

Landslide and Flood Risk from Tropical Cyclones in Western North Carolina

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Abstract

Despite being far from the coast, intense rainfall from tropical cyclones is known to cause flash flooding and landslides in Western North Carolina (WNC). A study was conducted to investigate tropical cyclones in WNC during the period 2009-2019 and determine what synoptic and mesoscale features increase the risk of landslides and floods from these events in the Pigeon River Basin (PRB). A case study of two meteorologically similar storms with vastly different surface responses was chosen to begin to answer this question. Both storms tracked west of the Appalachians and reported the same rainfall in the PRB, but Tropical Storm Alberto in May 2018 caused multiple landslides that resulted in two deaths in WNC while Hurricane Nate in October 2017 resulted in no direct effects. To understand why these events had such different consequences, three aspects were analyzed: the preconditioning of the soil from previous precipitation events, the 500 hPa steering flow, and the flow of moisture at 850 hPa. Despite initial analyses indicating otherwise, the difference in moisture flow between Nate and Alberto was not significant enough to suggest that was the reason for their different impacts. Alberto occurred during a prolonged period of anomalous precipitation and was a longer event while Nate was a shorter event that occurred in a relatively dry period.

1. Introduction

According to the 2010 census, Appalachian North Carolina saw an 11.3% rise in population¹ and while Asheville's population growth has been slowing in recent years, surrounding areas are seeing an increase². More development in these mountainous areas increases the need to understand precipitation processes and hazards that occur there. Despite being far away from the coast, tropical cyclones do affect the Appalachians, contributing to a peak in precipitation between August and November³. While the effect of climate change on tropical cyclones is not fully understood, climate scientists are confident that there will be an increase in sea surface temperatures, which will likely enhance intensities of future storms that could have greater impacts inland in the mountains.

The remnants of Hurricanes Frances and Ivan in September 2004 caused at least 155 landslides in the North Carolina Blue Ridge Mountains⁴. In a study simulating rainfall from Ivan, Sun and Barros (2012) state that due to the lack of observations in high elevations, orographic enhancement could have contributed to higher precipitation than simulated⁵. Tao and Barros (2013) investigated the precipitation and flood estimates and forecasts during the passage of Tropical Storm Fay in 2008 in Western North Carolina. They generated these values by creating a high-resolution hydrological model with quantitative precipitation estimates derived from assimilation of the available observations from the Duke Great Smoky Mountains Rain Gauge Network (Duke GSMRGN) gauges and found that it could successfully predict stream gauge observations in flash flood scenarios⁶.

Harville (2009) used North America Regional Reanalysis and the Weather Research and Forecasting model to analyze rainfall distributions from tropical cyclones that have affected the southern and central Appalachians. Four storm tracks and areas of highest flooding potential of each track were identified. Tropical cyclones running along the eastern side of the Appalachians and those that track more orthogonal to the mountain range exhibited the heaviest

rainfall over Western North Carolina. One focus of this study was extratropical transition (ET) of tropical cyclones which intensify the storm and increase precipitation. When ET occurs the effect of the mountains increases precipitation from the cyclone northwest of the Appalachians⁷.

Previous research with landslides in this region can be found in a study by Miller et al. (2019) which continued research looking at the association between atmospheric rivers (AR) and heavy rain events in the southern Appalachian Mountains. This study found a high linkage between societal hazard in downstream locations between these AR associated events. It also concluded that long periods of intense precipitation were correlated with days having at least one landslide in western North Carolina⁸.

With a changing climate and an increasing population in the mountains, it is important to understand the events behind these risks to determine their costs in the face of an uncertain future. This study examines the period of 2009–2019 and creates a database of tropical cyclones that precipitated in WNC. Since the sample size during this period was not large enough to perform a statistical analysis on, a case study of two cases with similar tracks but different outcomes, Hurricane Nate (2017) and Tropical Storm Alberto (2018), was conducted. This paper will first present the study’s data and methodology, next cover a discussion of the results from the climatology and case study, and finish with concluding thoughts and acknowledgements.

2. Data and Methodology

The study was confined to the Pigeon River Basin (PRB) which begins in Haywood County, North Carolina and flows into the French Broad River in Cocke County, Tennessee. Only events that occurred between July 1st, 2009 and November 30th, 2019 in this area were included in the analysis. They were selected based on precipitation directly attributed to the cyclone from the Weather Prediction Center’s (WPC) Tropical Cyclone Rainfall Data maps in this area. These limitations were chosen because of the existence of the Duke Great Smoky Mountains Rain Gauge Network (Duke GSMRGN), a series of rain gauges in Haywood County that became operational on July 1st, 2009 (see figure 1 for map of gauges).

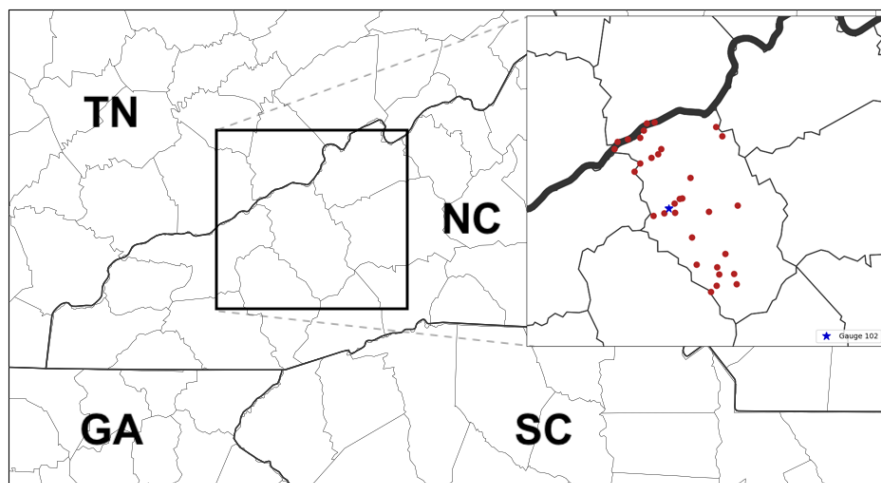


Figure 1. Map of Duke GSMRGN in Haywood County, North Carolina. Gauge 102 is used to compare preconditioning between the two events

The Duke GSMRGN was the main source of precipitation observations, but ASOS stations provided a comparison to other areas in WNC. Cyclone track information was obtained from the WPC and the National Hurricane Center’s (NHC) tropical cyclone reports, and upper-level maps were generated from archived reanalysis gridded data from the Global Forecast System (GFS) model. Flood report data, divided into minor, moderate, and major flood stage, were obtained from the United States Geological Survey’s (USGS) stream gages and NWS flood reports, and landslide data from the NC Geological Survey.

The first step of analysis was making a database of tropical storms that affected WNC during this period. Archived weather maps, surface analyses from the Weather Prediction Center (WPC), and NCEI archived radar imagery helped determine the length of each event. Total precipitation from the Duke GSMRGN was calculated throughout the event’s

period. Landslides and flood reports that occurred during and up to a week following the event were noted as directly attributed to TC event and those that occurred within 30 days were noted as indirectly attributable. In the case study of Nate and Alberto, several variables from the GFS gridded data were compared to examine their differences: 500 hPa flow, 850 hPa flow and precipitable water, and rainfall totals in the PRB and ASOS stations in WNC leading up to each event. To investigate the 850 hPa moisture transport of the two events, further analysis was performed to determine the strength and precipitation potential of cross elevation contour flow using this equation:

$$CCF = p_{wat} * (\nabla z \cdot \vec{V}), \quad (1)$$

where p_{wat} is precipitable water, z is elevation, and \vec{V} is the 850 hPa wind vector. Elevation data was obtained from the Scripps Institute for Oceanography. Cross sections of equivalent potential temperature from GFS gridded data and NOAA's Hysplit trajectory model was used to investigate stability for each event. The Hysplit model was also used to determine the moisture source.

3. Results

Throughout the study period, there were 18 events tropical in origin that precipitated in the PRB (see table 1 on the next page). The majority tracked parallel to the ridgeline, half along the western slope and less than a third along the eastern slope. Most of the events (13) had flooding in the following 30 days while seven contributed to flooding within the next week. A little more than half played a role in landslides with only three TCs having landslides within a week of the event.

None of the events recorded particularly high accumulations in the PRB, the highest not even reaching 10 cm (or 4 inches). Tropical Storm Andrea occurred during a time of high rains in the summer of 2013 with all the landslides taking place in the beginning of July. Most of these events played a more destructive role other areas of the country, except Tropical Storm Alberto which contributed by far the most landslides out of any event.

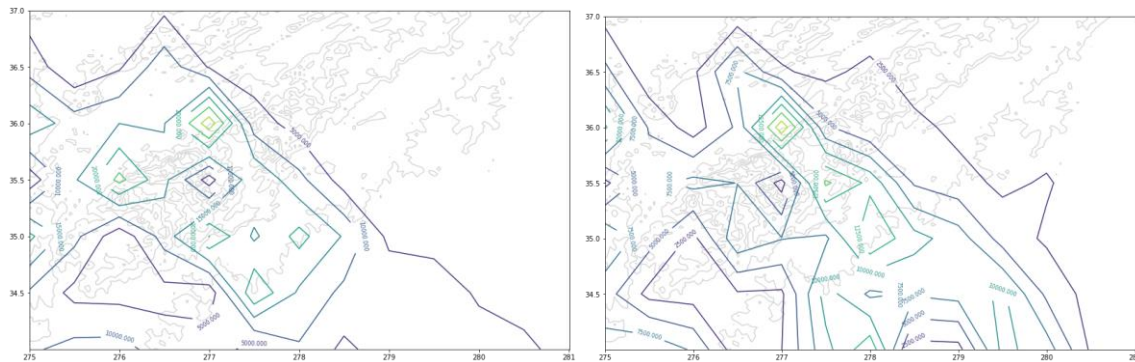


Figure 2. Calculated CCF (see equation 1 above) over study area during Alberto (left) and Nate (right) when the low centers were in the center of Alabama plotted against elevation contours plotted every 250 m. Higher values of CCF suggest higher moisture transport perpendicular to the ridge line.

3.1. Case study of Hurricane Nate and Tropical Storm Alberto

Nate and Alberto's similar tracks but very different consequences made for a useful case study to identify some features that might enhance flood and landslide risk to WNC. The weakness in the initial analysis of limiting the study area to the PRB to determine general risk to the entire WNC became very apparent in this case study. While Nate and Alberto had similar precipitation in the PRB, accumulations recorded farther east on the Blue Ridge escarpment told a different story. Both cases had similar patterns of maximum precipitation in this area, indicative of southeasterly flow, but more areas recorded higher accumulations during Alberto. This pattern suggested that there was more efficient cross elevation contour moisture transport during Alberto than during Nate. However, when the CCF parameter

discussed above during both events was calculated, the results suggested the opposite (see Figure 2 on previous page). If CCF were an accurate and applicable indicator of precipitation in this case study, higher accumulations would have been recorded during Nate. Trajectory analysis showed similar stability between the two cases and confirmed that this flow could not have been a major factor in differentiating the two events. Therefore, two other factors were determined as possible reasons why Alberto resulted in higher flood and landslide risk than Nate.

Table 1: Climatology of Tropical Cyclone Events that affected Western North Carolina

| STORM NAME | EVENT PERIOD (UTC) | TRACK | TOTAL ACCUMULATION (MM) | FLOOD (DIRECT/INDIRECT, MAX STAGE) | LANDSLIDE (DIRECT/INDIRECT, # IN WNC) |
|-------------------------|---------------------------------|-------------------------|--------------------------------|-------------------------------------------|----------------------------------------------|
| <i>H. IDA</i> | 04z 10 – 06z 12 Nov 2009 | to eastern slope | 92.42 | Direct, moderate stage | Direct (3) |
| <i>T.S. LEE</i> | 03z 5 – 00z 7 Sep 2011 | SW to NE across ridge | 72.38 | | |
| <i>FLORIDA GALE</i> | 22z 10 – 07z 12 Oct 2011 | SE to NW across ridge | 21.36 | | |
| <i>H. ISAAC</i> | 03z 3 – 12z Sep 4 2012 | to western facing slope | 9.52 | | |
| <i>H. SANDY</i> | 14z 29 – 22z 31 Oct 2012 | to eastern slope | 8.32 | | Indirect (1) |
| <i>T. S. ANDREA</i> | 6z 7 – 06z 8 Jun 2013 | to eastern slope | 17.18 | Indirect | Indirect (9) |
| <i>T. S. CINDY</i> | 00z – 12z 24 Jun 2017 | to western facing slope | 19.87 | | |
| <i>H. HARVEY</i> | 03z 31 Aug – 18z 01 Sep 2017 | to western facing slope | 29.71 | Indirect (Irma) | Indirect (1) |
| <i>H. IRMA</i> | 09z 11 – 20z 12 Sep 2017 | to western facing slope | 52.77 | Direct, action | Indirect (1) |
| <i>H. NATE</i> | 06z 8 – 12z 9 Oct 2017 | to western facing slope | 61.06 | Indirect | Indirect (2) |
| <i>T. S. ALBERT</i> | 6z 28 – 3z 31 May 2018 | to western facing slope | 59.10 | Direct, flood stage | Direct (18) |
| <i>T. S. GORDON</i> | 20z 9 – 2z 12 Sep 2018 | to western facing slope | 18.01 | Indirect (Michael) | |
| <i>H. FLORENCE</i> | 14z 15 – 12z 18 Sep 2018 | SE to NW across ridge | 65.84 | Indirect (Michael) | Indirect (1) |
| <i>H. MICHAEL</i> | 23z 10 – 21z 11 Oct 2018 | to eastern slope | 69.16 | Direct, flood | |
| <i>H. BARRY</i> | 15z 17 – 09z 18 Jul, 2019 | to western facing slope | 4.24 | Indirect | |
| <i>POST T.C. NESTOR</i> | 15z 19 – 21z 20 Oct 2019 | to eastern slope | 29.87 | Direct, Action | Indirect |
| <i>POST T.C. OLGA</i> | 15z 25 – 12z 27 Oct 2019 | to western facing slope | 40.26 | Direct, Action | Direct (2) |

*Mean of total accumulation over all gauges in the Duke GSMRGN

3.1.1 Duration of the Event

The two events moved at different speeds, determined mainly by synoptic features that can be seen at the 500 hPa level in Figure 3. The location of Nate and Alberto can be identified in the figure as the local low in geopotential height in Alabama. When Nate made landfall, there was a zonal flow pattern across most of the US with the strong westerly winds accelerating the storm northeast. Nate moved over the study area at an average speed of 13.4 m s^{-1} . Alberto's movement when precipitating over the study area was dominated by a weak ridge to its west so its speed was only an average of 7.0 m s^{-1} . Because Alberto moved slower, it was located west of the Appalachians for a longer period which meant the pattern of circulation of southeasterly winds perpendicular to the ridgeline also occurred for a longer time. This suggests there was more time for lifted moist air from the Gulf of Mexico to precipitate on the eastern escarpment, causing the higher accumulations.

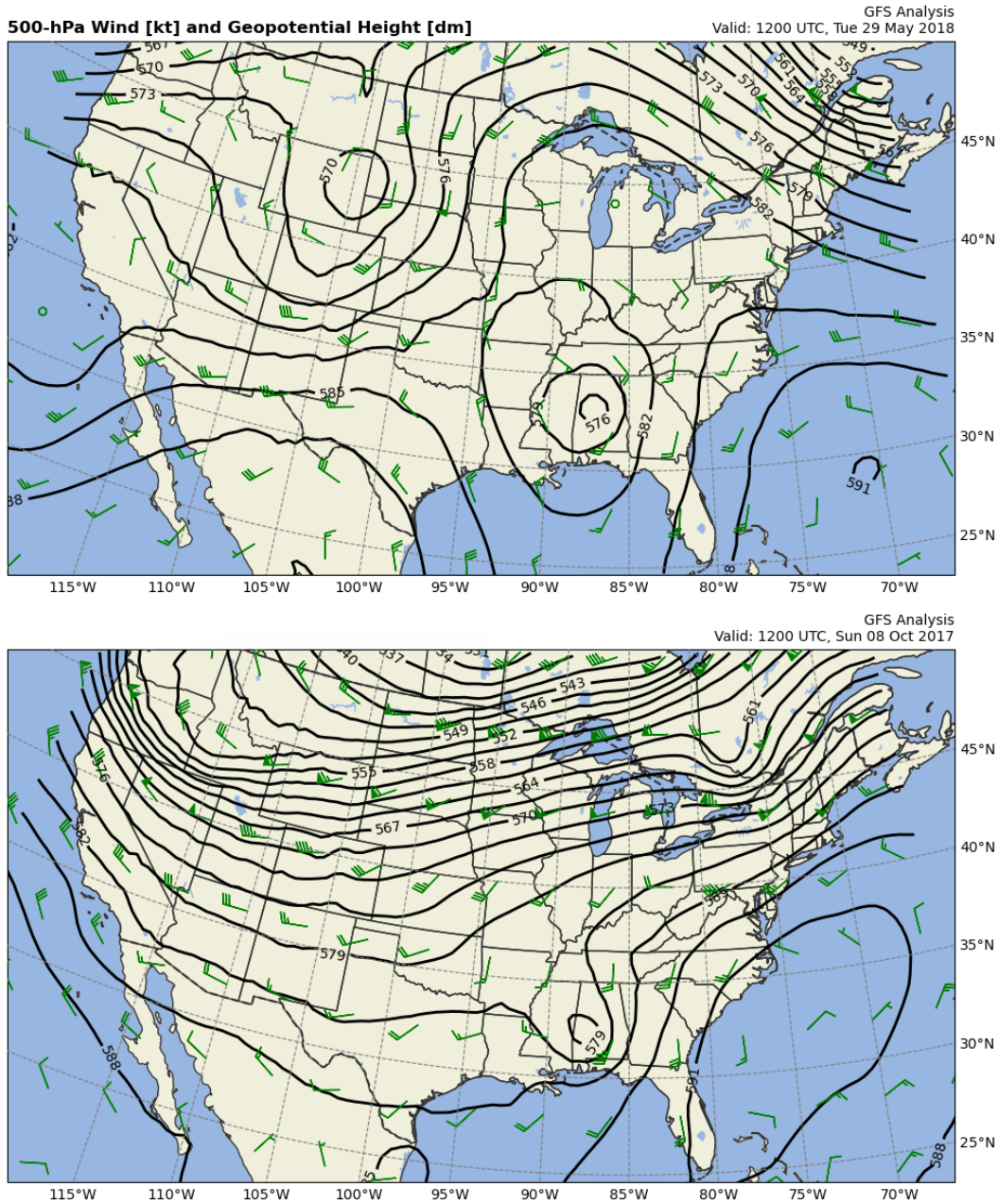


Figure 3. 500 hPa geopotential height and wind speed plot when Alberto (top) and Nate (bottom) were located in Alabama. Wind barbs are in green.

3.1.2 Soil Preconditioning

The precipitation preceding the events was largely different between the events which meant that the soil conditions were also different. In the 30 days leading up to Nate, there was a 59.26 mm average accumulation per gauge with Hurricane Irma in early September being the main precipitation event in this period. Before Alberto, there were consistent rain events with totals per gauge averaging 161.34 mm. This meant that when Alberto tracked by WNC, the soil was already saturated which most likely led to the landslides during and after the event. Figure 4 shows the general pattern of preconditioning precipitation through plots of Gauge 102 in the Duke GSMRGN.

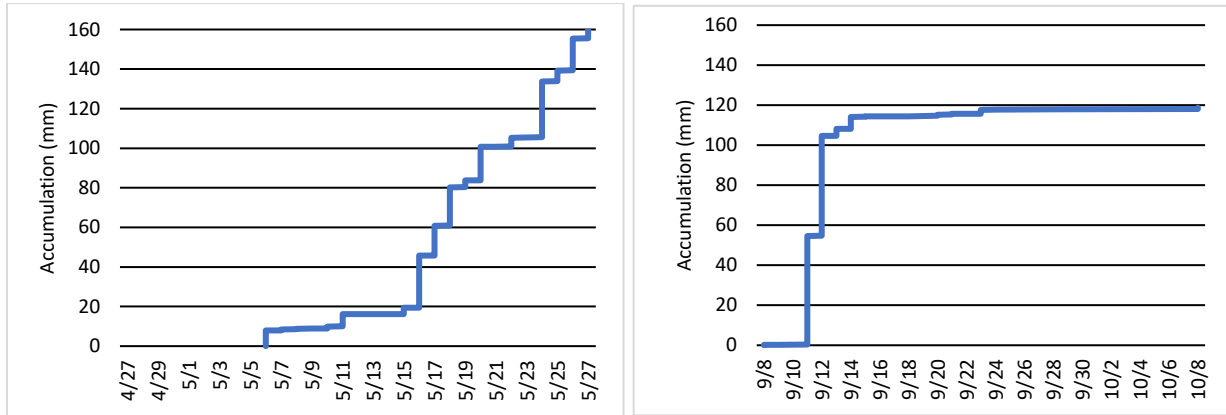


Figure 4. Accumulation plots of 30-day precipitation preceding Alberto (top) and Nate (bottom) measured by Gauge 102 from the Duke GSMRGN. Each increase represents a rain event.

4. Conclusion

Between 2009 and 2019, there were 18 tropical cyclones that contributed to precipitation in WNC. Nine of them tracked west of the Appalachians which allowed for moist southeasterly flow from the Gulf of Mexico to intersect the eastern Blue Ridge escarpment and cause local maximum precipitation accumulation. A case study was performed on two events where this occurred, Tropical Storm Alberto (2018) and Hurricane Nate (2017). Landslides and flooding occurred in the region that were directly attributed to Alberto and not to Nate. These events had very similar tracks and flow patterns but differed in their length and preceding precipitation which led to the high risk of flood and landslides following Alberto. Reanalysis data and trajectory analysis confirmed that cross ridge moisture transport efficiency was not a main player in differentiating these two events.

To confirm that these two factors are the only ones at play, future work will be done to compare the rain rates during Nate and Alberto at the locations of the landslides that occurred during or after Alberto. However, there is plenty of work that can be done outside of this case study. There are other options for comparison case studies in this database like one between Hurricane Michael (2018) and Hurricane Ida (2009). These two events had the highest rainfall accumulation in the PRB but different landslide risk. Since 2019, there have been several other examples of tropical cyclones that have the same flow pattern as Nate and Alberto, included Hurricane Zeta (2020) and Tropical Storm Fred (2021) that could be used to of this phenomenon further. This is only the start to investigating the impact of tropical cyclones in WNC.

5. Acknowledgements

This author would like to thank Doug Miller for advising this project and providing the GSMRGN data, Christopher Hennon for giving advice about tropical cyclone data sources, and Christopher Godfrey for helping through numerous

coding issues and giving the idea of the CCF calculation. Also much appreciated by this author is Massey Bartolini for his reanalysis data coding tutorial and Rick Wooten for the landslide dataset.

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