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Associations between the Slowdown in North Atlantic Tropical-Cyclone Translation Speed and Intensifying Storm Precipitation

A. Rationale

North Atlantic hurricanes are catastrophic natural phenomena with the potential to destroy and destabilize coastal communities, economies, and environments. In recent decades, scientists and government institutions alike have observed increasingly severe hurricane impacts often attributed to anthropogenic (human-induced) warming (Kossin, 2018). Although the intensifying strength and frequency of North Atlantic hurricanes is well-documented in the media and in scientific literature, a comprehensive understanding of the complex and often contradictory links between anthropogenic warming and hurricanes in the Atlantic basin continues to elude the scientific community.

The standard explanation for the increasing severity of North Atlantic storms is that an increase in global sea surface temperature fuels stronger and more destructive hurricanes that advect increased oceanic heat through convection. While this statement certainly accounts for a portion of the changes to North Atlantic hurricane activity observed over the last few decades, the physical mechanisms impacted by shifting climate patterns are far more complex and nuanced, often impacting hurricanes in conflicting and inconsistent ways.

This study aims to examine one specific aspect of the link between anthropogenic warming and North Atlantic hurricane activity: the decline in hurricane translation speed \and the subsequent increase in storm precipitation accumulation and associated flooding. Prior research in this realm has identified a reduction in the translation speed of North Atlantic tropical cyclones since 1950, but the connections between this translation speed reduction and other metrics of hurricane activity, such as rainfall accumulation at landfall, have not been readily studied. In a study conducted by Kossin in 2018, a proposed relationship between anthropogenic warming and a quantifiable slowdown in North Atlantic tropical cyclone translation speed is examined, but the primarily objective of the research is an investigation of the possible atmospheric causes underlying the slowdown rather than an analysis of the impacts of this slowdown on hurricane intensity and precipitation. As earlier research by Coumou et al. in 2015 stipulates, the physical mechanism linked to the global slowdown is the weakening of the summer prevailing wind circulation in the Northern hemisphere, a phenomenon directly linked to the increase in global temperatures associated with anthropogenic warming. Coumou *et al.* determined that rapid global warming influences the mid-latitude prevailing circulation by reducing the poleward temperature gradient, a hypothesis that initially garnered support in the 1970s and recently re-emerged at the forefront of scientific literature (Screen and Simmons, 2014). As human-induced warming heats the globe, the mid-latitude circulation that typically steers hurricanes towards the contiguous US and then up the coast becomes significantly reduced in strength, causing TCs to stagnate in one region for extended periods before continuing on their paths. The reduced speed of these TCs may intensity their impacts in a plethora of interconnected ways, increasing the amount of precipitation recorded by coastal regions, exacerbating pre-existing flooding risks, and compounding potentially catastrophic storm surge (Kossin 2018). An additional compounding factor is the increased moisture capacity of the atmosphere in a warming world, a variable that may heighten the already severe impacts of these lingering TCs on vulnerable regions.

This study will expand upon the findings of prior research in two crucial ways. First, an expanded dataset of years extending from 1851-2016 will be utilized to assess and quantify the global slowdown in translation speed based on the trajectories of 1,857 storms in the North Atlantic basin. This study will then further differentiats from prior research by taking a spatial approach and investigating the characterization of spatial patterns in the location of the slowest component of North Atlantic tropical cyclone tracks. A number of distinct statistical analyses, including a k-means clustering analysis of translation speeds and a k-nearest neighbor outlier detection analysis, will be employed to identify key trends and patterns in the nature of tropical cyclone translation speed over time. Shifting patterns in not only the speed of hurricane movement but the spatial distribution of tropical cyclones defined by unusually slow speeds can offer critical insight into the influence of anthropogenic warming on the location of stalling storms. An understanding of this relationship could inform tropical cyclone model forecasts and seasonal hurricane simulations responsible for the prediction and modeling of hurricane development based on key atmospheric factors.

Based on the results of the translation speed analysis, an examination of the rainfall associated with all storms contained within the dataset that make landfall in the contiguous US will then be undertaken to assess changes in both the extent and distribution of tropical cyclone rain fields. Although this component of the analysis is limited by the availability of accurate rain field data, a preliminary analysis will be conducted according to the described procedure. The full methodology developed for the completion of this examination is then detailed for future analyses. The precipitation accumulation rate of all storms within the dataset on their date of landfall will be initially examined through a linear regression analysis undertaken to uncover preliminary trends in rainfall intensity over time. The next component of the precipitation analysis involves a two-part study comprised of a visual observation of synoptic weather maps illustrating both the rain fields and geopotential height anomalies associated with each landfalling storm on the dates preceding and following the storm, followed by a comprehensive hierarchal clustering evaluation of the spatial characterization of the tropical cyclone rain fields at landfall. The research culminates in a discussion of the findings of both analyses in the context of anthropogenic warming and statistical hurricane modeling.

B. Research Questions and Hypotheses

Over the course of this study, two major questions are emphasized. These questions are summarized below:

I) How has the translation speed of North Atlantic hurricanes changed over time?

II) How has the slowdown in North Atlantic hurricane translation speed impacted the extent and spatial distribution of TC rain fields?

Two distinct hypotheses are formulated in response to the research questions stipulated above. These hypotheses do not encompass the entirety of the analyses conducted as part of this investigation, but they respond directly to the key research questions indicated above. These hypotheses are outlined below.

I) If the mid-latitude planetary circulation is weakened due to anthropogenic warming, and I examine the minimum translation speed of 1,857 tropical storms between 1851-2016, then this minimum translation speed will decline over this period.

II) If the slowdown in translation speed increases the duration of time that coastal regions are exposed to extreme precipitation, and I examine the precipitation accumulation rate associated with 185 landfalling hurricanes between 1950-2011, then the precipitation accumulation rate will increase during this period.

C. Procedure

A. Data

1. Hurricane Position Data

The tropical cyclone position data utilized in this study is derived from the HURDAT2 dataset, a comprehensive repository of storm track data maintained by the National Hurricane Center (NHC). The HURDAT2 dataset contains updated information on storm trajectory and internal storm conditions like pressure and wind speed at every measured interval throughout the hurricane’s track. The hurricane dataset modified for this analysis contains information on the complete lifecycle of 1,857 tropical cyclones classified as at least a tropical depression for one or more position observations. The dataset contains a record of the latitude and longitude of each storm at six-hour intervals, along with the date of the observation and the wind speed of the storm if available. The HURDAT2 record is considered less accurate pre-1944, the year that reconnaissance aircraft flights began to reliably document hurricane activity in the North Atlantic (Villarini *et. al* 2011). Missing values observed in the data prior to the mid-1900s can be attributed to inconsistencies and inaccuracies in the HURDAT2 dataset prior to the implementation of flight-based data collection.

2. Precipitation Datasets

Two separate precipitation datasets of varying resolutions are utilized to conduct the rainfall component of the analysis. To produce the rain field synoptic maps for the dates of hurricane landfall, an appended dataset modified to combine the CPC Retro Global Unified Gauge-Based Analysis of Daily Precipitation and CPC Realtime Global Unified Gauge-Based Analysis of Daily Precipitation (Chen et al, 2008) is constructed.

This dataset encompasses the interpolated daily precipitation data for the entire contiguous US at 0.5 x 0.5-degree resolution. To improve experimental accuracy and obtain more authentic conclusions during the second component of the precipitation analysis, a spatial precipitation dataset with a finer resolution is selected. The Livneh daily CONUS near-surface gridded meteorological and derived hydrometeorological data for precipitation accumulation, available at an extremely precise 1/16-degree resolution from 1911-2011, is selected for the hierarchal clustering component of the analysis. The Livneh dataset interpolates the daily precipitation accumulation across the entirety of the contiguous US, providing an accurate reconstruction of the precipitation conditions associated with each landfalling storm at its time of landfall.

3. Geopotential Height Anomalies Dataset

As part of the investigation into the links between the slowing translation speed of North Atlantic landfalling hurricanes and rainfall patterns, the geopotential height at 950 mb across the contiguous US on the tropical cyclone's date of landfall is analyzed for the full set of storms included in the study. Geopotential height is a vertical coordinate height that approximates the actual height of a pressure surface above mean-surface level. Lines drawn on a geopotential height map connect the locations on the map characterized by equivalent geopotential heights. A map of geopotential height anomalies depicts the deviations from the expected or average geopotential heights on a particular day. This variable is examined in conjunction with the precipitation fields on each date of landfall to assess the shape and location of each storm, enabling a more reliable and comprehensive analysis than would otherwise be possible if the latitude and longitude of the center of the storm were considered the most accurate measure of the storm's position. In this study, the Daily Intrinsic Pressure Level Geopotential Height from NOAA NCEP-NCAR CDAS-1 Reanalysis Project dataset is selected for the creation of geopotential height images for each landfalling date (Kalnay et al, 1996).

B. Analysis of Translation Speed Slowdown

To conduct the analysis of the slowdown in translation speed, a master spreadsheet of all of the relevant data for each North Atlantic tropical cyclone is first compiled and processed. In this spreadsheet, the year, month, date, and time of each TC observation is separated and filtered, and the latitude and longitude at each observation is carefully matched to its proper time of occurrence. Because the observations for hurricane position are processed with the corresponding wind speed at that point in time, the proper hurricane category according to the Saffir-Simpson hurricane classification scale (Tropical Depression, Tropical Storm, Category 1-5) could be used to categorize each storm into its appropriate category at each observation along its track. Thus, the storms incorporated into this clustering assessment include tropical depressions, tropical storms, and tropical cyclones, but these three classifications are collectively referred to as “hurricanes” or “tropical cyclones” in this study. This step allowed for a later analysis of trends in translation speed according to the category of each storm in the dataset.

After assembling a baseline spreadsheet with the processed data, the data could be inputted into ‘R’ programming software for a complete statistical analysis of translation speed (R, Core Development Team 2019). R is utilized to complete all statistical analyses pertaining to this study, as the program is well-suited to the manipulation, organization and processing of large data sets. Once the dataset is transferred from Excel to R, a loop function is applied to the data to calculate the minimum distance traveled by each storm during a moving 24-hour window throughout the storm’s development. Because the position data available for each track is recorded as a set of latitude-longitude coordinates, the Haversine formula is used to convert the difference between coordinates to the Euclidian distance in meters between two points on a sphere. Some pseudocode for the Haversine calculation is provided below for reference. The radius of the Earth is approximated as 6,371 meters in this analysis.

```
#Defining difference in latitude and longitudes between two points

dLat = (lat2-lat1)
 dLon = (lon2-lon1)

#Calculation of Euclidian distance between two points

  a = sin(dLat/2) * sin(dLat/2) + cos(lat1) * cos(lat2) * sin(dLon/2) * sin(dLon/2)
  distance = 6371 * 2 * atan2(sqrt(a), sqrt(1-a))
```

With the minimum distance traveled in 24 hours for all storms calculated in a table, the minimum translation speed could then be analyzed through three distinct statistical analyses. A preliminary linear regression analysis, a k-means clustering analysis, and a k-nearest neighbor outlier detection test are all conducted to visualize temporal and spatial patterns in the translation speed of the North Atlantic hurricanes. The methodologies for these separate analyses are described below.

1. Linear Regression

A prefatory linear regression analysis is undertaken to assess the time series of minimum translation speeds associated with each TC. The statistical significance of the correlation is recorded and assessed. Based on a visual examination of the graph, a more complex statistical analysis is deemed necessary to dissect trends in the data.

2. Spatial and Temporal Analysis of Translation Speed

To gain a more nuanced understanding of the trends indicated by the preliminary analysis, the dataset of TCs is separated into three distinct time periods: 1851-1906, 1907-1960, 1961-2016. The latitude-longitude coordinate location of each storm while undergoing the slowest 24 hours of its track and the relative quantification of each storm's minimum speed is overlaid on a map of the North Atlantic basin. Three maps are produced to display the storm data for each subset of years. The purpose of this analysis is to enable both an assessment of the spatial characterization of the minimum translation speed over time and an evaluation of the changes to translation speed since 1851.

2. K-means Clustering Analysis of Translation Speed

A secondary statistical analysis is undertaken to classify the minimum translation speed of each TC according to five clusters determined through the supervised k-means clustering algorithm. K-means clustering is an organic methodology for grouping data that involves the identification of centroids that define the central points of each cluster and the subsequent allocation of specific data points to the nearest cluster. A methodology known as the elbow test is undertaken before clustering the translations speeds to identify the optimal number of clusters prior to the analysis. After the translation speeds are sorted into clusters, temporal trends are analyzed with respect to time to assess patterns in cluster membership since 1851.

3. K-nearest neighbor Outlier Detection

A final statistical test is devised to detect any significant outliers in translation speed. The k-nearest neighbor outlier detection test identifies outliers in datasets by comparing one data point to a specified number of neighboring points and examining the proximity of the points to one another according to some defined comparison metric. This analysis is pursued to identify any trends in the extremity of translation speeds in recent years.

C. Analysis of Storm-Related Precipitation at Landfall

1. Linear Regression Analysis

A linear regression examination is conducted for a subset of 181 landfalling storms contained within the larger dataset to examine trends in the maximum precipitation accumulation rate at landfall over time. The maximum precipitation within a 1 degree latitude-longitude box centered around the eye of each storm is recorded and processed. A time series is graphed with time in years on the x-axis, precipitation accumulation rate (in mm/day) on the y-axis, and linear regression line of best fit overlaid to illustrate the trend line.

2. Synoptic Precipitation Maps and Geopotential Height Anomaly Images

After assessing preliminary trends through a linear regression analysis, a program in ‘R’ is built to access and process reconstructed images of the rain fields and geopotential height anomaly fields over the contiguous United States on the dates of landfall for each storm. The precipitation and geopotential height field images are also generated for the three days preceding and three days following the date of landfall for each storm. The primary objective of this component of the analysis is to visually examine spatial trends in the precipitation fields over time rather than relying exclusively on the maximum precipitation accumulation rate as the sole metric of hurricane activity. This strategy is advised by a number of researchers, as hurricane rain fields are often asymmetrical and peculiar in shape (Zhou, 2018; Matyas, 2009; Matyas, 2017).

3. Hierarchal Clustering Analysis

The next step in this component of the analysis is a hierarchical clustering analysis of the spatial characterization of the main rain shields associated with each storm contained within the dataset. Hierarchal clustering is a clustering mechanism that organizes points into distinct clusters (much like the k-means clustering algorithm) and then presents the results as a dendrogram (tree diagram), in which each link in the diagram groups together elements from the group below. To conduct this analysis, the Livneh hydrometeorological dataset is downloaded for each date of landfall for 21 storms for which data is available in the dataset. Next, a code is generated to center the rain field around the latitude-longitude coordinates of the center of the storm to restrict the data to the immediate rain shield surrounding the storm. The resolution of the dataset is extremely fine (1/16 degree), so a 256 x 256-pixel square surrounding the storm center is processed for each date before the hierarchal clustering analysis is performed. A sample of this spatial image can be found in Figure 1.

Risk and Safety

Risk and safety precautions are not applicable to this research.

Data Analysis

Due to the retrospective nature of this research, the entirety of the project can be considered data analysis. Refer to the above Procedure section for detailed information about data analyses conducted.

D. Bibliography

Alemany, S., Beltran, J., Perez, A., & Ganzfried, S. (2018). Predicting Hurricane Trajectories using a Recurrent Neural Network. ArXiv:1802.02548 [Physics, Stat]. Retrieved from http://arxiv.org/abs/1802.02548

Atallah, E., Bosart, L. F., & Aiyyer, A. R. (2007). Precipitation Distribution Associated with Landfalling Tropical Cyclones over the Eastern United States. Monthly Weather Review, 135(6), 2185–2206. https://doi.org/10.1175/MWR3382.1

Chen, H. (2015). Downstream development of baroclinic waves in the midlatitude jet induced by extratropical transition: A case study. Advances in Atmospheric Sciences, 32(4), 528–540. https://doi.org/10.1007/s00376-014-3263-8

Chen, M., W. Shi, P. Xie, V. B. S. Silva, V E. Kousky, R. Wayne Higgins, and J. E. Janowiak (2008), Assessing objective techniques for gauge-based analyses of global daily precipitation, J. Geophys. Res., 113, D04110, doi:10.1029/2007JD009132.

Chen, M., P. Xie, and Co-authors (2008), CPC Unified Gauge-based Analysis of Global Daily Precipitation, Western Pacific Geophysics Meeting, Cairns, Australia, 29 July - 1 August, 2008

Coumou, D., Lehmann, J., & Beckmann, J. (2015). Climate change. The weakening summer circulation in the Northern Hemisphere mid-latitudes. Science (New York, N.Y.), 348. https://doi.org/10.1126/science.1261768

data: Expert Mode. (n.d.). Retrieved August 23, 2019, from http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.UNIFIED_PRCP/.GAUGE_BASED/.GLOBAL/.v1p0/.RETRO/.rain/X/-150/-50/RANGE/Y/10/60/RANGE/SOURCES/.NOAA/.NCEP/.CPC/.UNIFIED_PRCP/.GAUGE_BASED/.GLOBAL/.v1p0/.REALTIME/.rain/X/-150/-50/RANGE/Y/10/60/RANGE/appendstream/prcp_fraction_colors/DATA/0/80/RANGE//color_smoothing/null/def/#expert

Estimating Tropical Cyclone Intensity by Satellite Imagery Utilizing Convolutional Neural Networks: Weather and Forecasting: Vol 34, No 2. (n.d.). Retrieved August 6, 2019, from https://journals.ametsoc.org/doi/abs/10.1175/WAF-D-18-0136.1

Finocchio, P. M., Doyle, J. D., Finocchio, P. M., & Doyle, J. D. (2019). How the Speed and Latitude of the Jet Stream Affect the Downstream Response to Recurving Tropical Cyclones. Monthly Weather Review. https://doi.org/10.1175/MWR-D-19-0049.1

Galarneau, T. J., Bosart, L. F., & Schumacher, R. S. (2010). Predecessor Rain Events ahead of Tropical Cyclones. Monthly Weather Review, 138(8), 3272–3297. https://doi.org/10.1175/2010MWR3243.1

Global Unified Precipitation Gridded Dataset. (n.d.). Retrieved July 26, 2019, from http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.UNIFIED_PRCP/.GAUGE_BASED/.GLOBAL/.v1p0/.RETRO/.rain/X/-150/-50/RANGE/Y/10/60/RANGE/SOURCES/.NOAA/.NCEP/.CPC/.UNIFIED_PRCP/.

GAUGE_BASED/.GLOBAL/.v1p0/.REALTIME/.rain/X/-150/-50/RANGE/Y/10/60/RANGE/appendstream/index.html#info

Grams, C. M., & Archambault, H. M. (2016). The Key Role of Diabatic Outflow in Amplifying the Midlatitude Flow: A Representative Case Study of Weather Systems Surrounding Western North Pacific Extratropical Transition. Monthly Weather Review, 144(10), 3847–3869. https://doi.org/10.1175/MWR-D-15-0419.1

Hall and Kossin—2019—Hurricane stalling along the North American coast .pdf. (n.d.). Retrieved from https://www.nature.com/articles/s41612-019-0074-8.pdf

Hall, T. M., & Kossin, J. P. (2019). Hurricane stalling along the North American coast and implications for rainfall. Npj Climate and Atmospheric Science, 2(1), 17. https://doi.org/10.1038/s41612-019-0074-8

Hanley, D., Molinari, J., & Keyser, D. (2001). A Composite Study of the Interactions between Tropical Cyclones and Upper-Tropospheric Troughs. Monthly Weather Review, 129(10), 2570–2584. https://doi.org/10.1175/1520-0493(2001)129<2570:ACSOTI>2.0.CO;2

Hodyss, D., & Hendricks, E. (2010). The Resonant Excitation of Baroclinic Waves by the Divergent Circulation of Recurving Tropical Cyclones. Journal of the Atmospheric Sciences, 67(11), 3600–3616. https://doi.org/10.1175/2010JAS3459.1

Lachmy, O., & Harnik, N. (2016). Wave and Jet Maintenance in Different Flow Regimes. Journal of the Atmospheric Sciences, 73(6), 2465–2484. https://doi.org/10.1175/JAS-D-15-0321.1

Liu, M., & Smith, J. A. (2016). Extreme Rainfall from Landfalling Tropical Cyclones in the Eastern United States: Hurricane Irene (2011). Journal of Hydrometeorology, 17(11), 2883–2904. https://doi.org/10.1175/JHM-D-16-0072.1

Lunga, D., & Ersoy, O. (2011). Spherical Nearest Neighbor Classification: Application to Hyperspectral Data. In P. Perner (Ed.), Machine Learning and Data Mining in Pattern Recognition (Vol. 6871, pp. 170–184). https://doi.org/10.1007/978-3-642-23199-5_13

Matsuoka, D., Nakano, M., Sugiyama, D., & Uchida, S. (2018). Deep learning approach for detecting tropical cyclones and their precursors in the simulation by a cloud-resolving global nonhydrostatic atmospheric model. Progress in Earth and Planetary Science, 5(1), 80. https://doi.org/10.1186/s40645-018-0245-y

Matyas, C. J. (2010). Associations between the size of hurricane rain fields at landfall and their surrounding environments. Meteorology and Atmospheric Physics; Wien, 106(3–4), 135–148. http://dx.doi.org/10.1007/s00703-009-0056-1

Matyas, C. J. (2013). Processes Influencing Rain-Field Growth and Decay after Tropical Cyclone Landfall in the United States. Journal of Applied Meteorology and Climatology, 52(5), 1085–1096. Retrieved from JSTOR.

Matyas, C. J. (2017). Comparing the Spatial Patterns of Rainfall and Atmospheric Moisture among Tropical Cyclones Having a Track Similar to Hurricane Irene (2011). Atmosphere, 8(9), 165. https://doi.org/10.3390/atmos8090165

Mei, W., Pasquero, C., & Primeau, F. (2012). The effect of translation speed upon the intensity of tropical cyclones over the tropical ocean. Geophysical Research Letters, 39(7). https://doi.org/10.1029/2011GL050765

Nakamura, J., Lall, U., Kushnir, Y., & Rajagopalan, B. (2015). HITS: Hurricane Intensity and Track Simulator with North Atlantic Ocean Applications for Risk Assessment. Journal of Applied Meteorology and Climatology, 54(7), 1620–1636. https://doi.org/10.1175/JAMC-D-14-0141.1

Nakamura, Jennifer, Lall, U., Kushnir, Y., & Camargo, S. J. (2009). Classifying North Atlantic Tropical Cyclone Tracks by Mass Moments. Journal of Climate, 22(20), 5481–5494. https://doi.org/10.1175/2009JCLI2828.1

Pohorsky, R., Röthlisberger, M., Grams, C. M., Riboldi, J., & Martius, O. (2019). The Climatological Impact of Recurving North Atlantic Tropical Cyclones on Downstream Extreme Precipitation Events. Monthly Weather Review, 147(5), 1513–1532. https://doi.org/10.1175/MWR-D-18-0195.1

Rasp, S., & Lerch, S. (2018). Neural Networks for Postprocessing Ensemble Weather Forecasts. Monthly Weather Review, 146(11), 3885–3900. https://doi.org/10.1175/MWR-D-18-0187.1

Sahoo, B., & Bhaskaran, P. K. (2019). Prediction of storm surge and coastal inundation using Artificial Neural Network – A case study for 1999 Odisha Super Cyclone. Weather and Climate Extremes, 23, 100196. https://doi.org/10.1016/j.wace.2019.100196

Schumacher, R. S., Galarneau, T. J., & Bosart, L. F. (2010). Distant Effects of a Recurving Tropical Cyclone on Rainfall in a Midlatitude Convective System: A High-Impact Predecessor Rain Event. Monthly Weather Review, 139(2), 650–667. https://doi.org/10.1175/2010MWR3453.1

Scoccimarro, E., Gualdi, S., Villarini, G., Vecchi, G. A., Zhao, M., Walsh, K., & Navarra, A. (2014). Intense Precipitation Events Associated with Landfalling Tropical Cyclones in Response to a Warmer Climate and Increased CO_2. Journal of Climate, 27(12), 4642–4654. Retrieved from JSTOR.

Villarini, G., Smith, J. A., Baeck, M. L., Marchok, T., & Vecchi, G. A. (2011). Characterization of rainfall distribution and flooding associated with U.S. landfalling tropical cyclones: Analyses of Hurricanes Frances, Ivan, and Jeanne (2004). Journal of Geophysical Research: Atmospheres. https://doi.org/10.1029/2011JD016175

Zhou, Y., & Matyas, C. J. (2018). Spatial Characteristics of Rain Fields Associated with Tropical Cyclones Landfalling over the Western Gulf of Mexico and Caribbean Sea. Journal of Applied Meteorology and Climatology, 57(8), 1711–1727. https://doi.org/10.1175/JAMC-D-18-0034.1

1. **Human Participants Research**
   Human participants will not be involved in this research.
2. **Vertebrate Animals Research**
   Vertebrate animals will not be involved in this research.
3. **Potentially Hazardous Biological Agents Research**
   Potentially hazardous biological agents will not be involved in this research.
4. **Hazardous Chemicals, Activities, & Devices**
   Hazardous chemicals, activities, and devices will not be involved in this research.

NO ADDENDUMS EXIST