The Role of Hurricane Joaquin (2015) in the South Carolina Flood

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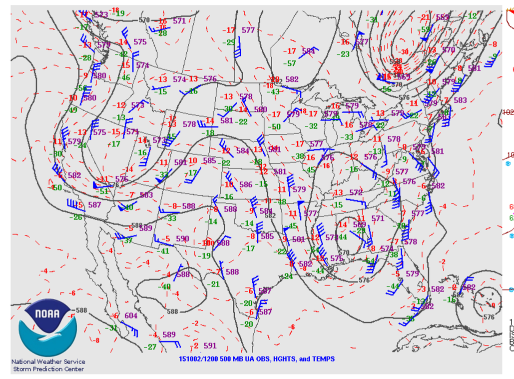
Introduction

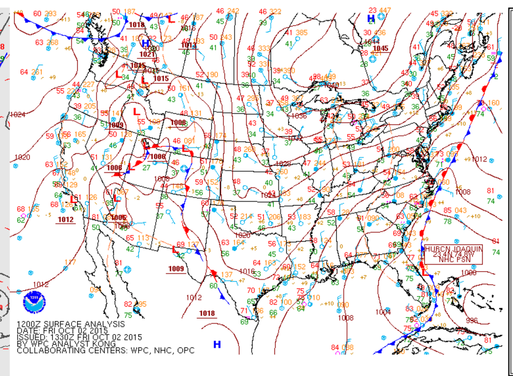
Tropical cyclones increase the potential for intense precipitation in states along the United States Atlantic Coast. The most significant precipitation usually occurs after a tropical cyclone makes landfall and starts to transition into an extratropical cyclone, as with Hurricane Agnes (1972) and Hurricane Floyd (1999). Several studies have researched the tropical-extratropical cyclone transition, but few studies have researched the other impacts that tropical cyclones can have on coastal states through large-scale atmospheric interactions. One impact occurs when a tropical cyclone interacts with a separate extratropical cyclone, as well as a coastal front, leading to elevated convection and significant precipitation in coastal states without hurricane landfall, as with Hurricane Joaquin (2015). The Hurricane Joaquin (2015) event provides the starting ground for an investigation of elevated convection and intense precipitation enhanced by the tropical cyclone interaction with a cold-core low and a coastal front.

Event Summary

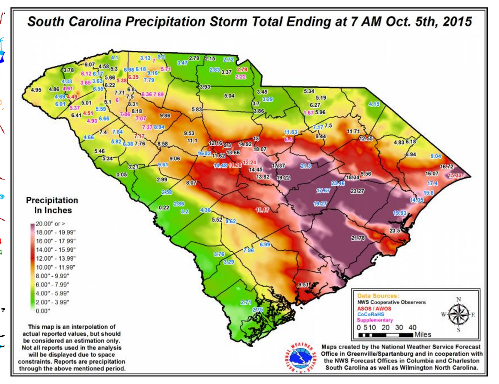
Hurricane Joaquin (2015) intensified near the Bahamas in early October, while a cold-core low was forming over the southeastern United States and a stationary front was laying along the East Coast. These three systems interacted and intensified with Hurricane Joaquin reaching a status of category 4, causing an intense and prolonged elevated convection event. A moisture plume formed around 1200 UTC 02 October 2015 along the axis of dilatation, associated with a deformation zone, between the upper-level low and Hurricane Joaquin. The moisture plume was directed towards South Carolina, even as Hurricane Joaquin moved northeast towards Bermuda, due to the positioning of both cyclones and their related propagation with a slight indication of the Fujiwhara effect. As a result, South Carolina received significant precipitation and flooding, causing extensive damage. It is likely that the combined effects from both cyclones, interacting with the coastal front, lead to the intensity, location, and timing of the elevated convection and precipitation.



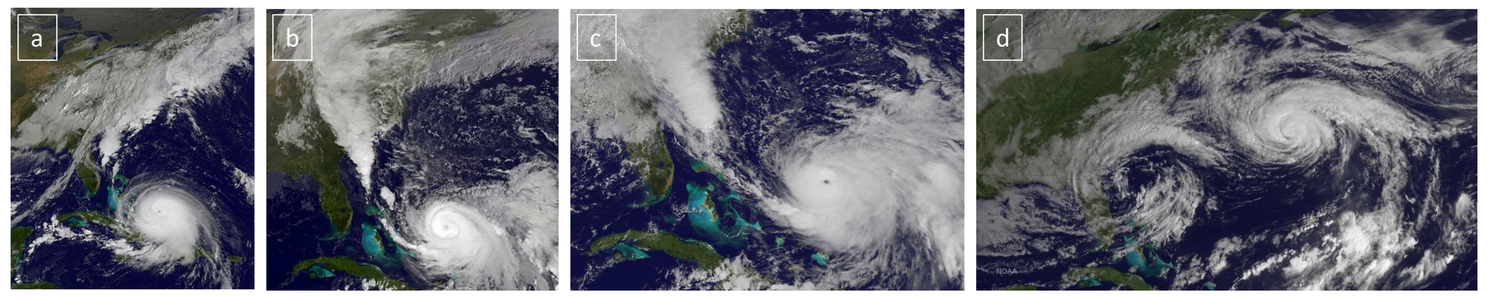
NOAA 500 mb analysis for 1200 UTC 02 October 2015, displaying an extratropical cyclone centered over Alabama with Hurricane Joaquin located near the Bahamas.



NOAA surface analysis for 1200 UTC 02 October 2015, displaying a stationary front just off the East Coast with Hurricane Joaquin located near the Bahamas.



Map of South Carolina, created by the NWS, displaying total rainfall amounts for the event, from 0000 UTC 01 October 2015 to 0600 UTC 05 October 2015. The maximum rainfall amount totaled 26.88 inches near Mt. Pleasant, S.C.



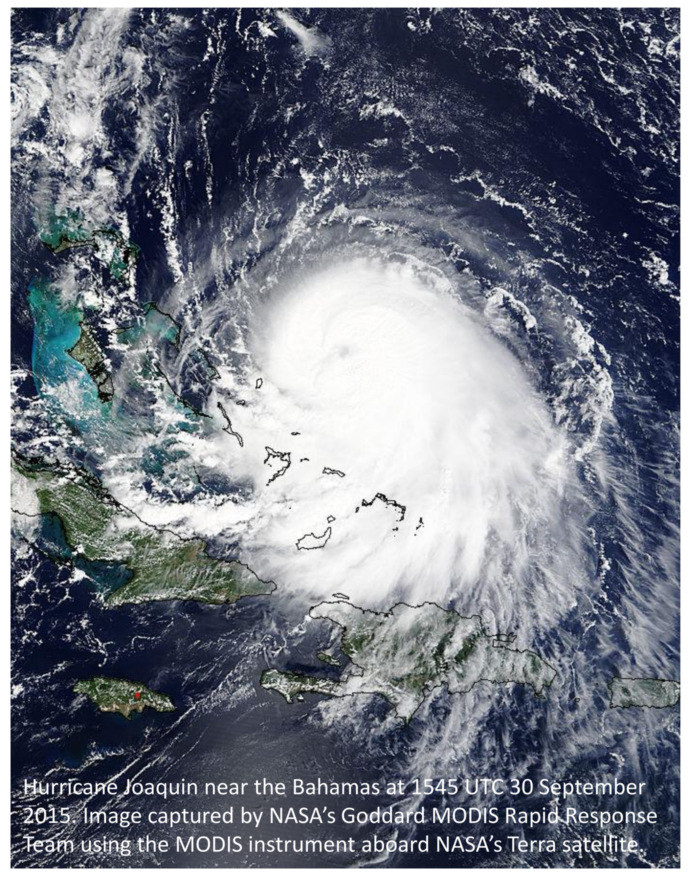
Visible satellite images of Hurricane Joaquin and the associated moisture plume for the extent of the South Carolina heavy rainfall event, beginning on 01 October 2015 and ending on 05 October 2015. Image dates: (a) 1315 UTC 01 October 2015, (b) 1200 UTC 03 October 2015, (c) 1600 UTC 03 October 2015, and (d) 1200 UTC 05 October 2015. Image (a) displays Hurricane Joaquin located over the Bahamas with a moisture plume beginning to develop to the northwest and cloud cover present along the East Coast frontal boundary. Image (b) displays Hurricane Joaquin shortly after departure from the Bahamas with the moisture plume at it's peak intensity directly pointed towards South Carolina. Hurricane Joaquin is located northeast of the Bahamas in image (c) with moisture still being advected towards South Carolina. Image (d) represents the aftermath of the event with Hurricane Joaquin near Bermuda and the extratropical cyclone now visible east of Georgia. The extratropical cyclone aligned with Hurricane Joaquin and they both propagated northeast into the Atlantic Ocean. Images captured by NOAA's GOES-East satellite.

Hypotheses

Hypothesis 1: Without the presence of the hurricane, it is possible for the extratropical cyclone to have weakened faster and propagated north along the coastal front, creating a widespread area of precipitation with little to no elevated convection.

Hypothesis 2: The absence of the extratropical cyclone would have likely resulted in a less intense hurricane, propagating north along the front, making landfall and causing widespread precipitation with a chance of short-lived elevated convection.

Hypothesis 3: The terrain played a role in the location and strength of the frontal boundary. Without the Appalachian Mountains, the coastal front could've been much weaker and further inland, leading to much less precipitation along the East Coast due to a weaker interaction with the aforementioned cyclones.



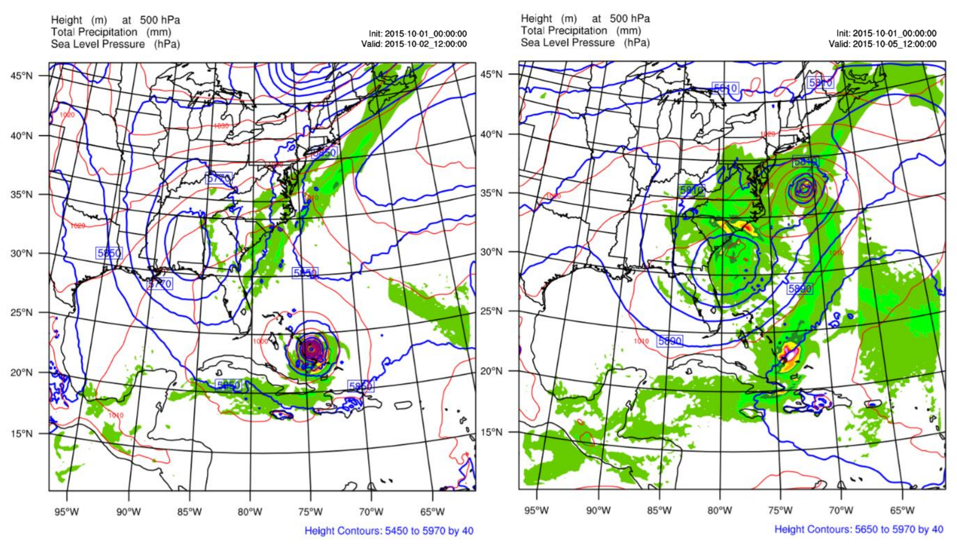
Hurricane Joaquin near the Bahamas at 1545 UTC 30 September 2015. Image captured by NASA's Goddard MODIS Rapid Response Team using the MODIS instrument aboard NASA's Terra satellite.

Methodology

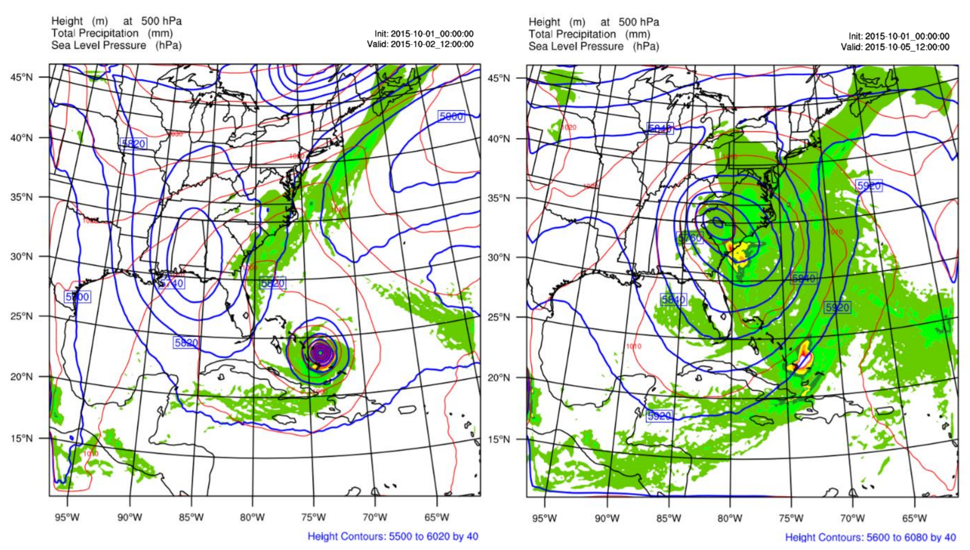
In order to investigate the Hurricane Joaquin (2015) event, a quantitative approach using numerical weather simulations can be used to provide insight into the contribution from both cyclones. The methodology of this research involves a vortex removal technique in WRF, following the methods of Tang et al. (2013). The vortex associated with Hurricane Joaquin (2015) was removed from the model initial conditions and integration to view the effects of the extratropical cyclone, while the vortex associated with the extratropical cyclone was removed to view the effects of the hurricane. Keeping the coastal front constant in both simulations, outcomes can be compared to the observed event through the use of atmospheric soundings and satellite images, in order to analyze the impacts on elevated convection intensity and location. Further, model simulations without topography will be analyzed to determine the role of the coastal front. Removing terrain, including the Appalachian Mountains, will likely alter the strength and location of the coastal front, further influencing the precipitation intensity and location along the East Coast. The initial results and analysis are described in this presentation.

Results

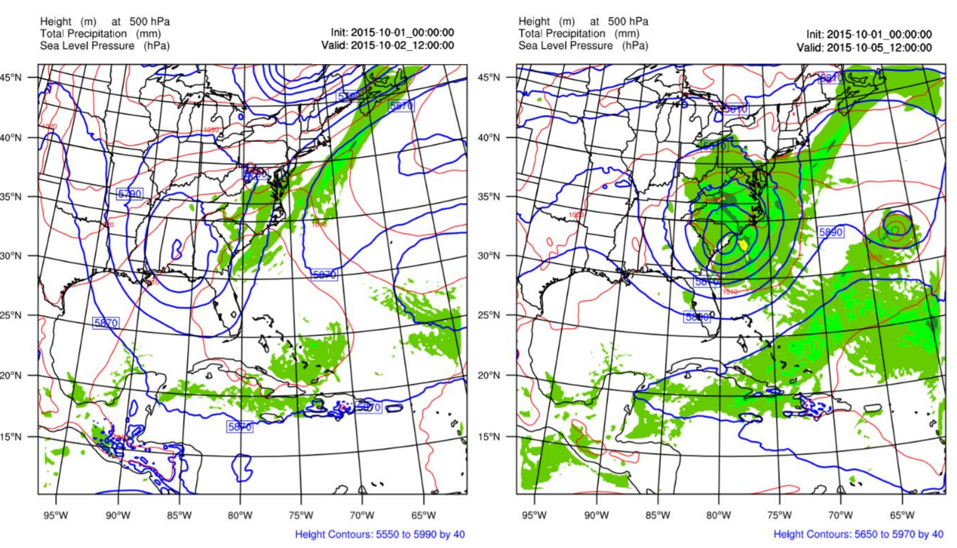
1. Control



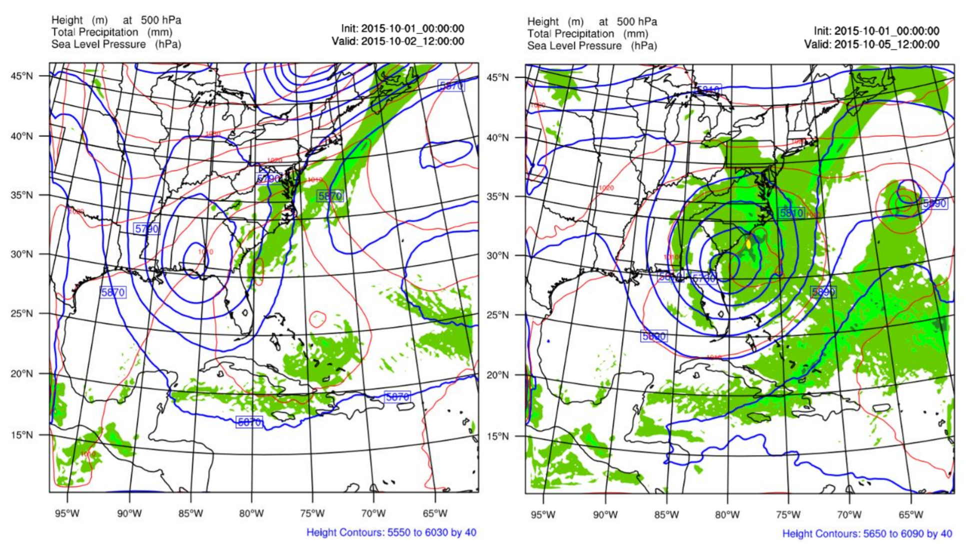
4. Control with Terrain Removed



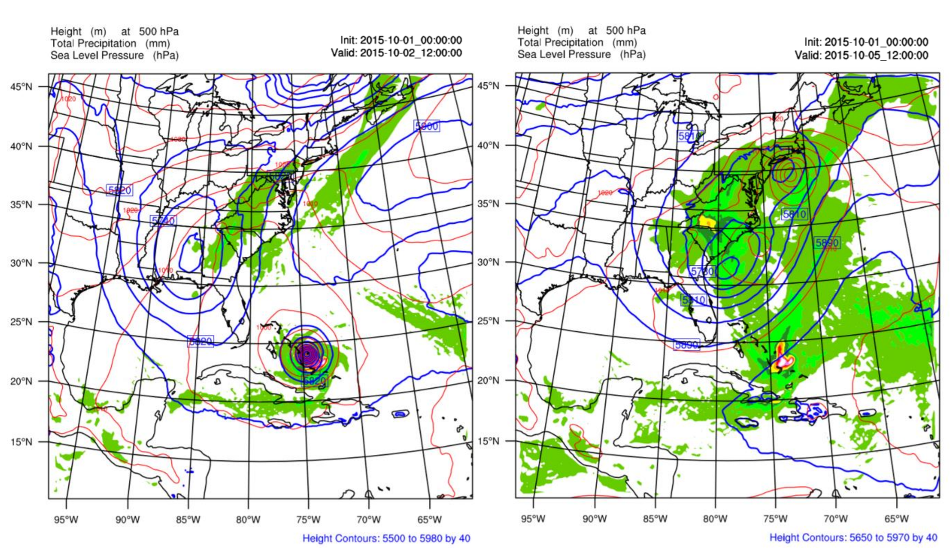
2. Tropical Cyclone Removed



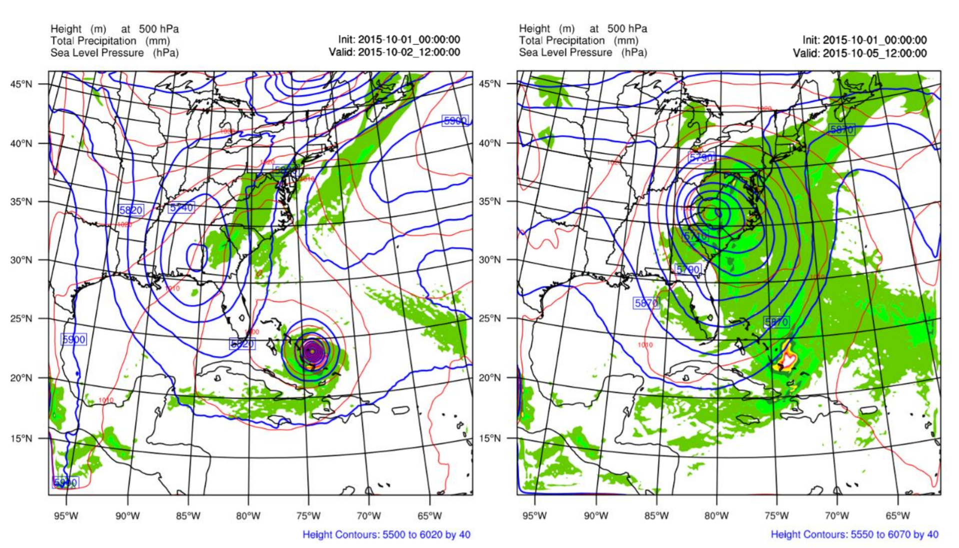
5. Terrain and Tropical Cyclone Removed

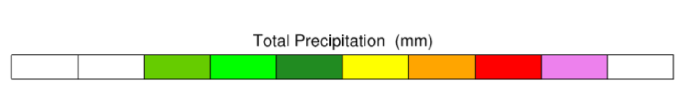


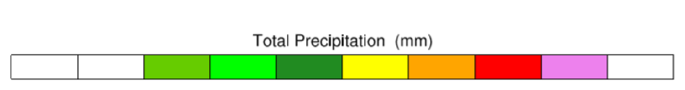
3. Extratropical Cyclone Removed



6. Terrain and Extratropical Cyclone Removed







Model Specifications

Weather Research and Forecasting (WRF) - Advanced Research WRF (ARW) Version 3.7

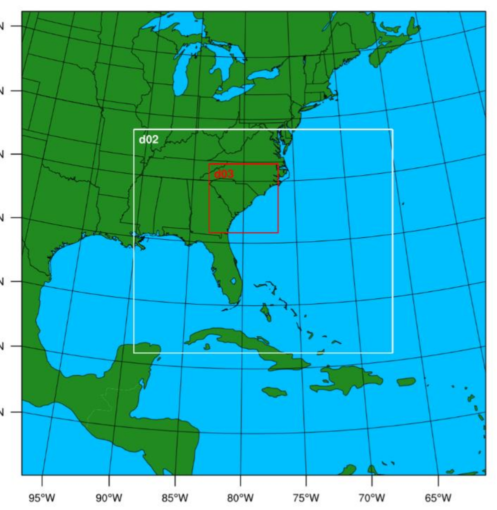
Start date: 0000 UTC 01 October 2015
End date: 1200 UTC 05 October 2015

- 30 vertical levels with a model top of 50 hPa
- 30 second averaged topography and landuse data
- Initial conditions from 0.5° GFS

Schemes:
WRF-single-moment (WSM) 6-class microphysics
Mellor-Yamada Nakanishi Niino (MYNN) level 2.5 PBL
MYNN Monin-Obukhov similarity theory surface
Rapid Radiative Transfer Model (RRTM) longwave radiation
Dudhia shortwave radiation
Kain-Fritsch cumulus (18 km only)

Tropical cyclone bogus/vortex removal (tc.exe)

WPS Domain Configuration



WRF model domains with the outermost domain having a grid spacing of 18 km, the intermediate domain is nested with 6 km grid spacing, and the innermost nested domain with 2 km grid spacing is centered over South Carolina.

Analysis

The results display 18 km solutions for six different model runs, with mean sea level pressure in red, 500 hPa heights in blue, and total precipitation recorded as shown by the color chart at the bottom of the results section.

Run 1: The control run simulates the actual event. The maximum precipitation for the event is shown to be between 635-762 mm (25-30 in.) just south of Jacksonville, North Carolina, which is displaced northeast of the actual event location.

Run 2: The vortex removal scheme is utilized to remove Hurricane Joaquin. The hurricane was mostly removed from the model initial conditions, but as the model progressed, a low pressure system develops as a result of diabatic heating.

Run 3: The vortex removal scheme is used to attempt a removal of the extratropical cyclone. Initial analysis reveals the extratropical cyclone to still remain in place for Run 3, but the 500 hPa level displays a stronger, more elongated trough than Run 1 and a low pressure system is removed from the 850 hPa level (not shown).

Runs 4-6 are similar to Runs 1-3 except for the removal of topography, resulting in less precipitation possibly due to a weaker coastal front.

Run 4: The maximum precipitation is near the South Carolina coast with roughly 635 mm (25 in.). Hurricane Joaquin makes landfall near the border of North Carolina and South Carolina.

Run 5: Similar results to Run 2, but with half the precipitation over Virginia and North Carolina.

Run 6: Hurricane Joaquin makes landfall around 1800 UTC 04 October 2015 in North Carolina, forming a large trough over the East Coast.

Further analysis is needed to determine whether each hypothesis is fully supported, but initial conclusions are stated below as related to each hypothesis.

Hypothesis 1: There would've been less precipitation with a more inland spread if Hurricane Joaquin wasn't a factor.

Hypothesis 2: Without the extratropical cyclone at 850 hPa and with an amplified trough pattern, the hurricane would've made landfall in the Northeast with the maximum precipitation occurring farther inland.

Hypothesis 3: The hurricane would've made landfall much sooner, near the Carolinas if the Appalachian Mountains weren't present.

Acknowledgements

Special thanks to Missouri EPSCoR and University of Missouri PRECIP for resources.

This material is based upon work supported by the National Science Foundation under Awards IIA-1355406 and AGS-1258358. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

Tang, Q., L. Xie, G. M. Lackmann, and B. Liu, 2013: Modeling the Impacts of the Large-Scale Atmospheric Environment on Inland Flooding during the Landfall of Hurricane Floyd (1999). *Adv. Meteor.*, **2013**, 1-16.