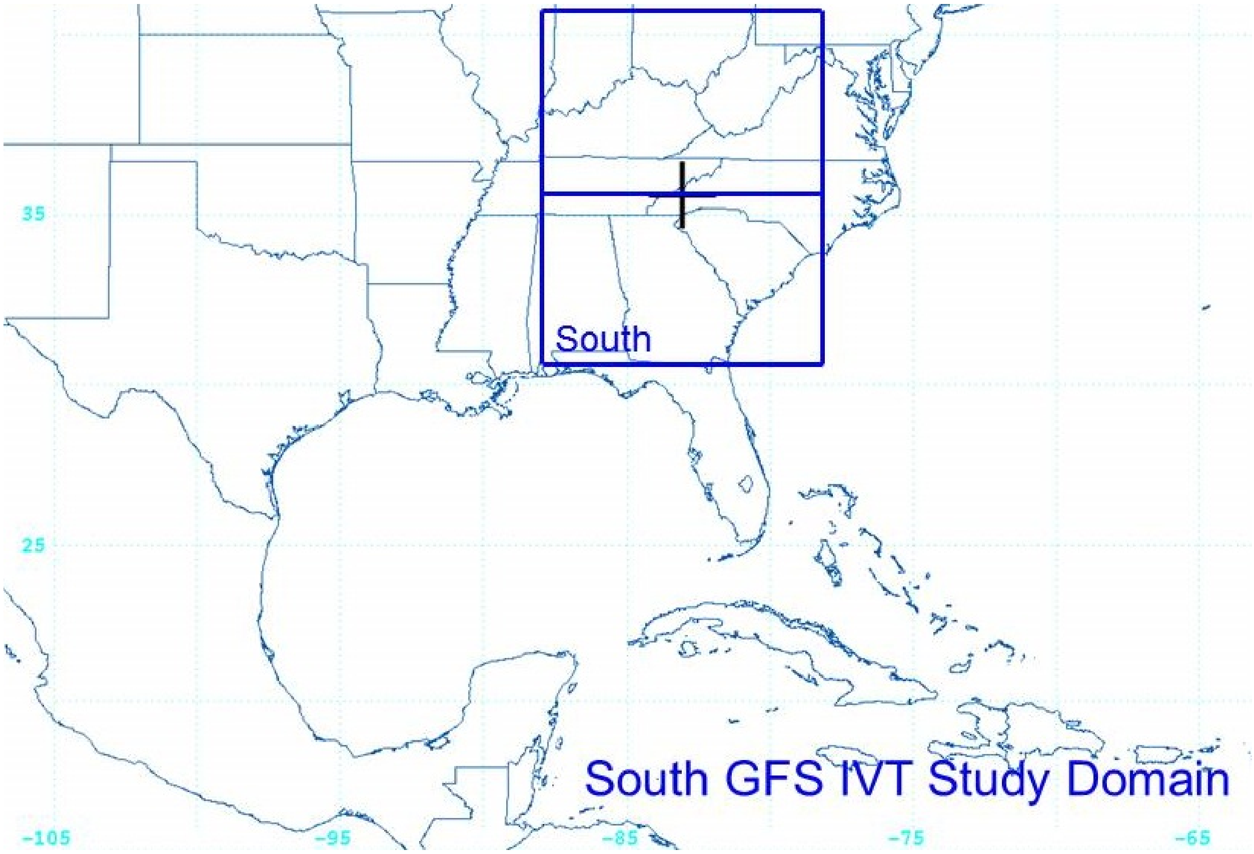
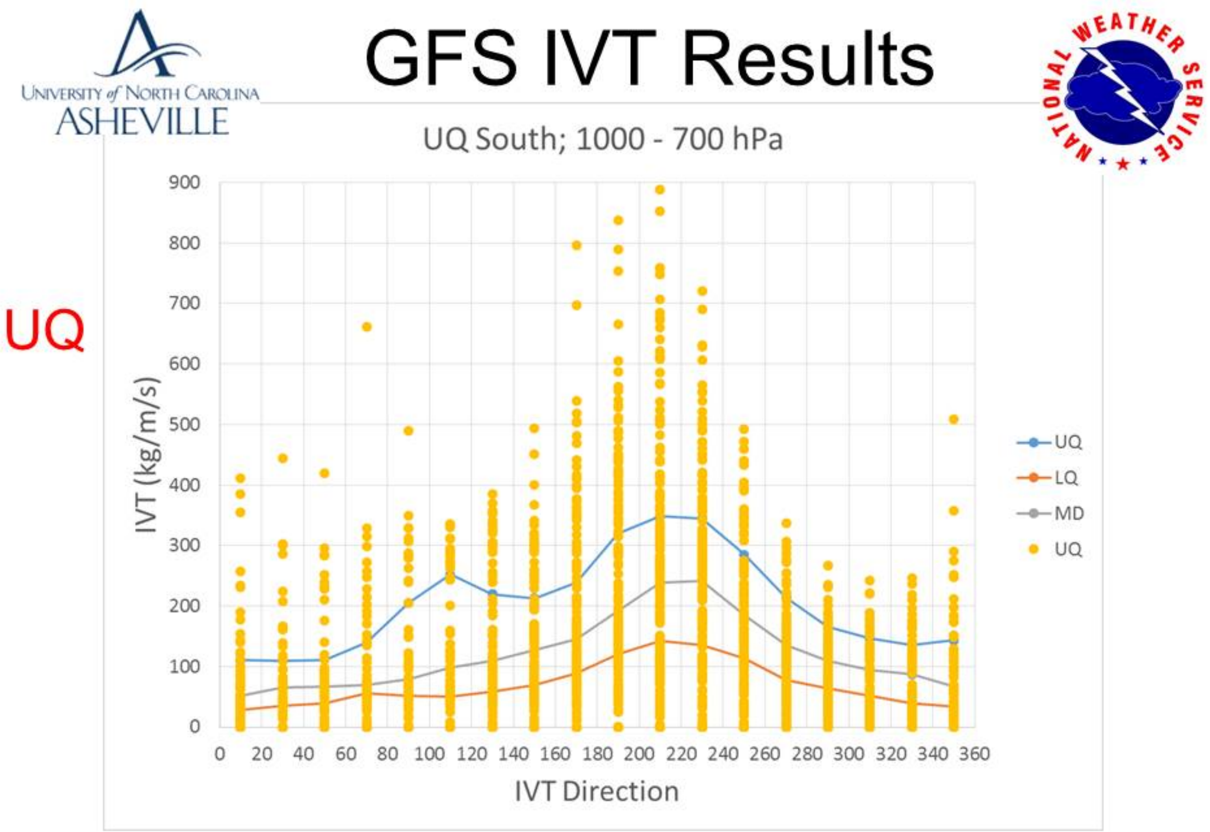


Figure 3. Domain for investigating GFS analysis-based IVT pattern evolution during the selected AM and UQ case studies.



GFS IVT Results

UQ

Figure 4. Layer (1000 – 700 hPa) integrated vapor transport (IVT, kg m^{-1} s^{-1}) based on GFS 0.5º x0.5º gridded analyses of upper-quartile (UQ) 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 (Figure 3). Orientation of the large-scale ridgeline of the southern Appalachian Mountains is 230º – 50º (southwest to northeast).

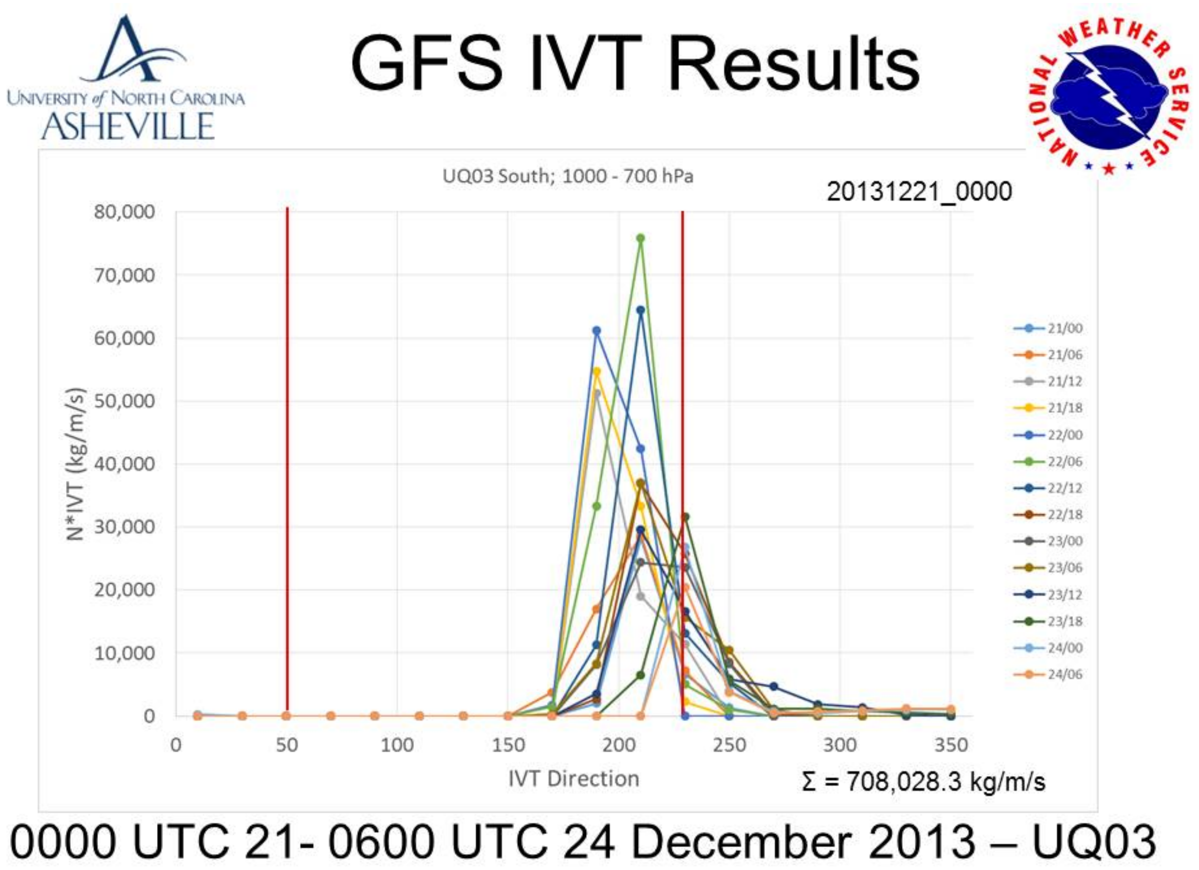
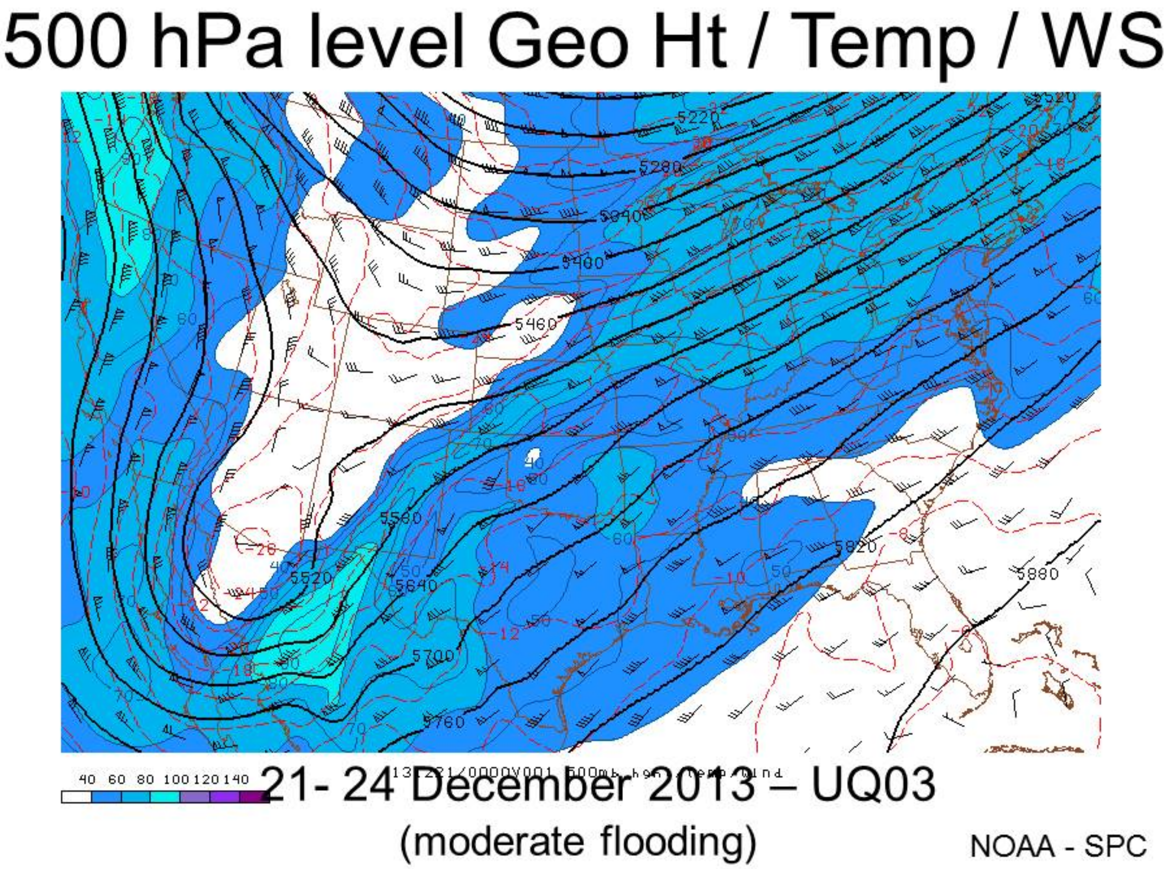


Figure 5. Layer (1000 – 700 hPa) integrated vapor transport (IVT, kg m^{-1} s^{-1}) based on GFS 0.5º x0.5º gridded analyses utilizing grid points located within the GFS search domain (Figure 3) impacting the Pigeon River Basin for event UQ03. Summation represents summed IVT values for grid points having an IVT direction within the 50º - 230º range (cross-mountain direction). Orientation of the large-scale ridgeline of the southern Appalachian Mountains is 230º – 50º (southwest to northeast).


500 hPa level Geo Ht / Temp / WS

21- 24 December 2013 – UQ03

(moderate flooding)

NOAA - SPC

Figure 6. Horizontal plot at the 500 hPa level of geopotential height (solid contours; m), air temperature (dashed contours; ºC), wind speed (shading; knots), and wind barbs (knots) for event UQ03.

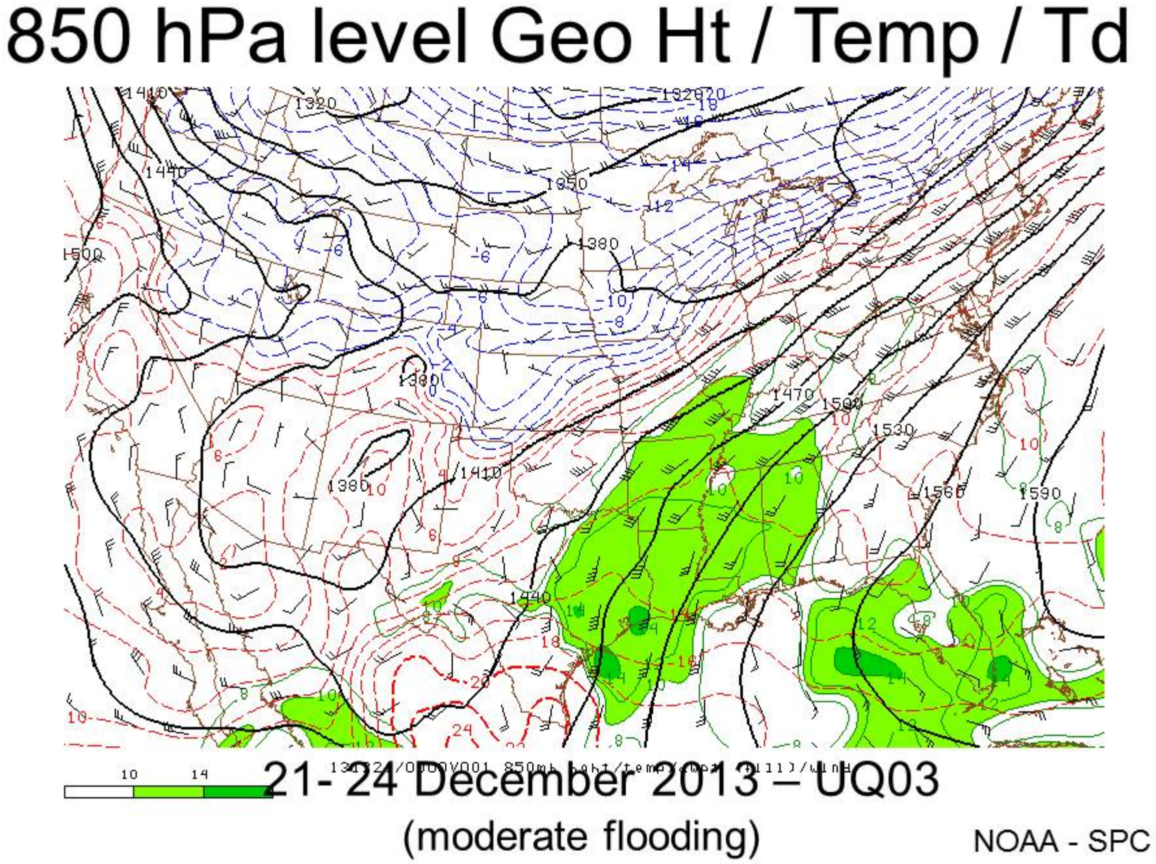


Figure 7. Horizontal plot at the 850 hPa level of geopotential height (solid contours; m), air temperature (dashed contours; ºC), dewpoint temperature (shading; ºC), and wind barbs (knots) for event UQ03.

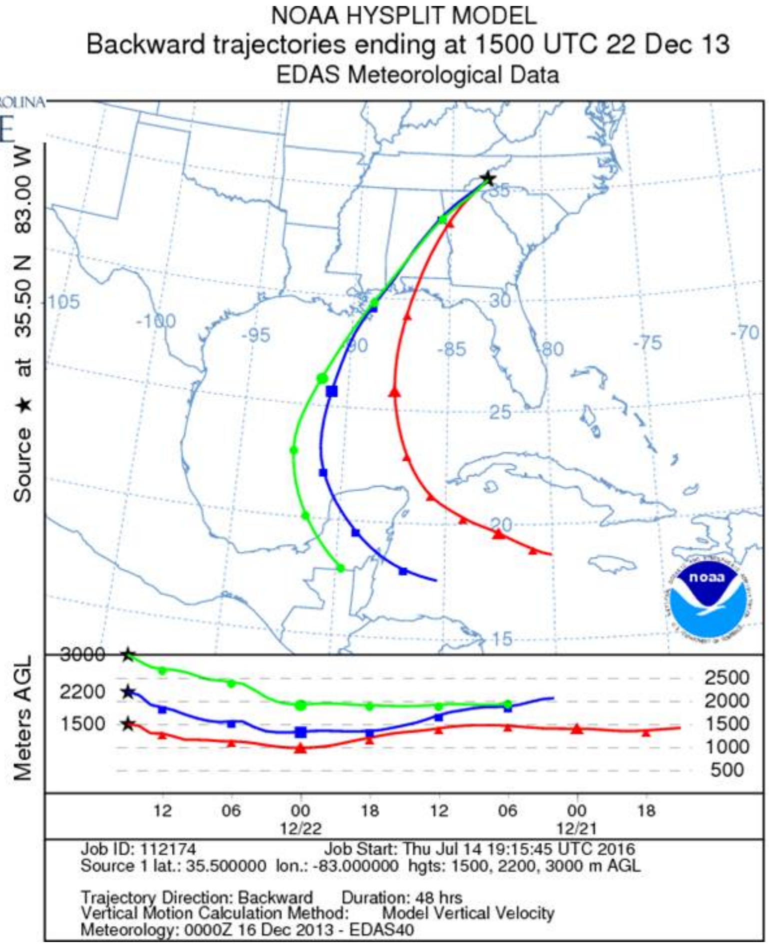


Figure 8. Backward trajectories via HYSPLIT for air parcels terminating at the center of the Pigeon River Basin at 1500 UTC 22 December 2013 at 1500 (red), 2200 (blue), and 3000 (green) meters above ground level for event UQ03. Trajectories are computed via HYSPLIT using EDAS gridded data.

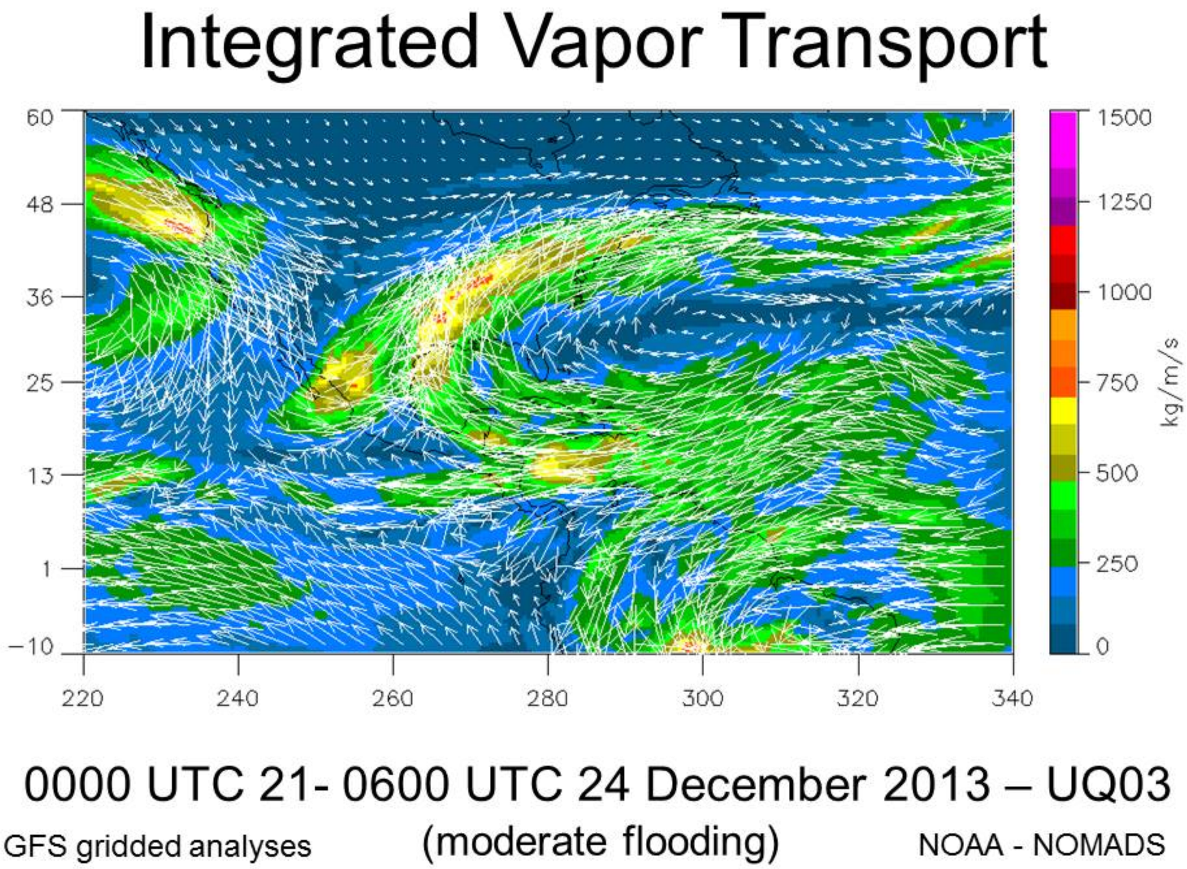


Figure 9. Layer (1000 – 100 hPa) integrated vapor transport (IVT, kg m^{-1} s^{-1}) based on GFS 0.5º x0.5º gridded analyses for event UQ03. IVT magnitude is shaded (color bar) and IVT vectors are plotted as light-colored arrows.