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Tropical Cyclone Translation Speeds in the Northern Atlantic Ocean

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Tropical Cyclone Translation Speeds under a Changing Climate:

An Analysis of 40 Years of Tropical Cyclone Translation Speeds in the North Atlantic Oceanic Basin

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Introduction

Over the past 40 years, tropical cyclones have caused over $1,076.9B in damage in the United States. These expenses make up over 52.5% of the total costs of all the weather and climate disasters in the US during that 40-year time period(NCEI, 2022). Despite the damage of the past four decades of droughts, floods, tornados, wildfires, and more climatic disasters, all of those combined still do not total the amount of destruction tropical cyclones have caused. The fatalities from tropical cyclones are just as devastating. Hurricane Katrina of 2005 caused over 1,800 deaths; Harvey in 2017 just under 90 deaths; Ike of 2018 took 112 deaths; and horrifically, Maria of 2017 claimed nearly 3,000 lives. The destruction that tropical cyclones have caused is astronomical, and a factor of tropical cyclones that is responsible for this level of destruction is their translation speeds.

Tropical cyclone translation speed (TCTS) is the speed at which a hurricane is moving. TCTS is not to be confused with the wind speed of the hurricane, but rather the duration of time it takes for a storm to move from Point A of its track to Point B. Therefore, the slower the TCTS, the greater the duration of time the affected regions are exposed to TC conditions. “Translation speed of TCs is one important feature because the slower TCs move, the longer is their influence time, and the greater is the impact of severe weather events associated with TCs such as heavy rain and stronger winds” (Yamaguchi, Chan, Moon, Yoshida, & Mizuta, 2020). This “staling” leaves regions vulnerable to strong winds for a longer time, driving greater storm surges and depositing more rain. In particular, tropical-cyclone related rainfall, which “is inversely proportional to its translation speeds” (Hall & Kossin, 2019) creates serious societal threats with an extended staying time over land.

Discourse regarding tropical cyclone translation speeds became more heavily discussed within the scientific community beginning with the publication from James P Kossin of "A Global Slowdown of Tropical-Cyclone Translation Speed" in 2018. Within his research, Kossin finds that TCTS has decreased by 10% globally from 1949 to 2016 (James P. Kossin, 2018). However, the claims made in this publication were met with disagreement. In 2019, Moon et al. published a response arguing that the trends found by Kossin could be attributed to a satellite bias between the pre-and post-satellite-era data availability and that the results "suggest the slowdown of TCTS is not a global phenomenon" (Moon, Kim, & Chan, 2019). Similarly, Lanzante published "Uncertainties in Tropical Cyclone Translation Speed" and found that the trend comes from a few step-like changes across the time series, particularly within the earlier part of the record, and that the trends are not consistent across the study period (Lanzante, 2019). Lanzante also references satellite bias as an issue within the claim of a global slowdown, explaining that "if satellites are able to sample portions of the domain that have climatologically slower cyclone movement, then the introduction of satellite sensing would bolster the recording number of slower cyclone tracks." Following these opposing publications, Kossin published a response to Moon and Lanzante defending his claims (J. P. Kossin, 2019). In response to the issue of satellite bias addressed by the authors, Kossin defends that in other studies, the same data used to conduct his analysis is used as "the best possible proxy for ground truth in century-scale Atlantic hurricane and variability trends." Further, after Kossin conducted a reanalysis of the data, he maintained a statistically significant trend, but instead of a 10% global decrease in TCTS, a 7% statistically significant decrease. More recently, a 2020 publication regarding changing TCTS found two significant conclusions in the discourse surrounding TCTS. First, historical simulations over 60 years (1951-2011) suggest that there has been "no significant decrease in the TCTS over the period" which holds consistent with the 2019 findings from Moon et al. The second finding of the publication is that with an increase in the relative frequency of TCs at higher latitudes in warmer future climate, it can be expected that the global average TCTS could actually be *faster* than present day (Yamaguchi, 2020). These different analyses and conclusions leave the scientific community in a position where further investigation and analyses regarding TCTS are needed.

Research Objectives

This research sets out to analyze the temporal trends of tropical cyclone translation speeds. As it is explicitly mentioned in Yamaguchi et al., and briefly in the discussion portion of other research articles, "further investigation . . . with finer grid spacing will be necessary for the future" (Yamaguchi, 2020). Therefore, this research will examine the translation speeds of not only the average TCTS of oceanic basin level but at a 2.5° by 2.5° grid cell level. The spatial scope of the research was narrowed to the North Atlantic oceanic basin. The temporal scope of the research is a time series from 1981 to 2020. Selecting this time series eliminates the discrepancies of pre and post-satellite-era bias referenced in critiques of Kossin's publications. These scopes establish the research question, "Has there been a statistically significant change in tropical cyclone translation speeds in the North Atlantic Oceanic basin over the past 40 years?"

Methods

The first step of conducting the analysis was creating a grid cell system for the basin. The data used to create this grid system was obtained from NOAA Physical Sciences Laboratory NCEP/NCAR Reanalysis Data (NOAA Physical Sciences Laboratory, 2022). Any of the surface datasets would be conducive for obtaining the coordinate points necessary, but for this study, the netCDF4 file belonging to the monthly mean air temperature was chosen. This data was brought into R Studio (R) and cleaned to get the latitudinal and longitudinal coordinates for every 2.5º. Next, the data was downloaded to ArcGIS Pro to create the global grid. To fit the scope of the research, only grid cells identified as being a part of the North Atlantic (NA) oceanic basin were selected. This created a grid cell system of 758 cells. (Figure 1).

The second step in preparing the analysis was gathering the TC data. The TC track data came from the International Best Track Archive for Climate Stewardship (IBTrACS) in which the shapefile containing data from 1980 to of current was downloaded (Knapp et al., 2018). This dataset included each tropical cyclone track since 1980, and the shapefile and tracks were created by a satellite locating the geographical coordinates of the TC every three hours. These "timestamps" were used to calculate the translation speed of each TC. Using ArcGIS, an intersection clip was performed on the tracks from the grid cells, separating the entirety of one storm track into different segments by grid cells. Those segments were then referenced to the time recorded by the three-hour time stamp. From this, the time of entry and time of exit of each segment of the grid cell was available so that the duration of time of each track within each cell was calculated. By running this calculation for each track, data was available for the TCTS by track or by grid cell.

As the TCTS within the cell were being calculated, it became clear that there was a discrepancy in the temporal frequency of TC data within each grid cell. Some grid cells were recording multiple TCs every year in the time series, whereas other grid cells only recorded an intersecting TC for one or two years over the entirety of the series. To ensure that in the analysis of the TCTS that those cells with very few years of data were not analyzed with the same weight as those that recorded a TC every year, the grid cell system was filtered to only include grid cells that had experienced TCs for 20 or more of the 40 years (n>20). This refined the number of grid cells in the basin from 758 down to 191 cells (Figure 2).

The statistical analysis that was conducted on the data was sens.slope. Sens.slope tests produce a numeric representation of the linear rate of change for the variable and a corresponding p-value for that rate. Using a confidence level of $\alpha=0.05$, any calculated trends that had a corresponding p-value $< \alpha$ are considered to be statistically significant.

This research question "has there been a statistically significant change in tropical cyclone translation speeds in the North Atlantic Oceanic basin over the past 40 years?" was analyzed on multiple different aggregated scales. The first was done on the grid cell level—each 2.5^o by 2.5^o cell was analyzed for statical significance individually. In this test, only the grid cells that had n>20 were selected for analysis. Further, the time series was aggregated into eight, 5-year averages across the forty years. Aggregation into 5-year averages was done to ensure that there were TCTS values consistent for each cell across the time series and that the lack of data for extended periods did not impact statistical conclusions.

In the next tests, the grid cells were aggregated by latitude. This included thirteen 2.5^o intervals, beginning with the first at 11.25^o, with the fourteenth latitudinal interval being 43.75^o and greater, which was aggregated into the same latitudinal analysis due to the minimal amount of data from 43.75^o and above. Latitudinal influence on TCTS was referenced in publications with the findings that TCTS had an increasing relationship with latitude (Moon, 2019) and that TCTS was dependent on the latitudinal distribution of tropical cyclones (Yamaguchi, 2020). At the latitudinal aggregation, both an n>20 analysis and an n>0 analysis were conducted, where n is the number of years a grid cell recorded TC data in the 40-year time series. Choosing to include both the n>20 and the n>0 grid cell systems was due to the emphasis the publications placed on the significance that latitude could have in TCTS. In previous studies, it was found that there were notably different rates of change in TCTS contingent on if the TC was above or below 30^{o} (Chan, K. T., 2019).

N>20 grid cells were also aggregated into quadrants within the basin and analyzed at four different levels within this aggregation: Northeast (NE) quadrant, Northwest (NW) quadrant, Southeast (SE) quadrant, and Southwest (SW) quadrant. The last aggregated analysis conducted within this research was the aggregation of land cells and ocean cells. These cells were selected from the NA basin of n>0 as opposed to the n>20 basins, due to the geographic distribution of where n>20 cells fell.

Results

The primary test conducted was sens.slope for each of the 191 grid cells within the refined basin. When the statistical test was performed, no single cell produced a p-value representing the statistically significant trends.

The next test performed was latitudinal aggregation. For n>20, one of fourteen aggregated latitudes returned a trend value with a corresponding statistically significant p-value. At 28.75^{o} – 31.25^{o}, there was a linear rate of change of 0.2256, with a corresponding p-value=0.003201 (Figures 3 and 4). When the fourteen latitudinal aggregations were tested again, this time including all of the data in the NA, not filtering by the number of years of TC data (n>0), there were two latitude ranges with statistically significant trends. At 26.75^{o} – $28.75^{o,}$ a trend of 0.1200721 with a corresponding p-value of 0.04146 and at 28.75^{o} – 31.25^{o}, a trend of 0.1650836 with the corresponding p-value of 0.01223 was output (Figure 5).

The next data analyzed was the aggregation into quadrants. The NW, NE, and SE, quadrants did not output statistically significant trends, however, the southwest quadrant did. With a p-value of 0.004152, the SW quadrant had a linear rate of change of 0.16892 (Figures 6 and 7).

Finally, the separation of grid cells aggregated into land and ocean basins was conducted. The land cells, which spanned the east and gulf coast of the United States did not output a statistically significant trend. The ocean data, however, did have a statistically significant trend of 0.07097 (p-value of 0.04385) (Figures 8 and 9).

Discussion

There were no statistically significant linear rates of change for the analysis of each 2.5^{o} by 2.5^{o} grid cell, meaning that this test did not find any statistically significant rates of speeding or slowing TCTS. One of the primary influences that could have lent to the results within this test was the aggregation of data in eight, 5-year averages. In efforts to eliminate complications of null values for specific years in each grid cell, an adverse effect of disrupting or misrepresenting the true trend of change in TCTS occurred. In future studies, it would be beneficial to reanalyze the 40-years of data, and rather than averaging the data into 5-year aggregations, running the sens.slope analysis omitting the null values in the calculation.

When calculating sens.slope for TCTS aggregated at the latitudinal scale, there were statistically significant trends found in both the n>20 and n>0. For both analyses, the range 28.75^{o} – 31.25^{o} produced statistically significant. For n>0, 26.25^{o} – 28.75^{o} was also statistically significant. It can be inferred that an additional range of latitudes was found to be statistically significant in n>0 due to the larger amount of data and grid cells being analyzed in the test. This reasoning could also be the cause of there being a more drastic increasing trend for 28.75^{o} – 31.25^{o} in n>20 (0.2256) than at n>0 (0.165086).

The SW quadrant was the only quadrant of the four that had a statistically significant change in TCTS across the time series. The SW quadrant is unique of the other three quadrants in its geography being composed of islands dispersed throughout the ocean. TCs lose energy after making landfall due to the loss of energy from the ocean (Tanimoto and Lamontagne, 2014). Therefore, it is a possibility that the islands, scattered amongst the SW quadrant and intersecting the paths of TCs, could be interrupting the heat and energy source—the ocean—and minimizing "fuel" to maintain a faster TCTS. The southwest basin also contains one of the n>0 latitudes (26.25^{o} – 28.75^{o}) which was found to be statistically significant, so there is also possibility for trends at the latitudinal level lending to trends seen aggregated at the quadrant level.

Finally, in the aggregation of the grid cells categorized as land versus the aggregated grid cells categorized by the ocean, the ocean categorization produced a statistically significant trend of 0.07097. The land cells did not output a statistically significant trend. The results seen in this aggregation could be attributed to the selection of grid cells for each category. Cells were manually chosen from the basin to represent "land" or "ocean" cells. The ocean had a larger sample size than that of land and therefore could have been statistically significant simply due to less influence from the variability of null data across the time period. Land analysis of grid cells is also highly dependent on how many of the TCs actually make landfall yearly, again, presenting fewer data to be analyzed.

Implications

All statistically significant trends found across the different aggregations were positive linear rates of change. The trend being calculated was the duration of time each TC track spent in each grid cell, so therefore, an increasing linear rate of change and increasing duration means a slowing in TCTS.

When interpreting these results by the different spatial aggregations, this slowing has significant implications. For the latitudinal aggregation, the latitude range of $28.75^o – 31.25^o$ was recorded to be significantly increasing at both latitudinal tests. When understanding these results in terms of human geography, it can be seen that $28.75^o – 31.25^o$ contains multiple major population centers (Figure 10). Cities across this latitude include Jacksonville and Tallahassee, FL; Mobile, AL; New Orleans and Baton Rouge, LA; and Houston, TX. Not coincidentally, these cities and this latitude are also where some of the most infamous and devastating TCs in the United States have struck, such as Hurricane Katrina in New Orleans and Hurricane Harvey in Houston. Hurricane Harvey of 2017 stalled near Houston and generated torrential rainfall that caused widespread inland flooding unprecedented in historical observation (Zhu, Emanuel, & Quiring, 2021). Even more, the frequency of Harvey-like rainfall events is projected to "increase substantially" by the late 21st century (Hall & Kossin, 2019). With major metropolis being in the region of the country where these slowing TCTS are occurring, a large number of communities and the individuals within them are exposed to the danger of experiencing the effects of TC for longer durations of time. These effects include some of the most devastating aspects of TC storms such as extreme rainfall, windspeeds, and flooding. Increased exposure to these elements could and will likely translate to a rise in both economic devastation and fatalities.

The increasing trend of TC duration staying time within the southwest quadrant of the study zone will hold similar implications. When the 46 cells located in the Southwest quadrant of the North Atlantic were aggregated, they showed an increasing linear rate of change at a rate of 0.16892. The southwest quadrant contains cells ranging from 13.75º – 28.75º. Just as the geography and communities within that geography were significant for latitudinal aggregations, so are those within the southwest quadrant. (Figure 11). Specifically, the Central American and Caribbean Islands are located within the region. Countries located in the Southwest quadrant have unsurprisingly recorded some of the most devastating TC storms to date. In most recent years Hurricane Dorian, one of the most devastating TCs to devastate the Bahamas "stayed around 3 days and caused 74 deaths, 292 missing people, and USD 3.4 billion in damages" (Zhu, 2021). Hurricane Maria caused over USD 90 billion in damage to Puerto Rico and the US Virgin Islands, leaving less than 8% of roads open a month after the storm, and over 5 months later, over 25% of the country still lacks electricity (Scott, 2018). Puerto Rico's financial fragility, with an economic crisis beginning in the early 21st century, reduced the capacity to maintain critical energy, health care, transportation, and communication means after these TCs hit (Rivera, 2020). The majority of these island communities do not have the same financial resilience and funds to build back their infrastructure as the United States, and increased length of exposure to the dangers of TCs with slowing TCTS is critical to the impacts of these storms in their future.

Conclusion

This study analyzed tropical cyclone translation speed in the North Atlantic Oceanic basin from 1981-2020. The analysis was performed on multiple spatial scales, including by 2.5º by 2.5º individual grid cells; latitude, both using grid cells with over 50% or more years of TC data and with grid cells with no restrictions of years recording TC data. Grid cells were also aggregated into four quadrants within the basin as well as being aggregated by land grid cells and ocean grid cells. A sens.slope test calculating the linear rate of change and significance of that trend found that at a 5% confidence level, at the latitudinal aggregation, analyzing n>20 grid cells, the range of latitude at $28.75^o – 31.25^o$ had a statistically significant trend of slowing TCTS. Similarly, analysis of latitude n>0 output statistically significant increases in duration at 26.75^o – 28.75^o and at $28.75^o – 31.25^o$. Of the four aggregated quadrants, the southwest quadrant showed a statistically significant linear rate increase in the duration of TC staying time. Finally, the aggregations of land versus ocean cells found that the oceanic cells showed a statistically significant increasing linear rate of change. All the statistically significant trends were positive, indicating an increase in the duration of the forty-year time series and therefore, slowing TCTS.

Within the scientific discourse regarding changing tropical cyclone translation speeds in our changing climate, this research adds information regarding specific regions within oceanic basins where there has been a slowing of tropical cyclone translation speed. This research provides data on the geographic trends in changing TCTS and narrows the span of the communities that will be most at risk of the dangers of slowing TCTS.

Further avenues within this research could include analyzing the translation speeds during ENSO years and incorporating sea surface temperature into the analysis to see if either of these factors impact the trends. Moreover, a comparison of the different oceanic basins at this level of geographic focus could provide insight into if trends are global or regional.

Acknowledgments

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Figure 1**:** North Atlantic 2.5° by 2.5° cells

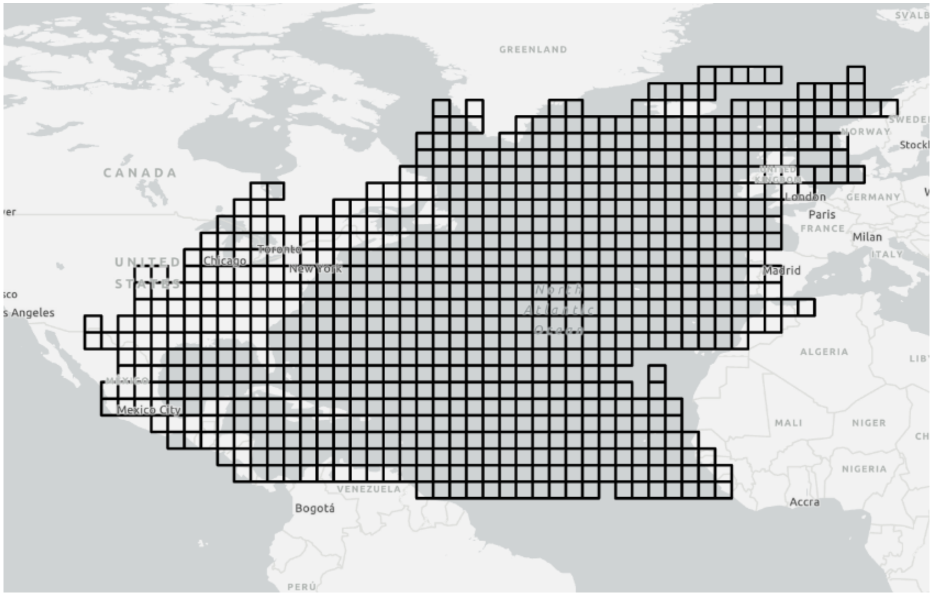


Figure 2: North Atlantic Grid Cells refined to cells with n>20 years of data

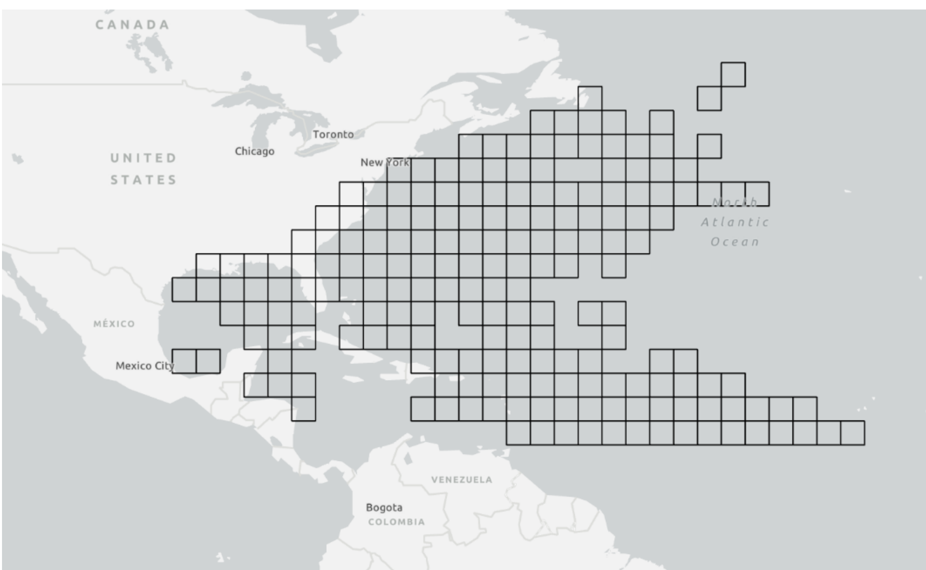


Figure 3: N>20 Statistically Significant Aggregated Latitudes (28.75° -31.25°)

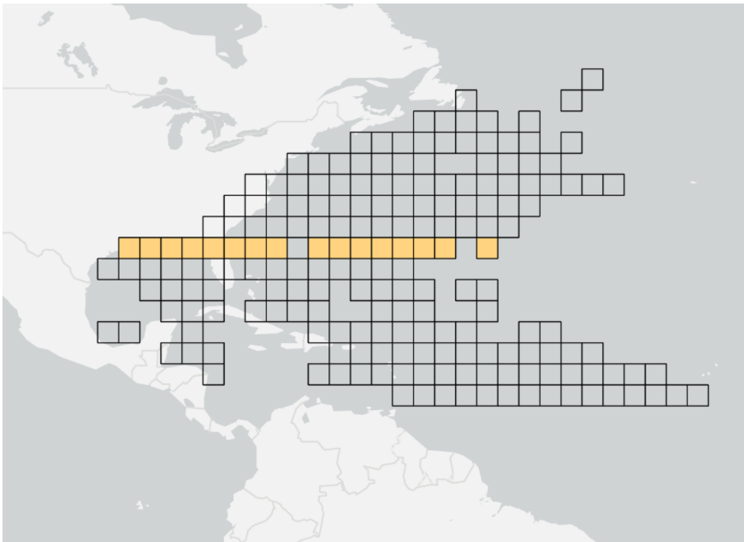


Figure 4: Temporal Trend of TCTS at 28.75° -31.25° with trend line

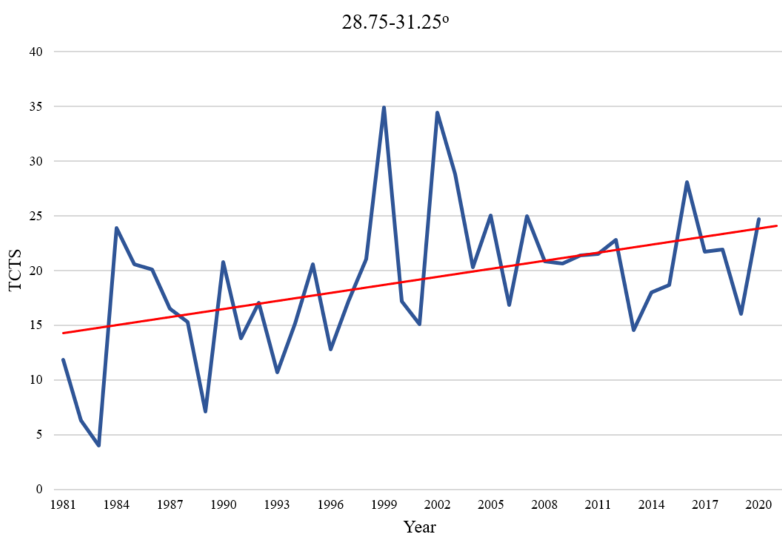


Figure 5: N>0 Statistically Significant Aggregated Latitudes (26.25º-28.75º) and (28.75º - 31.25º)

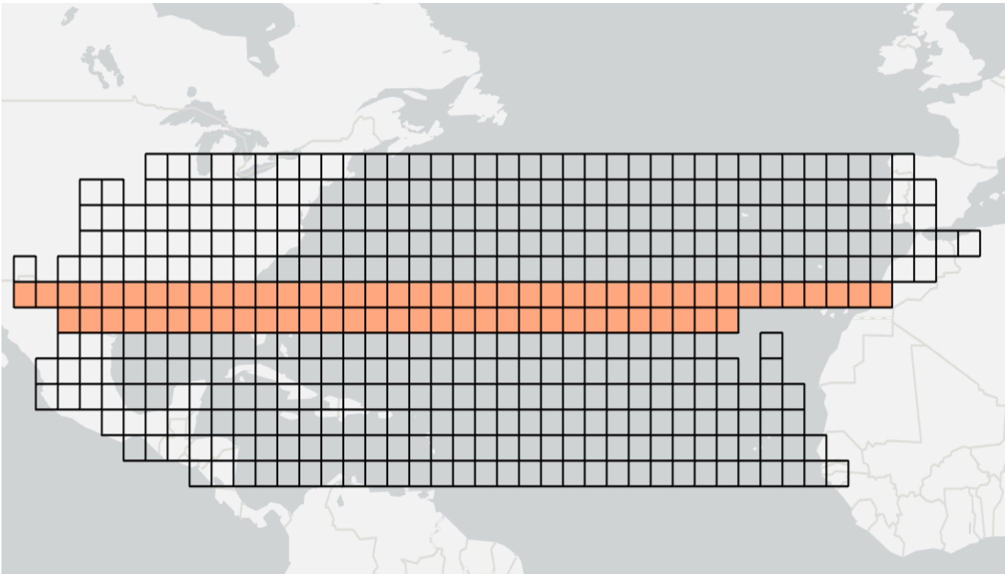


Figure 6: Statistically Significant Southwest Basin

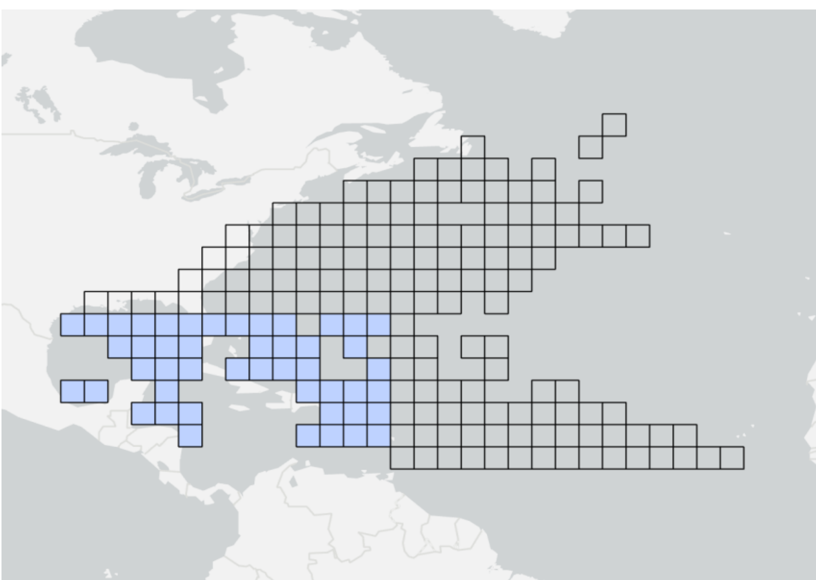


Figure 7: Temporal Trend of Southwest Basin with Trendline

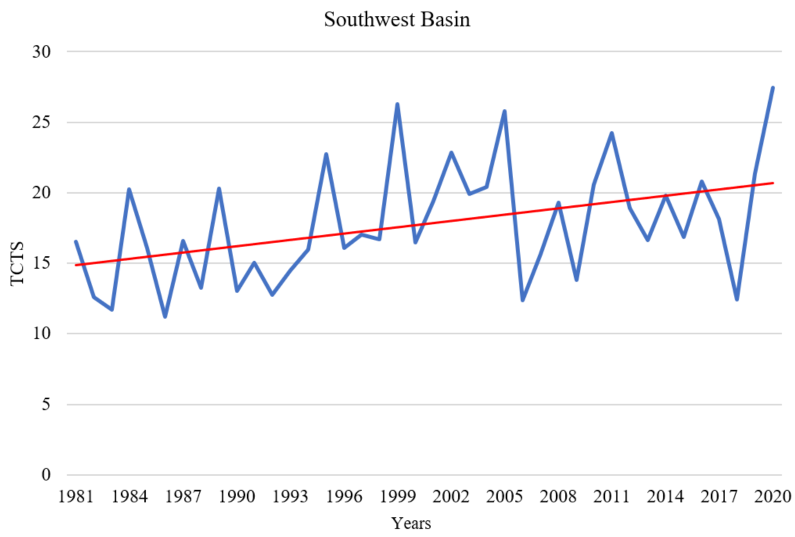


Figure 8: Aggregation of Land (green) and Ocean (blue) Grid Cells

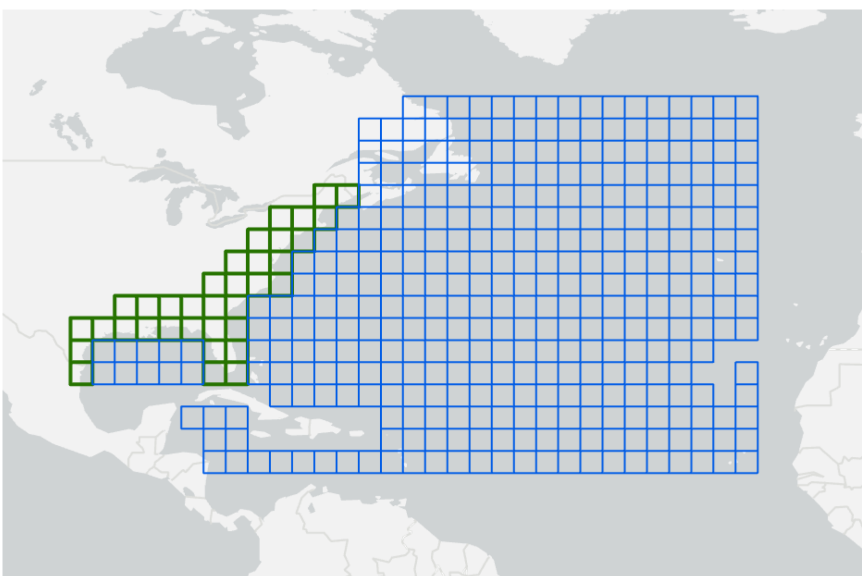


Figure 9: Statistically significant Temporal Trend of Oceanic Grid Cells with Trend Line

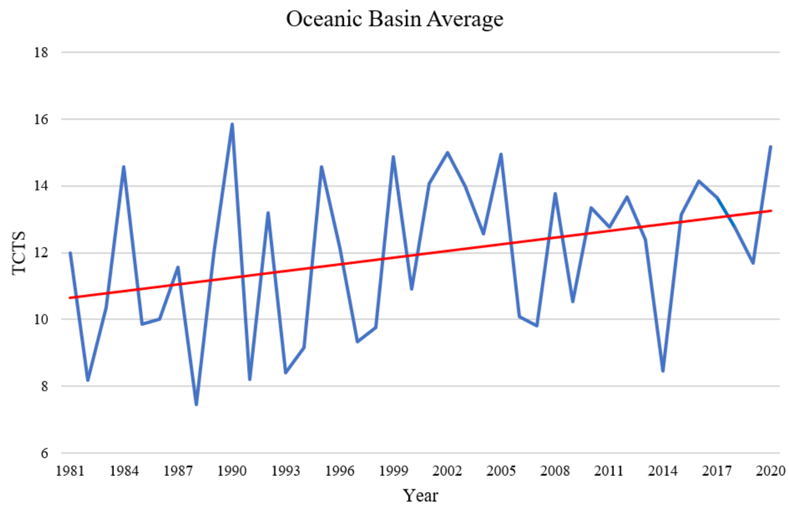


Figure 10: Population Centers highlight in red at 28.75° – 31.25°

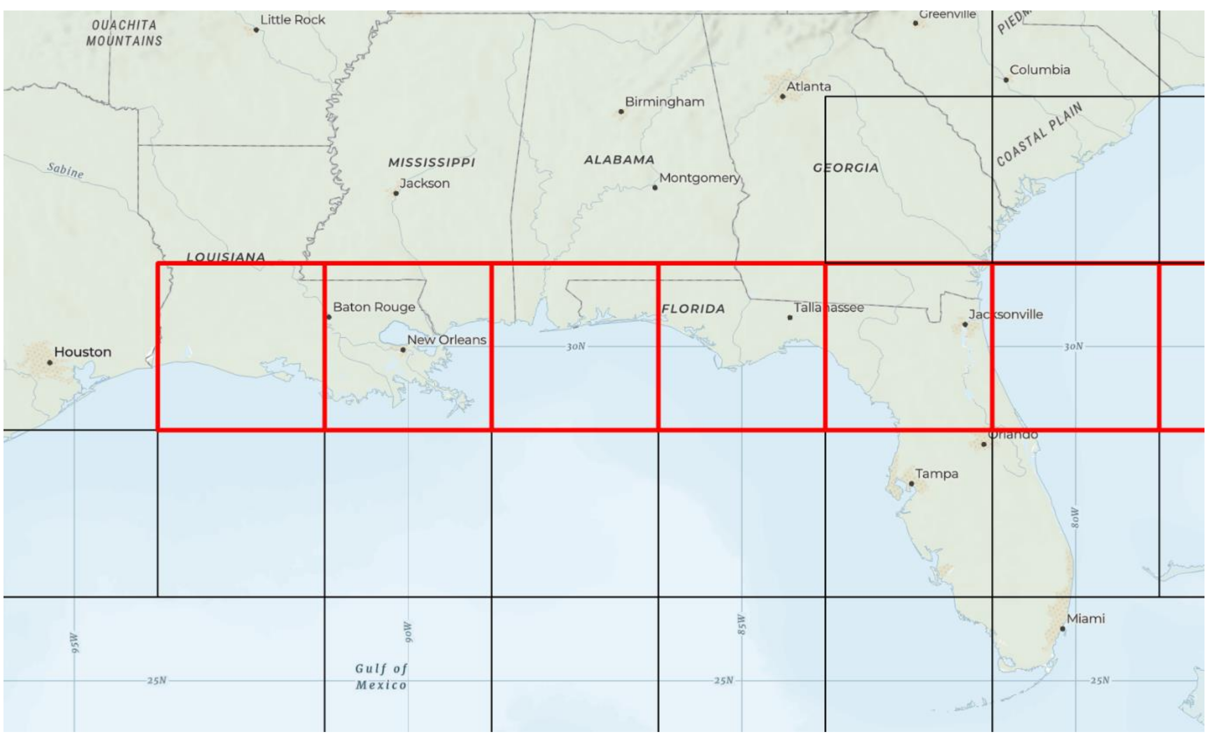
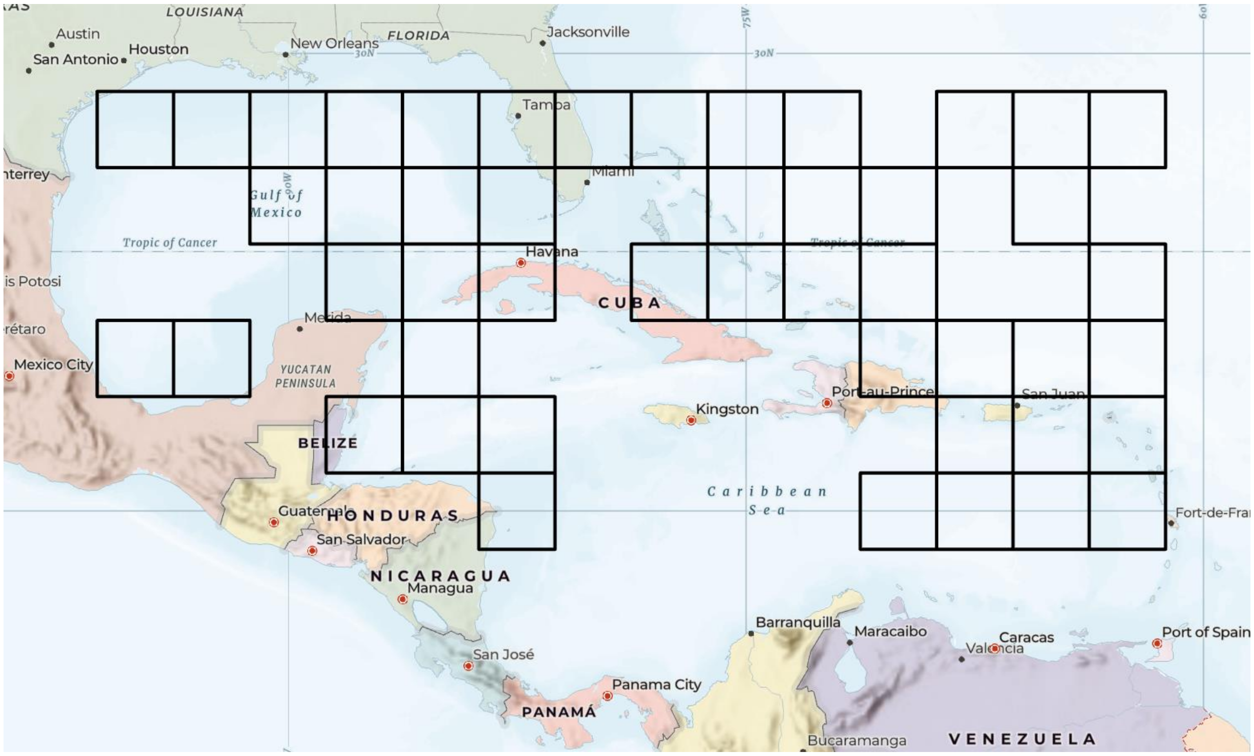


Figure 11: Countries and Territories impacted by the Overlayed Statistically Significant Southwest Basin



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