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The Influence of Atmospheric Rivers on Extreme Precipitation Events Observed in the Southern Appalachians

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Abstract

The central purpose of this project is to improve the understanding of Atmospheric Rivers (ARs), narrow lower-tropospheric air streams having high amounts of integrated water vapor, and the meteorological factors that produce flooding by ARs through investigating the influence of extreme precipitation in the southern Appalachian Mountains. Recently, much research has been conducted in order to find the impact of ARs on precipitation events in the United States. AR climatology suggests that precipitation of the Appalachian Mountains is minimally influenced by ARs, compared to regions immediately upstream and downstream of the mountains. A possible outcome for this research will be testing for robust results, supported by true atmospheric processes, or determining AR climatology artifacts from estimating precipitation in remote locations of the mountains. If ARs indeed prove to be an important contributor to the production of heavy precipitation events in the southern Appalachian Mountains, they can provide a good warning flag to the operational forecaster as their spatial and temporal evolution occur on scales large enough that they are detectable and predictable via current technological capabilities. The research methodology includes: (1) examining a five-year climatology of satellite total precipitable water (TPW) observations, mid- and high- elevation rain gauge network observations, USGS river and stream gauge observations, and gridded atmospheric data to determine the frequency of ARs impacting the southern Appalachians and the intensity of precipitation and severity of flooding that occurs during the interaction with the mountains, (2) collecting and archiving AR-influenced case studies with significant societal impacts in order to assemble a storm atlas, and (3) diagnosing the associated synoptic and/or mesoscale conditions favorable for maximizing the production of intense rainfall. The synoptic-scale characteristics associated with upper quartile events were found to consist of a positively-skewed 500 hPa seasonal stream of air, called the jet stream, and a deep, slow-moving mid-level low pressure system (trough). The integrated vapor transport was the most significant in determining whether an AR was involved in a heavy rainfall event.

Keywords: Atmospheric Rivers, Southern Appalachians, Flooding

1. Background

The mountainous terrain of the southern Appalachians is quite vulnerable to flash flooding due to its steep slopes and narrow basins. Each year, flooding and flash flooding are some of the leading causes of weather fatalities and damage in the region. Forecasters need a thorough understanding of the meteorological factors that produce heavy rainfall events. The improved understanding of Atmospheric Rivers (ARs) will increase the accuracy of both the flash watch and warning program, thus saving lives and protecting infrastructure.

ARs are very prominent off the west coast of the United States of America, and much research has been conducted in the past years in order to define ARs and their characteristics. Research was able to define Atmospheric Rivers as narrow plumes of Special Sensor Microwave Imager (SSM/I) integrated water vapor (IWV) greater than 2 cm that were greater than 2000 km long and less than 1000 km wide. Although IWV was found to be stronger in the summer and weaker in the winter, integrated vapor transport (IVT) was found to be strong when accompanying ARs in the winter and weak when accompanying ARs in the summer.[1]

Recently, research has been conducted on the possibility of an AR in the southeastern United States (U.S.). Looking at a case study of a major flooding event in Nashville, Tennessee, it was determined that an AR was to blame, and it was created by a low-level jet (LLJ) transporting a lot of moisture from the Caribbean Sea and the eastern tropical Pacific to central Mississippi Valley. The LLJ and the convectively generated outflow boundaries were fundamental in the generation of convection in the case study, which resulted in the development of two quasi-stationary Mesoscale Convective Systems (MCSs) and astonishing 200–400 mm (≈ 8–16 in.) rainfall totals.[2]

Another recent study discusses AR climatology in the United States, which suggests that ARs affect the Southern Appalachians very little compared to immediately upstream and downstream of the Appalachian Mountains. It is possible that this was an artifact created due to very few observations in the mountains and poor estimation of precipitation, so this project will help test to see if the results were robust or not.[3]

ARs can play a significant role in causing massive flooding and sometimes loss of life, and it is important to be able to recognize an AR and its characteristics. If significant flooding events can be predicted more accurately in the future, then fewer lives will be lost overall. Since ARs have not been researched as much in the southeastern U.S., this project can be the foundation for future research on ARs and the Southern Appalachians. The objectives for this study included determining the frequency that ARs impact the Southern Appalachians and the severity of the flooding problems encountered in eastern Tennessee when ARs are impacting the area, assembling a storm atlas for documenting heavy rainfall events in the southern Appalachians over the 1 July 2009 – 30 June 2014 period of study, and identifying the characteristics of different case studies to define the synoptic and/or mesoscale atmospheric conditions favorable for producing heavy rainfall.

2. Methodology

The particular interest in this project is to examine a five year climatology (1 July 2009 – 30 June 2014) of Moderate Resolution Imaging Spectroradiometer (MODIS) total precipitable water (TPW) observations, mid and high elevation rain gauge network (Duke/UNC Asheville [UNCA]/NASA) observations[4], USGS river and stream gauge observations, and gridded atmospheric data (e.g., GFS analyses)[5] to determine the frequency of ARs impacting the southern Appalachians and the intensity of precipitation and severity of flooding that occurs during their interaction with the mountain. The 500, 700, and 850 hPa level maps from the Storm Prediction Center (SPC) map archive were collected in order to investigate synoptic scale patterns of the sustained rainfall events described in section 2.3.

2.1 Rain Gauge Network

In 2007, the Great Smokey Mountain Rain Gauge Network (GSMRGN) was installed in the Pigeon River basin in western North Carolina.[4] In the GSMRGN there are a total of 32 gauges, ranging in elevation from 2003 m to 1036 m.[4] As a side note, there are two different types of rain gauges in the GSMRGN, and they are the 0.1 mm and the 1.0 mm tipping bucket rain gauges. The Pigeon River Basin (PRB) is important because the Pigeon River is a tributary that is connected to the Tennessee River and flows through Knoxville, Tennessee. If enough rain falls over this region, this could cause serious flooding in Tennessee, which shows why this rain gauge network is so valuable for future research. ARs could cause the massive flooding discussed and endanger lives.[2]

2.2 Data Sets

In total, this project looked at 6 data sets. They are (1) tipping bucket rain gauge observations from Duke University's GSMRGN[4], (2) GFS Analyses from NOAA Operational Model Archive and Distribution System[5], (3) GOES Sounder TPW from the University of Alabama Huntsville[6], (4) blended TPW (a.k.a IWV) from Colorado State University[7,8], (5) U.S. Geological Survey (USGS) stream gauge observations at Newport, Tennessee[9], and (6) NOAA's National Centers for Environmental Information's (NCEI's) Storm Data Publication[10]. These data sets were collected, used in other calculations and statistical processes, and analyzed in order to discover patterns and/or significant features among the data sets from the five-year climatological time period. The USGS stream gauge observations and Storm

Data Publications were both used by the NWS collaborators to assess societal impacts of the heavy rainfall categories determined from the rain gauge observations.

2.3 Sustained Rainfall Events

In order to determine if ARs can cause significant flooding in the Southern Appalachians and surrounding area, the tipping bucket rain gauge observations needed to be turned into *events* that could help distinguish periods of rainfall among the rain gauges. It was determined that for each rain gauge an *event* started/finished when a tip did not occur within six hours of the previous tip. Then, an event needed to have a numerical value, so that it can be ranked from least to greatest; thus, a rainfall parameter (RP) was created. For a single event, the RP was the duration of the event in hours, *dt,* multiplied by the total number of tips, *tips,* for the specific rain gauge and event as seen in equation (1). Next, RP values were ranked from least to greatest for each rain gauge. Since the bucket sizes differed, the current RP values could not be compared accurately. The 0.1 mm tipping bucket rain gauge would have more tips than the 1.0 mm tipping bucket rain gauge for the same amount of rainfall; thus, the RP values had to be normalized. In order to normalize the RP values and make RP become a normalized RP (NRP) shown in equation (2), every RP value, *RP*, for a specific rain gauge must be divided by the rain gauge's greatest RP, RP_{max}.

$$RP = tips \cdot dt \tag{1}$$
$$NRP = \frac{RP}{RP_{max}} \tag{2}$$

Next, I took every NRP value and multiplied it by one of the following five weights: (1) +4.0 upper quartile (UQ) NRP, (2) +1.5 above median (AM but NOT UQ), (3) +1.0 median NRP (no weighting), (4) -1.5 below median NRP, and (5) -4.0 lower quartile NRP. Then, results from all gauges needed to be combined; thus, events between rain gauges were considered as one single event if the start/finish time of a rain gauge event falls within one hour of the finish/start time of a different rain gauge's event. When combining the rain gauges' events, sum all of the weighted NRPs that go into the single final event. Once this was completed, the decision was made that in order for a combined event to qualify as an event of study, at least 27 of the 32 rain gauges had to report. This was for the purpose of having results across the entire GSMRGN. Lastly, the upper quartile and above median qualifying final events were ranked according to the weighted NRP. The top 17 upper quartile events and the top 15 above median events became these two groups to study: Upper Quartile events (UQ events) and Above Median events (AM events). The reason for including 2 more UQ events than AM events is for the possibility of the top two events being outliers since they are extreme events.

2.4 Integrated Vapor Transport

Calculating the integrated vapor transport (IVT) from the IWV, equation (3) was used exactly like it was used in Moore et. al. (2015) and for the similar purposes of verifying the presence of an AR.[3] The IVT was calculated as

$$-\int_{p_0}^{p} (q\boldsymbol{V})\,\frac{dp}{g} \tag{3}$$

where p_o is 1000 hPa, p is 300 hPa, g is the acceleration due to gravity, q is the specific humidity, and **V** is the horizontal wind. Using the GFS 0.5 by 0.5 degree gridded analysis, this equation can be used to calculate the IVT.

3. Results

3.1 Case Studies And Flooding

When analyzing the 17 UQ case studies and the 15 AM case studies (Table 1), there were important characteristics to note about both groups of events. For the UQ events, there were no case studies that occurred in the summer season (June, July, and August). There were 7 out of 17 UQ events that occurred in 2013. During 2013 there was a very weak La Niña to neutral. As for the AM events, they happened in all parts of the year, but it is important to note that 6 out of 15 AM events occurred July – October 2009. In 2009, there was a strengthening El Niño.

Table 1. 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 1–4 below. Duration of each event is located in the column label 'Δt (h)'. Possibility of the presence of an AR defined using synoptic maps and HYSPLIT trajectories are 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

ARs can cause major flooding, and the Newport, TN USGS Pigeon River gauge can show flooding from the GSMRGN. Therefore, looking at the river gauge for all AM events and UQ events can help show how many events caused flooding. One should note that the term *action stage* means that a river has reached or slightly run over its banks. Out of the 15 AM events, there were no minor, moderate, or major flooding events, but there were four action stage events. Out of the 17 UQ events, there were two minor flooding events, four moderate flooding events, three major flooding events, and two action stage events. Clearly, the UQ events would be assumed to cause more flooding, and this helps support that idea.

3.2 Synoptic Features

Looking at the collected 500 hPa level synoptic maps, there were some surprising common features that show up for both UQ events and AM events. For AM events, the 500 hPa jet stream was neutrally skewed, meaning that , and the 500 hPa level low pressure was located in northern-central U.S. A good example (Figure 2) that showed characteristics of UQ events is the 500 hPa level map on 21 December 2013 (UQ03).

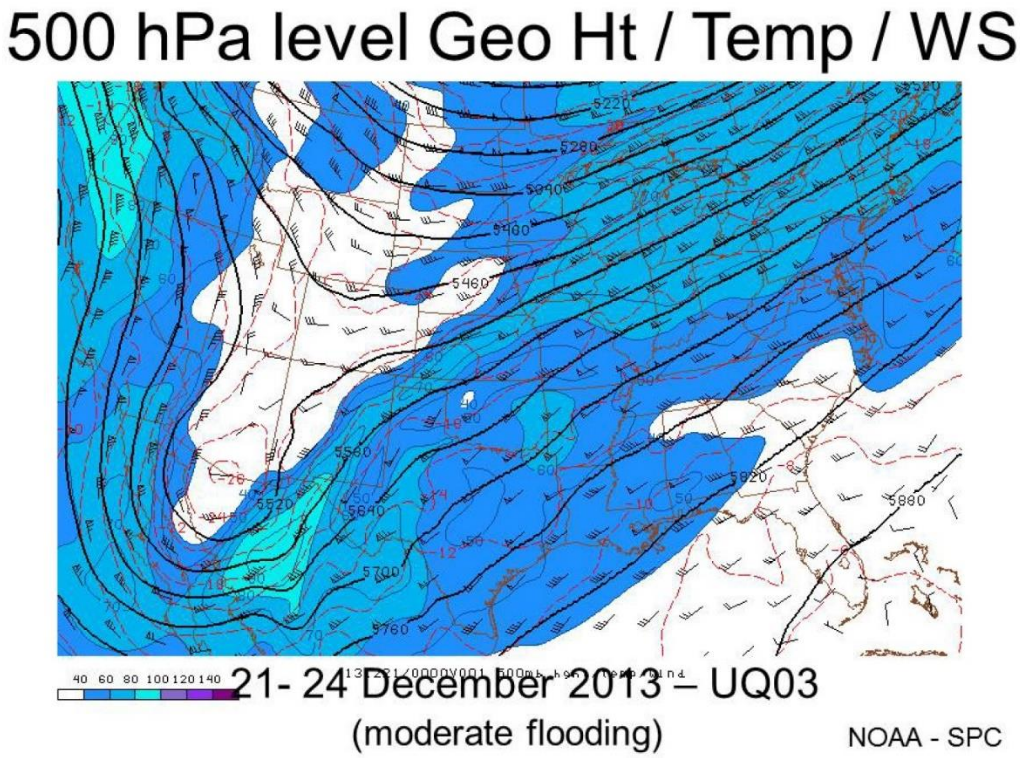

Figure 1. 500 hPa level geopotential height (solid contours; m), air temperature (dashed contours, °C), wind speed (shading; knots), and wind barbs (knots) for UQ03.

In the example above (Figure 1), a strong positively-tilted 500 hPa level polar jet stream along with a deep and slow-moving trough over the western United States (Arizona/New Mexico area). The moist air parcels that end up over the Southern Appalachian region must originate from some location, so we used the HYSPLIT model to find the paths that the air parcels traveled (Figure 2). The event is more likely associated with an AR when the air parcels originated from either the Atlantic Ocean or the Caribbean Sea.

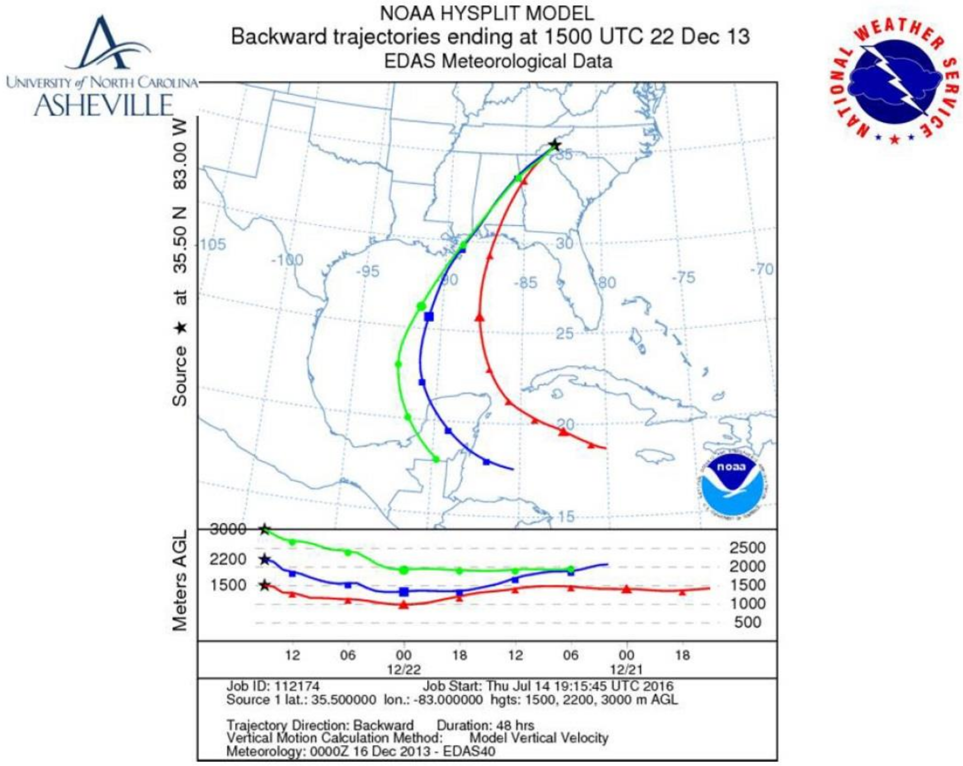

Figure 2. Backward trajectories computed via HYSPLIT using EDAS gridded data for air parcels ending at the center of the Pigeon River Basin at 1500 UTC 22 December 2013 at 1500 (red), 2200 (blue), and 3000 (green) meters above ground level for event UQ03.

3.3 Total Precipitable Water

The GOES Sounder TPW[6] images were plotted, and an investigation of statistical TPW analysis for an area centered on the Pigeon River Basin (PRB) of western North Carolina and eastern Tennessee. The center point of the area of study is located at 35.5°N, 83.0°W, and that area is 20° by 20° box centered on the center point. The initial stages of this statistical analysis began with histograms of all TPW values in the area of study for all AM events (Figure 4) and all UQ events (Figure 5).

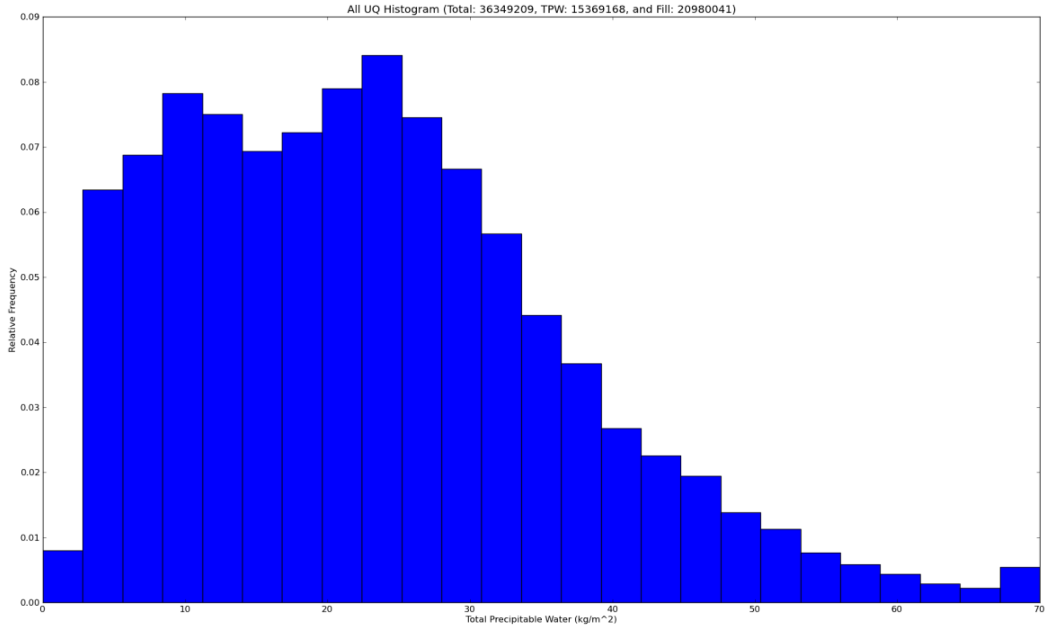

Figure 3. Histogram of GOES Sounder TPW values for all 17 UQ events.

The UQ events histogram (Figure 3) has very few high TPW values, which was somewhat surprising when higher values are expected for the more extreme events. Two thoughts about the cause of the surprising results were as followed: (1) there were many higher TPW values missing due to the filler values caused by clouds and (2) that there were no summer season UQ events, which would carry larger TPW values. More statistics will be computed in the near future for more results.

3.4 Integrated Vapor Transport

Looking at the integrated vapor transport (IVT) and the IVT direction for both AM events and UQ events, it shows what direction the most IVT is coming from. The IVT v. IVT direction binned plots show both two maximums for the IVT direction, the direction from which it comes, are 100°-120° and 200°-240°. Higher IVT values are more associated with UQ events IVT values were above the IVT upper quartile values line. As an example, the strong IVT in Figure 4 conveys a reason to believe that it is somehow related to ARs. Mahoney et al. (2016) identified that a strong AR occurs when the IVT zone exceeds 500 kg m^{-1} s^{-1} is less than 1500 km in width and at least 1500 km in length.[11] We were able to find that nine out of 12 possible AR events were considered strong AR events, and only one out of seven AM events was considered a strong AR event.

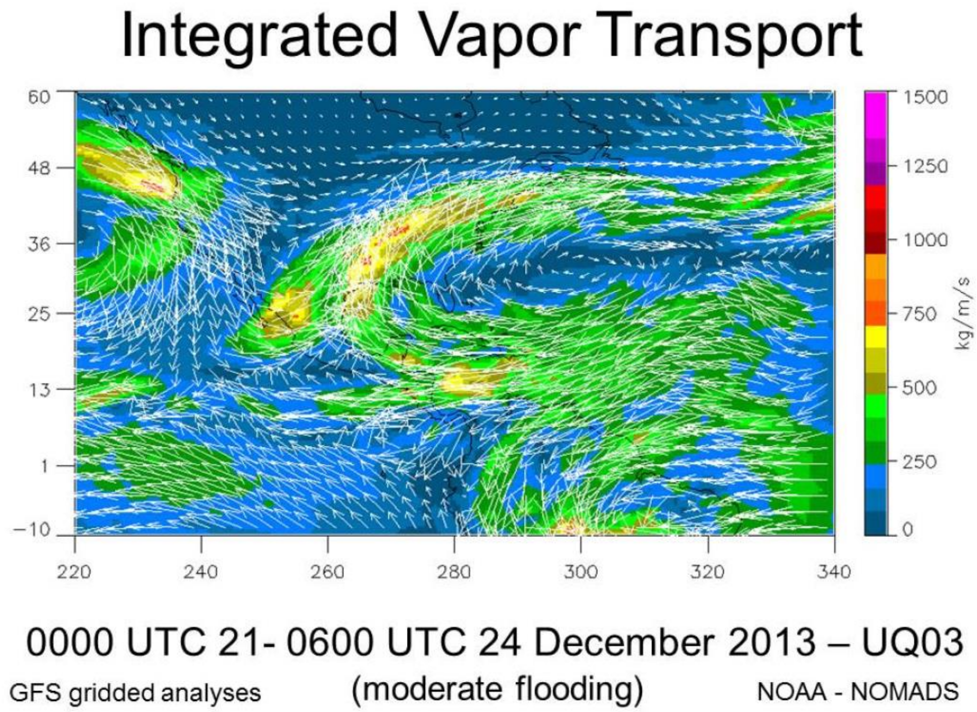

Figure 4. Layer (1000 – 100 hPa) IVT (kg m^{-1} s^{-1}) based on GFS 0.5°x0.5° gridded analyses for event UQ03. IVT magnitude is shaded (color bar) and IVT vectors are plotted as light-colored arrows.

4. Conclusions

From the results received so far, ARs do impact both the UQ and the AM events. In order to further prove this fact, the IVT calculated shows two prominent directions that IVT travels during heavy rainfall events. By using the definition of a strong AR defined by Mahoney et al. (2016), we were able to deduce that nine out of 12 "possible AR" UQ events were considered strong AR events, and only one out of seven "possible AR" AM events was considered a strong AR event. Another finding to note is that the event was more likely associated with an AR when the air parcels originated from the Atlantic Ocean or the Caribbean Sea. The event was also more likely associated with an AR when the air parcels showed a counterclockwise trajectory when originating from the Caribbean Sea and a clockwise trajectory when originating from the Atlantic Ocean.

ARs do impact the Southern Appalachians; however, can the GOES Sounder detect ARs? We found that with current GOES satellite, the answer is no. Most of the time the GOES Sounder has problems if there is much cloud cover. An interesting future study would be if the new GOES-R does a better job at detecting ARs. The current launch date for the GOES-R satellite is 4 November 2016.

Because we created a storm atlas for extreme precipitation events over the Southern Appalachians (more specifically the PRB), determined characteristics of these extreme events, and found different datasets that were both important and unimportant, many forecasters can use this research for predicting extreme precipitation events in the Southern Appalachians. This extreme precipitation can cause massive flooding as seen by the USGS Pigeon River Gauge. Due to the lack of research completed surrounding this AR in the eastern United States, the research is also intended to help support a better foundation surrounding the topic.

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