Evaluation of Tropical Cyclone Flood Discharges Estimated with Rainfall From Parametric Models for Flood Risk Studies

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Abstract

From 1960 through as recent as 2018, tropical cyclones (TCs) have produced greater than 1000-year rainfalls over time periods ranging from 1 to 5 days for the states in Federal Emergency Management Agency Region IV (except Kentucky, where the TC rainfall of record produced between a 200- and 500-year rainfall event). Therefore, TC rainfall events have the potential to affect the tail of flood risk statistical distributions, even for inland states. For flood risk modeling purposes, it is important to be able to simulate expected TC rainfall from a joint distribution of parameters like TC track, size, and intensity. Four existing parametric models already attempt to predict rainfall hyetographs from these variables, and an evaluation of the storm-total precipitation fields produced by these models was completed in Brackins and Kalyanapu (2020). In this study, the rainfall from the parametric models serves as the precipitation forcing to a Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) model of the Swannanoa River (HUC10 0601010506), a tributary of the French Broad in western North Carolina. The objective of the current study is to perform a case study using a HEC-HMS model of the Swannanoa River to determine if rainfall produced by four parametric TC rainfall models allows for sufficient representation of TC flood discharge. While Brackins and Kalyanapu (2020) demonstrated that the IPET (2006) model was the most skillful at reproducing storm-total precipitation for thresholds above 75 millimeters (3 inches), preliminary HEC-HMS results indicate that the IPET model suffers from serious limitations for weakening TCs which are sufficiently far inland.

Introduction

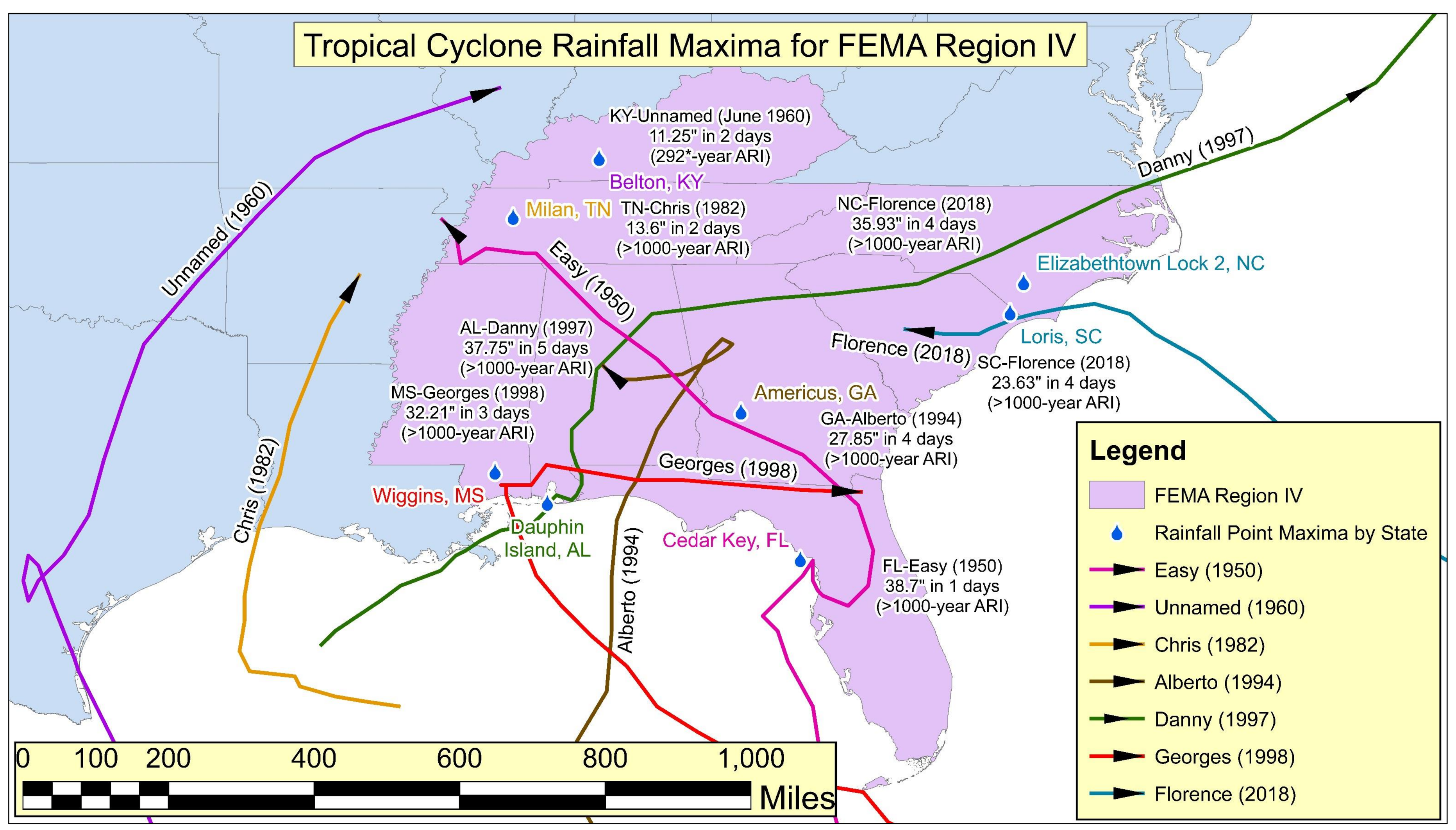

Figure 1: FEMA Region IV tropical cyclone rainfall maxima (1950-2019) estimated Annual Recurrence Interval (ARI).

- TC rainfall events affect the tail of flood risk statistical distributions, even for inland states.
- A need exists to simulate expected TC rainfall from a joint distribution of parameters like TC track, size, and intensity:
  - Track (latitude and longitude)
  - Intensity (maximum winds V_{max} or central pressure deficit ΔP)
  - Radius to maximum wind (R_{max}, indicates size)
- Four existing parametric models already attempt to predict rainfall patterns from these variables.
- Parametric models suffer from averaging effects, e.g. "storm smearing" of Ogden and Julien (1994).

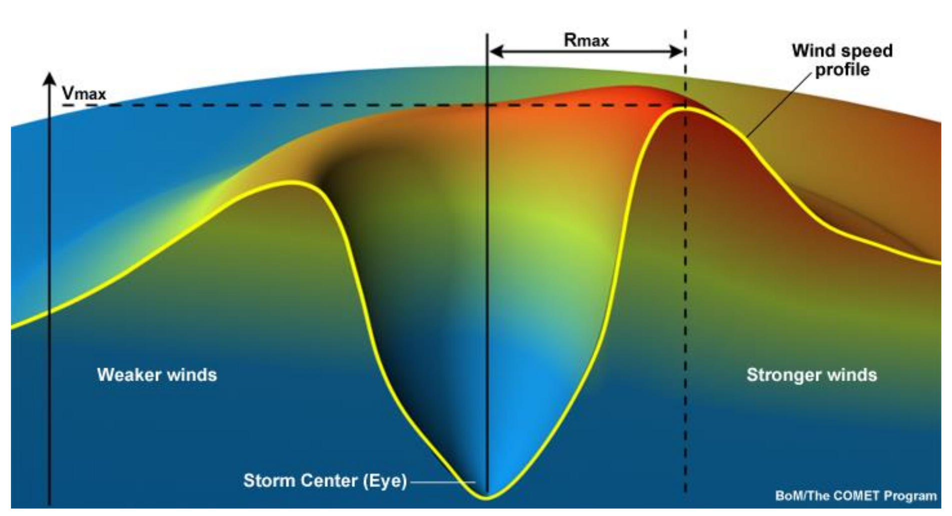

Figure 2: Wind speed profile in a hurricane. Image courtesy The COMET Program.

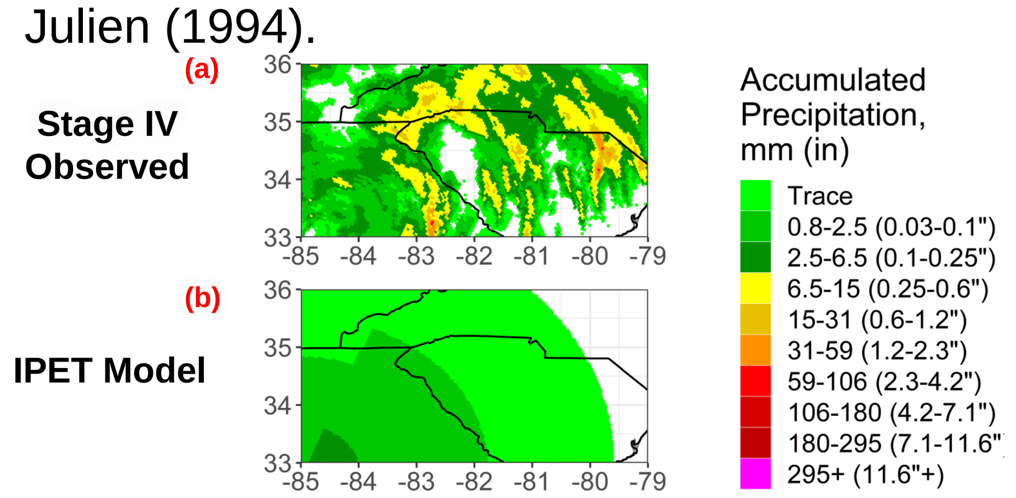

Figure 3: Representations of precipitation fields at hourly timestep.

Research Objective

"…to perform a case study using a HEC-HMS model of the Swannanoa River to determine if rainfall produced by four parametric TC rainfall models allows for sufficient representation of TC flood discharge."

Methodology

- Four Existing Parametric Models
  1. R-CLIPER (Marks and DeMaria 2003)
  2. IPET (IPET 2006)
  3. PHRaM (Lonfat et al. 2007)
  4. P-CLIPER (Geoghegan et al. 2018)

R-CLIPER

- Climatological mean rain rate from NASA TRMM
- Curve fit from 482 global TCs 1998-2002
- 2 parameters: radius from track r and V_{max}

$$TRR(r, V_{max}) = T_0 + (T_m - T_0)\left(\frac{r}{r_m}\right); r < r_m$$

$$TRR(r, V_{max}) = T_m \exp\left[-\frac{r - r_m}{r_e}\right]; r \geq r_m$$

T_0 = rain at center; T_m = rain at maximum; r_m = radius of maximum rain; r_e used for curve fit

IPET

- Relatively coarse model of 3 parameters: radius from track, ΔP and R_{max}
- Accounts for asymmetry by multiplying right side of track rain rates by 1.5

$$m_i(r) = 1.14 + 0.12\Delta P \;; r \leq R_{max}$$

$$m_i(r) = (1.14 + 0.12\Delta P)\exp\left[-\frac{0.3(r - R_{max})}{R_{max}}\right]; r > R_{max}$$

PHRaM

- Modifies R-CLIPER using ~~wind shear~~ and topographic effects (orography)

$$R_{PHRaM} = R_{R-CLIPER} + R_{shear} + R_{topography}$$

Where: $R_{topography} = c\vec{V_s} \cdot \nabla h_s = c\bar{w}$

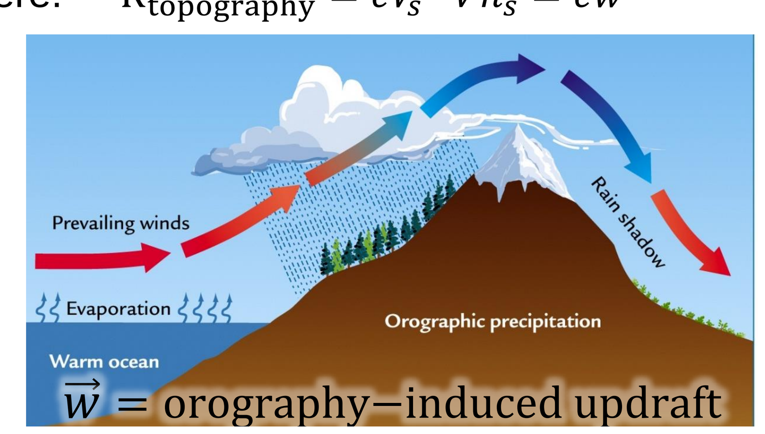

Figure 4: Orographic effects in PHRaM. Image courtesy http://kbkb-wx.blogspot.com

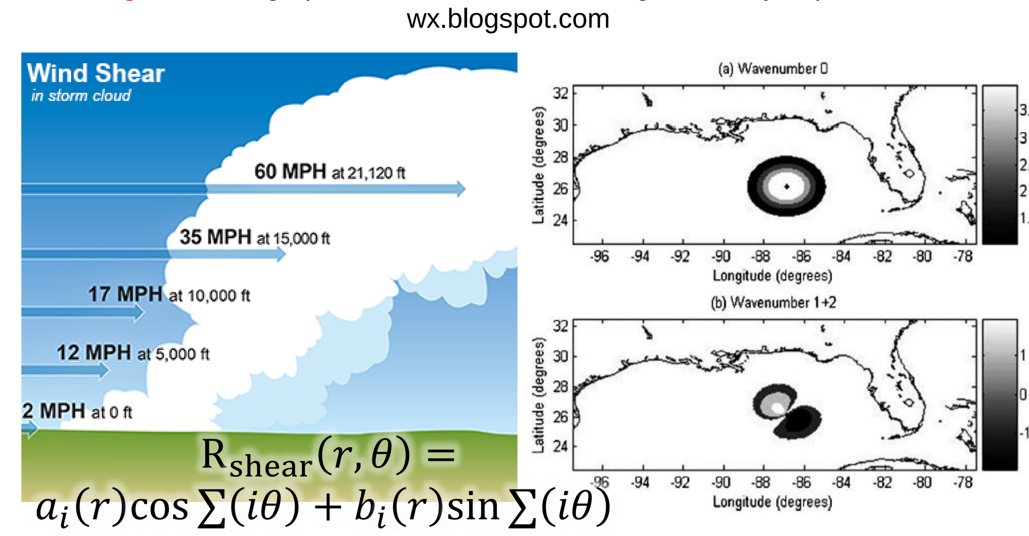

Figure 5: Wind shear effects of shifting rainfall in PHRaM. Images courtesy cliffmass.blogspot.com and Lonfat et al. (2007).

P-CLIPER

- Probability distribution functions (PDFs) based on TRMM and frequency f
- -90 (least severe) $\leq f \leq$ 90 (most severe)
- E.g. for TS intensity:

$$R(r, f) = Ae^{Bf}; r < 50\ km$$

$$R(r, f) = (2.06E{-}5 * r^2 - 1.67E{-}2 * r + 3.84)e^{Bf}; r \geq 50\ km$$

HEC-HMS Model

- Swannanoa River watershed (HUC 0601010506) HEC-HMS Model
- 133 sq. mi. area watershed simulated
- Muskingum-Cunge routing with 8-point XS, channel slopes range from 0.04% to 7%
- 35 subbasins:
  - 18 subbasins as Green and Ampt (37% of total area; area-weighted-average 15.2% impervious)
  - 17 subbasins as SCS Curve Number (63% of total area; area-weighted-average CN of 40)
- Snyder unit hydrographs used for transforms

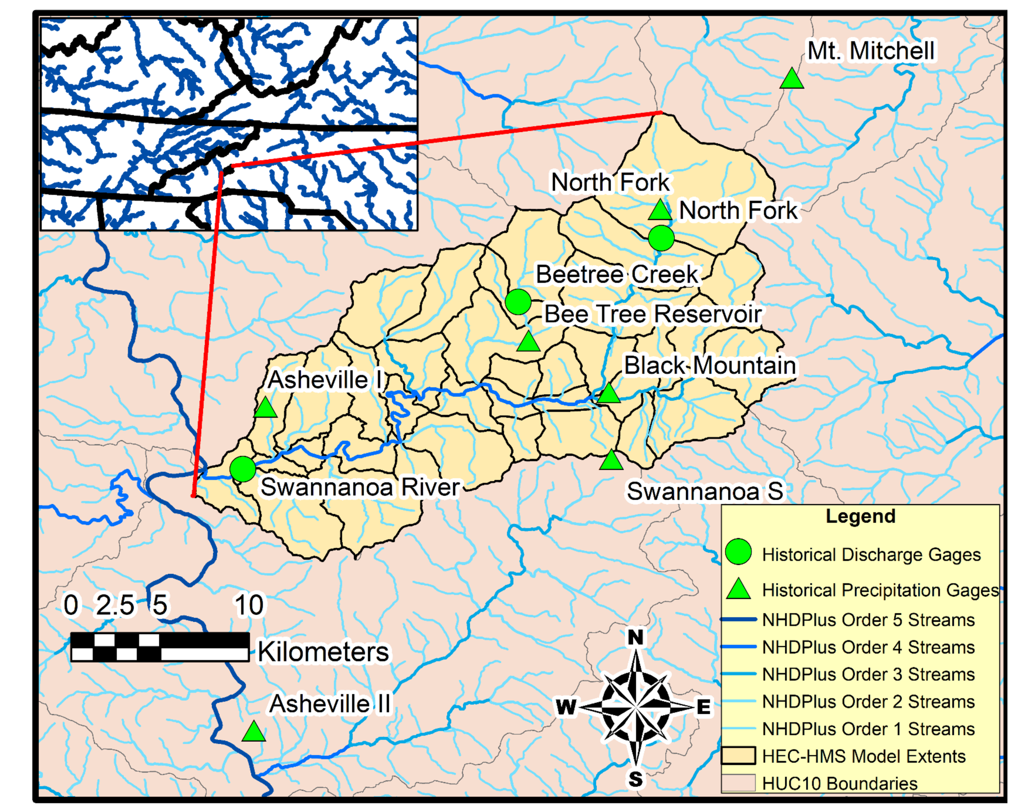

Figure 6: HEC-HMS model extents.

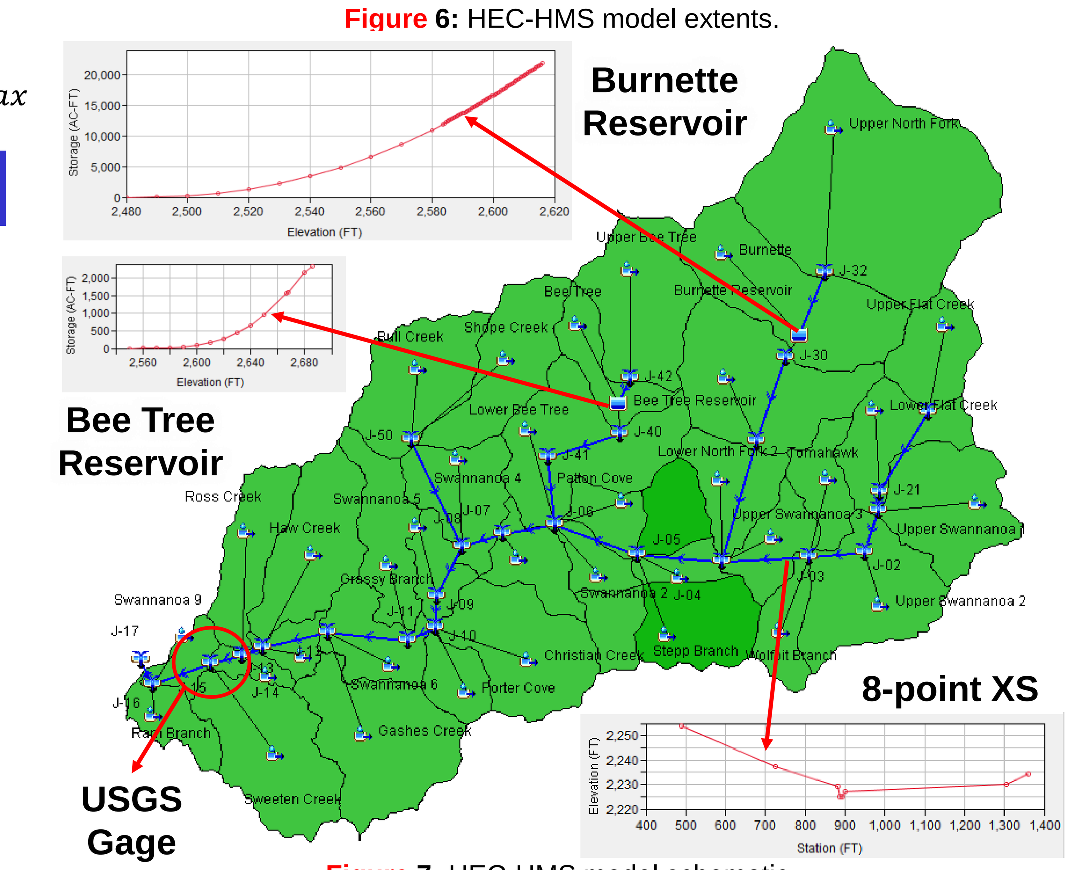

Figure 7: HEC-HMS model schematic.

Storm Events

- 2004 Hurricanes Frances and Ivan
- Two storms within same month (Sep. 2004)

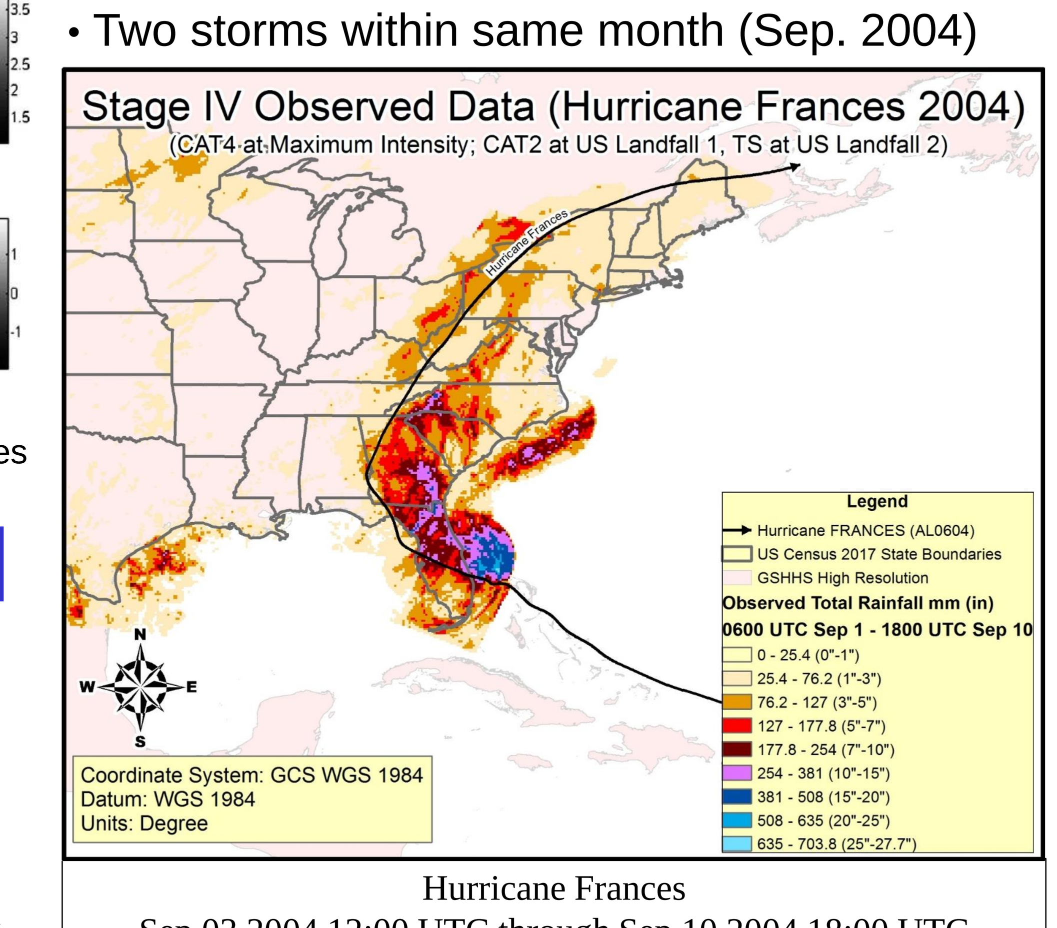

Figure 6: Observed Hurricane Frances (2004) Rainfall.

Results

- Comparison of parametric rainfall model with multiple sources of observed data:
  - NLDAS (North American Land Data Assimilation System)
  - Historical gage at Asheville, NC
  - Stage IV Quantitative Precipitation Estimate (QPE)
- Some variation evident in observed data, even at same location
- IPET model does not produce sufficient rainfall to reproduce peak discharges

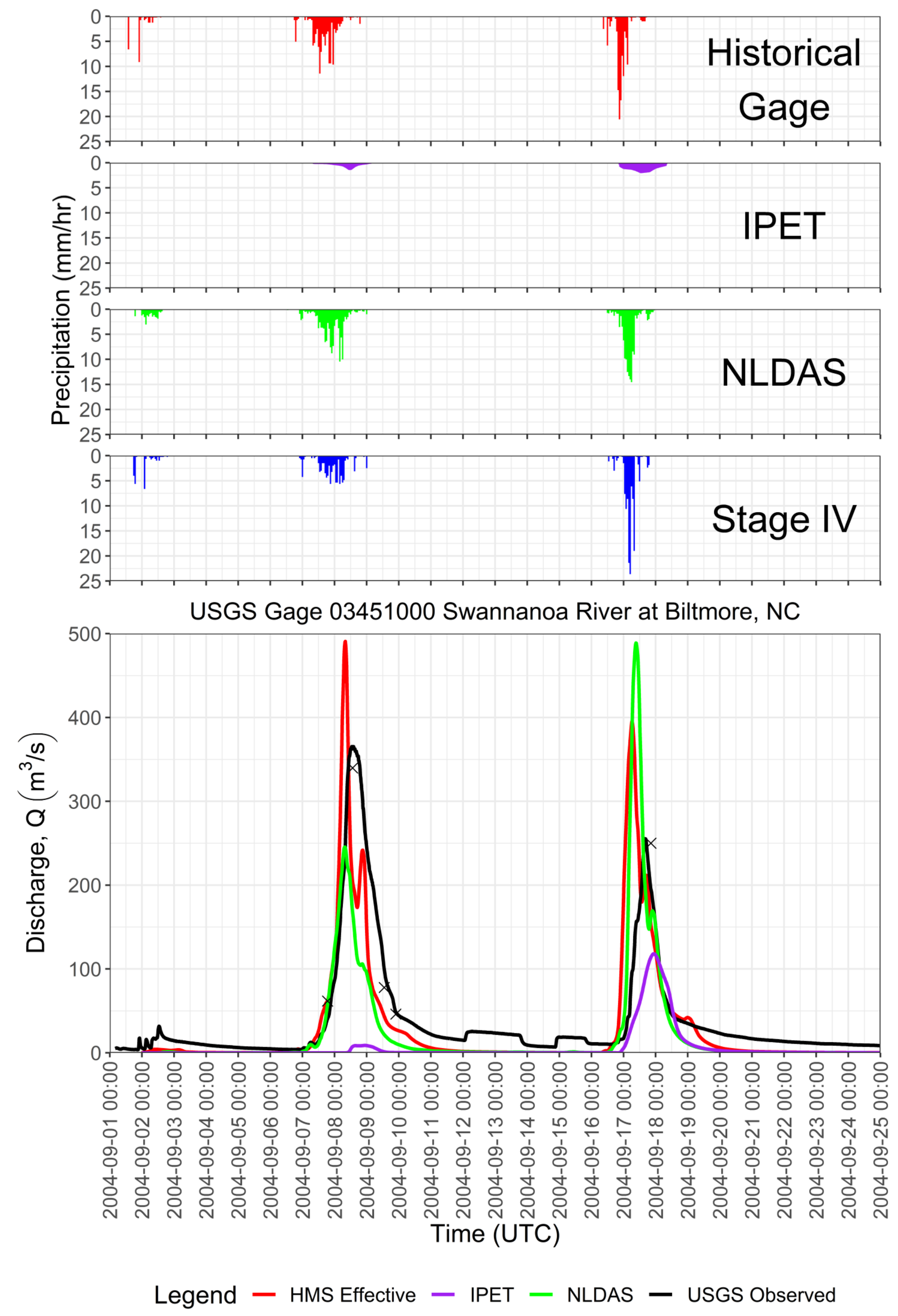

Figure 9: Rainfall hyetographs from each model/data source, with resulting discharge hydrographs as routed by the HEC-HMS model.

Conclusions/Future Studies

- Parametric rainfall models evaluated in Brackins and Kalyanapu (2020) likely insufficient for modeling TC flood discharges, especially for inland TCs
- Only P-CLIPER capable of producing storm-total >20"
- Future Work: Consider TCR rainfall model of Emanuel et al. (2008) as an additional parametric model

References

- Brackins, J.T., and Kalyanapu, A.J. (2020). "Evaluation of parametric precipitation models in reproducing tropical cyclone rainfall patterns." *Journal of Hydrology* 580 124255. https://doi.org/10.1016/j.jhydrol.2019.124255
- Geoghegan, K. M., Fitzpatrick, P., Kolar, R. L., and Dresback, K. M. (2018). "Evaluation of a synthetic rainfall model, P-CLIPER, for use in coastal flood modeling." *Nat. Hazards* 92(2), 699-726. https://doi.org/10.1007/s11069-018-3220-4
- Interagency Performance Evaluation Task Force (IPET). (2006). "Performance evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System draft final report of the Interagency Performance Evaluation Task Force volume VIII – engineering and operational risk and reliability analysis".
- Lonfat, M., Rogers, R., Marchok, T., and Marks Jr., F.D. (2007) "A parametric model for predicting hurricane rainfall." *Mon. Weather Rev.,* 135(9), 3086-3097. https://doi.org/10.1175/MWR3433.1
- Marks, F.D., DeMaria, M. (2003). "Development of a tropical cyclone rainfall climatology and persistence (R-CLIPER) model". Technical report, NOAA/OAR/AOML/Hurricane Research Division.
- Ogden, F.L., and Julien, P.Y. (1994). "Runoff model sensitivity to radar rainfall resolution." *Journal of Hydrology* 158, no. 1-2: 1-18. https://doi.org/10.1016/0022-1694(94)90043-4

Acknowledgments

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