Methods for Analyzing Tropical Cyclone Distribution in the North Atlantic

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***Abstract*— Tropical cyclone (TC) activity around the world has accounted for thousands of deaths and billions of dollars in damage. It has already been found that the intensity of these storms systems is likely to increase due to global warming, but the geographic distribution of tropical cyclones has not yet been examined in great detail. As many of the world's most populous cities and centers of wealth are on or near the coast, understanding how tropical cyclone distribution patterns may shift in the future is important for preparedness and response to these events. Four methods to determine the average coordinates of tropical cyclones were examined using the National Oceanic and Atmospheric Administration's (NOAA) Historical Hurricane data HURDAT database. It was found that there may be a south easterly shift in the average location of TC since 1851, with the shift east more than the shift south. While each of the four methods used to average the coordinates was useful in determining trends over a decadal scale, it did not give the more detailed track information. Future research may include exploring the possible mechanisms for the observed shifts in the average latitude and longitude and changing the number of measurements used in the coordinate average methods in order to further refine these methods and results.**

***Index Terms*—hurricanes, tropical cyclones, distribution, North Atlantic**

I. Introduction

A. Background Information

BECAUSE many of the world's most populous cities and centers of wealth are on, or near, the coast, understanding how global tropical cyclone (TC) distribution patterns may shift in the future is important because of the damage they can cause. Due to the fact that past damages to the US measured in the billions of dollars [1], risk maps for New England have been recently developed [2]. Much of the current literature focuses on examining the trends in the frequency and intensity of tropical cyclones in the past. In one paper [3], it was suggested that the Atlantic Multidecadal Oscillation (AMO) was a major player in TC frequencies since about 1940. Another [4] argues that a changing radiative forcing has more of an impact on frequencies. In another [5], they found that there was little evidence for long term trends in TC and that intensities would remain the same or slightly increase for a CO_2 doubling. However, for the future, they found it was difficult to determine the distribution of intensities and frequencies. However, in the Intergovernmental Panel on Climate Change (IPCC) report it was established that the issue is still up for debate with evidence on both sides, but more in favor of increasing intensities and frequencies [6], though that has been called into question recently [7]. Clearly the question of potential trends in frequency and intensity is unresolved.

Much of the current literature focuses on examining the trends in the frequency of tropical cyclones during the past 160 years. While there has been much research done investigating the frequencies and intensities of TC, there has been little research done examining the geographic distribution of TC. There was one study [8] that looked at the spatial distribution of TC in the southwest Pacific Ocean which concluded that west of 170° E the main factor determining location is sea surface temperature and east of 170° E it is more related to the Southern Oscillation Index (SOI), also known as the El Niño-Southern Oscillation (ENSO). ENSO has been shown to be a major factor in the inter-annual variability of TC in the Pacific Ocean [9], [10]. A typical storm track season can have storms beginning off the coast of Africa or in the Gulf of Mexico.

Because of the minimal research done in the spatial distribution of TC, this study examines those trends for the Atlantic basin using the HURDAT database. The HURDAT database has been re-evaluated and documented to provide the most accurate database of TC activity in the Atlantic [11], [12] and is therefore a good source of data. This study adds to the body of scientific knowledge for the spatial distribution over time of TC in the North Atlantic Ocean and examines four methods for determining the TC location. This is important because as climate changes it brings with it changes to the frequency and intensity of TC, so it is feasible that the spatial distribution of TC may change as well.

B. Study Area

The region of interest for this study is the North Atlantic Ocean. The Atlantic Ocean is the second largest ocean in the world and covers about 20% of the Earth's surface. The North Atlantic is known for its strong TC activity, especially during the autumn months. While the Atlantic spawns the TCs, it is the Gulf of Mexico, the US eastern seaboard, and the Caribbean that suffer much of the loss of life and damage to property. The Gulf of Mexico is connected to the Atlantic Ocean and borders the southern United States. The Caribbean is a group of islands off the coast of Florida in between the Gulf of Mexico and the greater Atlantic Ocean. TCs are a

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major concern for those living in and around the Gulf of Mexico and the greater Caribbean in general.

C. Study Period

The project uses data of tropical cyclones in the North Atlantic from 1851-2010. Spatial distribution of observations was conducted on both a decadal scale and over the entire time period of the data.

II. Research Objectives

The main goal of this study was to examine different methods used in determining the geographic distribution of tropical cyclones in the Atlantic basin. While it would be useful to examine the entire pathway, due to time constraints only an average point of the tropical cyclones was studied. This still yields useful insight into the changes in geographic distribution of TC over time.

III. Data

The data source that was used in this study was the National Oceanic and Atmospheric Administration's (NOAA) HURDAT Best Track Database from the National Hurricane Center (NHC), found at http://www.aoml.noaa.gov/hrd/hurdat/. The data is stored in lines as a single header for each storm and subsequent daily data in an ascii text file. It contains the 6-hourly (0000, 0600, 1200, 1800 UTC) center locations (latitude and longitude in tenths of degrees) and intensities (maximum 1-minute surface wind speeds in knots and minimum central pressures in millibars) data from all tropical cyclones in the East Atlantic Ocean during the period 1851-2010 [13].

There were some known issues with the HURDAT database, but a recent reanalysis has taken care of many of them [11]. Some of the analysis techniques at the NHC changed over the years and led to biases in the database that had not been addressed as the understanding of tropical cyclones has changed over time [14]. In addition, because the methods used to collect the data have changed over time due to better technology, the more recent data is more reliable. Figure 1 shows that before 1944, the two major sources of data about TC were land stations and ships at sea. Because of this, many storms may have gone unaccounted for. However, because forecasts were limited, ships during this time encountered TCs more often because they did not know where they would be in order to avoid them.

IV. Methodology

For each TC, the 6 hourly latitude and longitude was spatially averaged using four different methods in order to get a single geographic location for each TC. These locations were then compared for each methodology. To do this, a Python script was written to read the HURDAT database text file, calculate and save attributes for each storm measurement, and output these results to a text or csv file for further analysis in Microsoft Excel and Quantum GIS. This script can be posted online to allow others to examine the HURDAT database using the same methodologies used in this study. The following four methodologies were examined:

A. All observations (method 1)

The first method of calculating a single geographic location uses the geographic midpoint method as detailed in Appendix A.

B. Middle 48 hour period observations (method 2)

The second method identified the first observation of greatest intensity and the 4 measurements on either side (48 hour period) were averaged to calculate the location of the tropical cyclone when it is most powerful. This was done to get a metric of the geographic location about the most intense part of the storm. If there were not enough observations methods, as many points as were available were used.

C. First 24 hour period observations (method 3)

The third method took the first 24 hour period of measurements and averaged the coordinates together using the geographic midpoint method. If there were not enough observations methods, as many points as were available were used.

D. Last 24 hour period observations (method 4)

The fourth method took the last 24 hour period of measurements and averaged them together using the geographic midpoint method. This can allow for changes to be detected in the location of first detection and dispersion. If there were not enough observations methods, as many points as were available were used.

V. Discussion and Results

Four methods were used to examine the trends in the average distribution of coordinates over a decadal period. Figure 2 shows the distribution of the average points using each of the four averaging methods. In each of the four methods, the points are clustered together, without overlap between the methods. While there is a fairly even spread across the longitude, the latitude in each of the four methods is fairly distinct, as seen in Figure 2. The northernmost cluster is the last 24 hours of observations (purple). Moving south, all the observations and the middle 48 hours and are next (red and black, respectively), with the first 24 hours of observations the most south (green). The distribution of these clusters is logical as the storms generally move from the warmer southern waters to the cooler northern waters of the Atlantic. Therefore, the first observations would be expected to be the furthest south, the last observations the furthest north, the middle to be in between, and all observations to be an aggregate of the previous three.

A. All observations (method 1)

As seen in Figure 3, which shows the all observations method, over most of the entire study period (year 2010 was excluded) the average latitude appears to be shifting south and the average longitude appears to be shifting east. The shift of the longitude east seems to be more consistent (R^2 = 0.36) than the shift south of latitude (R^2 = 0.11). The southward shift is surprising as one would expect that as the climate and oceans warm the subtropical waters would expand leading to a northward shift in TC storm average locations instead of the southward shift described above. It should be noted, however, that there is much variability in the latitude component of these TC observations over each decade.

B. Middle 48 hour period observations (method 2)

A similar shift as was seen for all the observations is seen for the middle observations in Figure 4, though with lower R^2 values. These trends also appear to be more or less stable as compared to those seen in the previous section that included all the observations.

C. First 24 hour period observations (method 3)

Figure 5 shows an even stronger trend in the latitude (R^2 = 0.16) and longitude (R^2 = 0.52) shift, south and east, respectively. This may indicate a shift in the genesis location of TC, though more likely the earliest detection of TC has changed with newer observation techniques. Even though there appears to be a slight shift both trends are relatively stable.

D. Last 24 hour period observations (method 4)

The weakest relationship is shown in Figure 6 with the average of the last four observations. There still appears to be an eastward shift in the longitude, but the latitude remains relatively unchanged in the long term, with minor fluctuations throughout. While there is no general trend in the latitude, as consistent with the other methods, the longitude seems to be rising over the long term.

The observed easterly shift in the longitude may indicate an actual trend, but more likely the earliest detection of TC has changed with newer observation techniques causing the skew towards the east. A similar skewing may be occurring in the latitude, though the effects are less pronounced.

The advantage to using each of the methods above to average the coordinates is that it allows clear visualizing of the data, both in a time series and on a map. A disadvantage is that it is not particularly numerically robust as it uses a relatively simple average function to compute the average location for TC over a specified time period. In addition, its use as a numerical model to forecast future events is limited.

VI. Future Work

Further study is needed to further explore the best methodologies for determining the possible mechanisms for the observed shifts in the average latitude and longitude. Changing the number of measurements used in the last, first, and middle observations would help to further refine these methods. In addition, future work could consist of limiting the measurements to only Tropical Storms and stronger as denoted by the Saffir-Simpson Scale in Figure 7. This would eliminate the noise from the many Tropical Depression observations and allow a more narrow focus on the true TC observations. The Python code already has this functionality, but due to time limits, this was not explored in great detail.

Additionally, the development of an early warning system/operational system based on past hurricane tracks can be developed. Constructing a model based on the trends found in order to forecast where future tropical cyclones may be more likely to make landfall and creating a map of high risk areas can be a useful application of this research.

VII. Conclusion

The methodologies used to address the research questions each had their advantages and shortfalls. While each of the four methods used to average the coordinates was useful in determining trends over a decadal scale, it did not give detailed track information. This knowledge is critical for emergency responders and decision makers in preparing for and responding to TC events that make landfall. Determining which of the four methodologies is the most useful and meaningful is a further area of inquiry for the future.

Overall, the southward shift in the latitude and the eastward shift in the longitude are consistent throughout all of the four methods used to average the coordinates. The location of TC observations has been moving south easterly over time, with more movement east than south. It should be noted, however, that the observed easterly shift in the longitude may indicate an actual trend in TC location, but, more likely, the earliest detection of TC has changed with newer observation techniques causing the skew towards the east. A similar skewing may be occurring in the latitude, though the effects are less pronounced. Regardless, more research is needed to have a better understanding of what variables underlie these observed shifts.

Appendix A

Below are details of the geographic midpoint formula used to average latitude and longitude coordinates. This methodology was adapted from http://www.geomidpoint.com/calculation.html.

1. Given the values for the first location in the list:
   Lat1 and lon1
2. Convert lat/lon to Cartesian coordinates for first location.
   X1 = cos(lat1) * cos(lon1)
   Y1 = cos(lat1) * sin(lon1)
   Z1 = sin(lat1)
3. Repeat steps 1-2 for all remaining locations in the list.
4. Compute total measurements.
   Totmeas = m1 + m2 + ... + mn
5. Compute average x, y and z coordinates.
   x = (x1 + x2 + ... + xn) / totmeas
   y = (y1 + y2 + ... + yn) / totmeas

z = (z1 + z2 + ... + zn) / totmeas

6. Convert average x, y, z coordinate to latitude and longitude.
   Lon = atan2(y, x)
   Hyp = sqrt(x * x + y * y)
   Lat = atan2(z, hyp)
7. Special case:

If abs(x) < 10-9 and abs(y) < 10-9 and abs(z) < 10-9 then the geographic midpoint is the center of the earth.

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LIST OF FIGURES

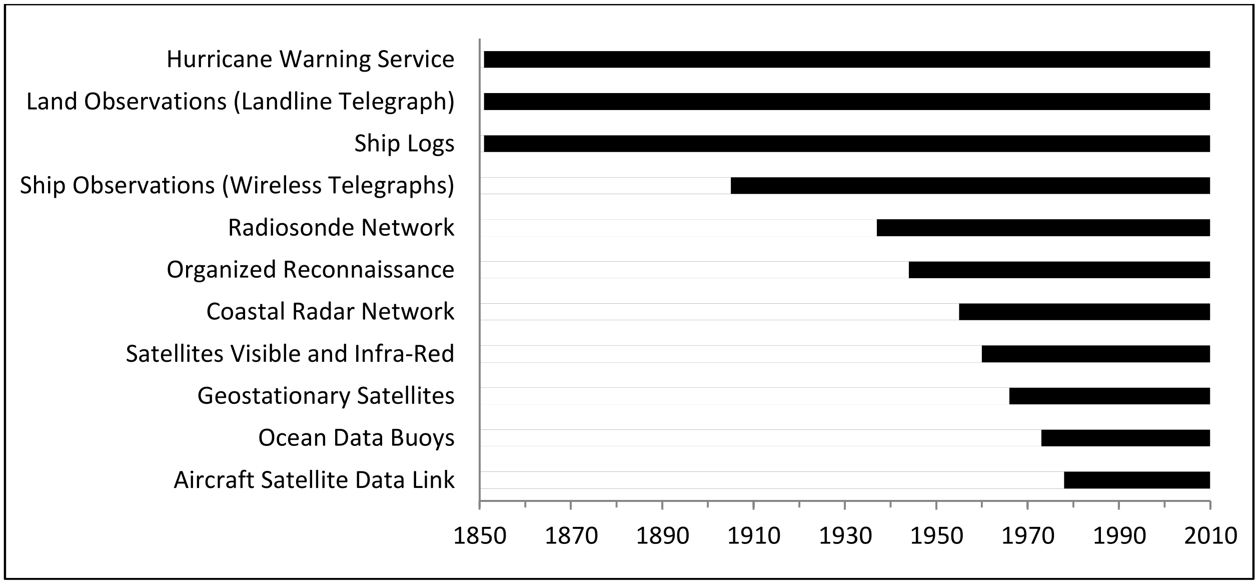

Figure 1: Advances in systems for observing tropical cyclones, 1851-2010.

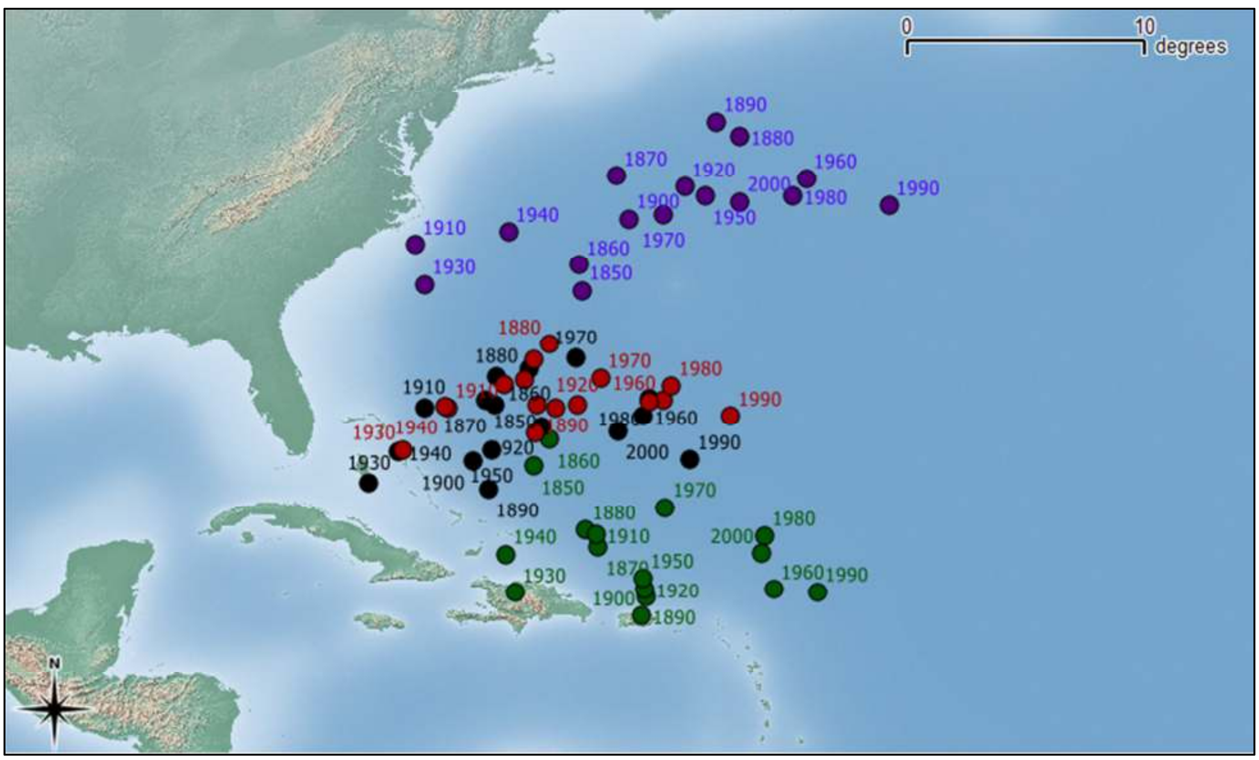

Figure 2: Map with each of the methods plotted. The methods are color coded, moving from north to south: last 24 hours of observations (purple), all observations (red), middle 48 hours of observations (black), and first 24 hours of observations (green).

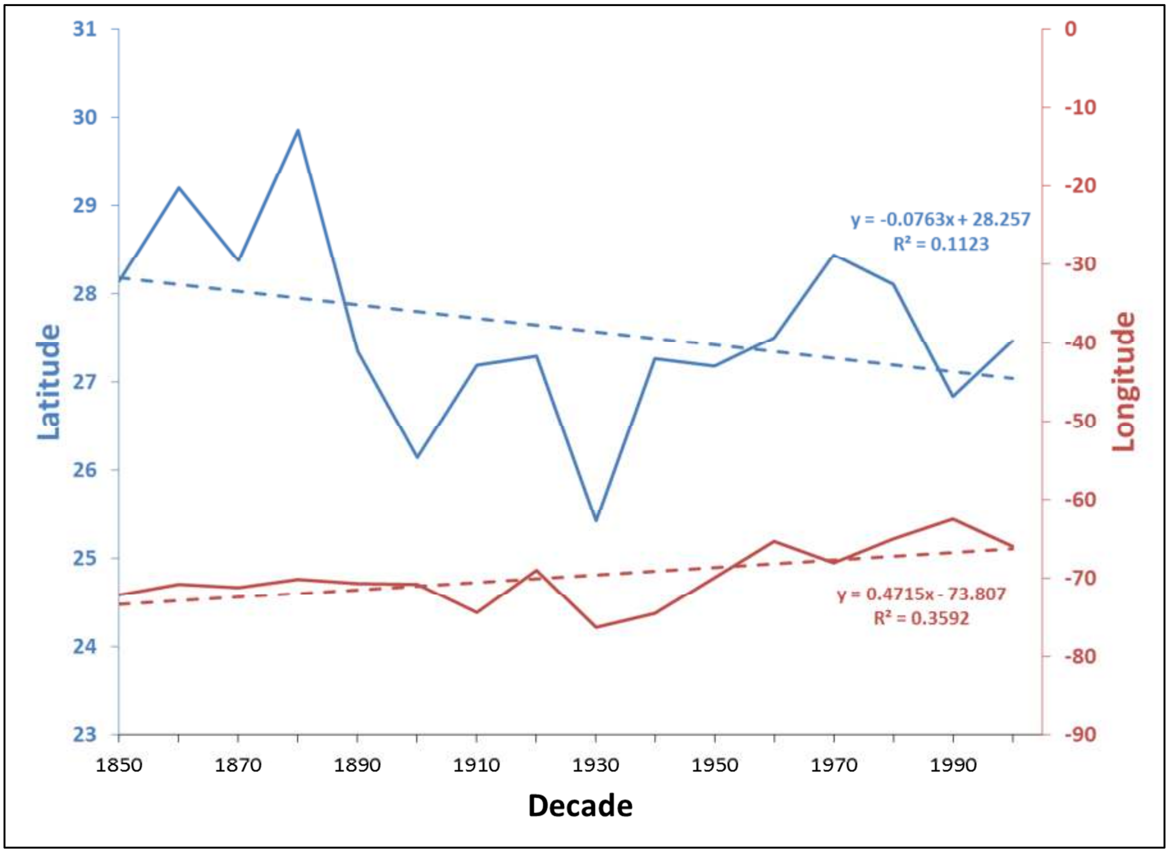

Figure 3: All observations method with latitude and longitude averaged over all the points, 1851-2009.

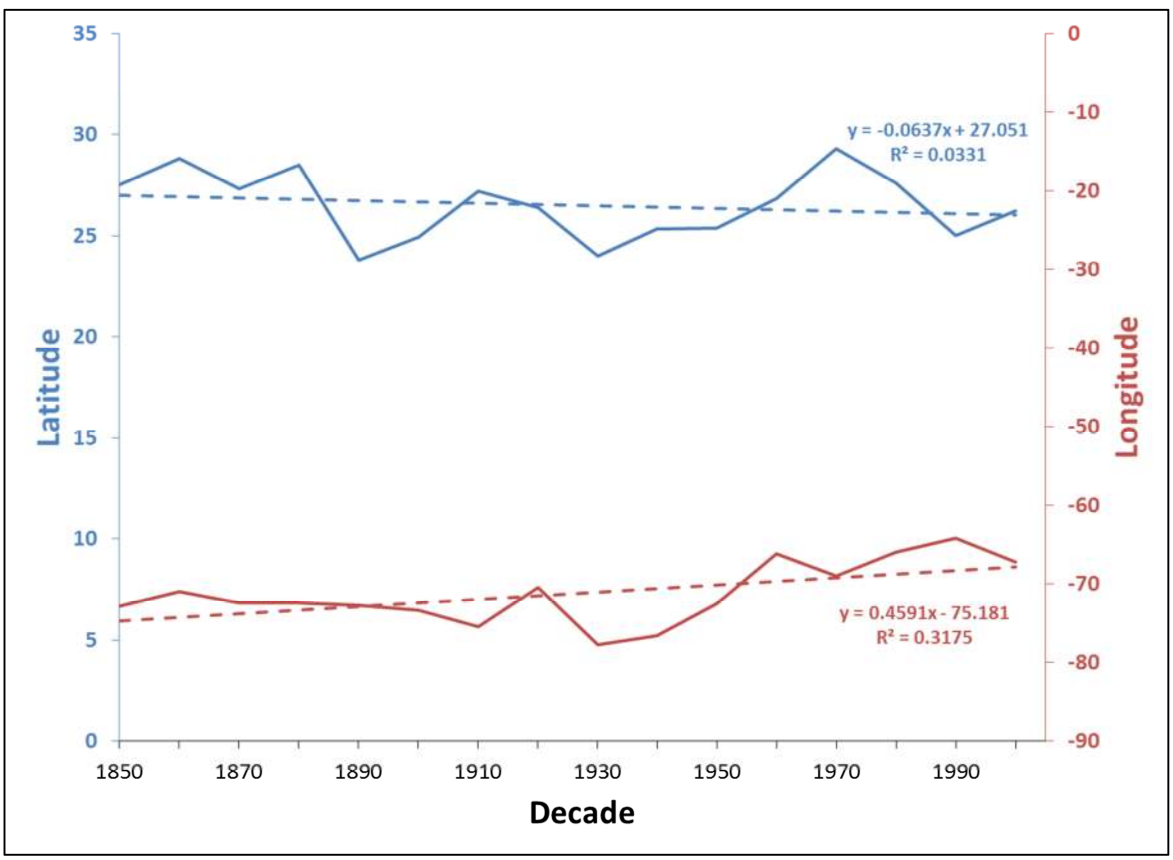

Figure 4: Middle 48 hour period method with latitude and longitude averaged over the most intense part of the TC, 1851-2009.

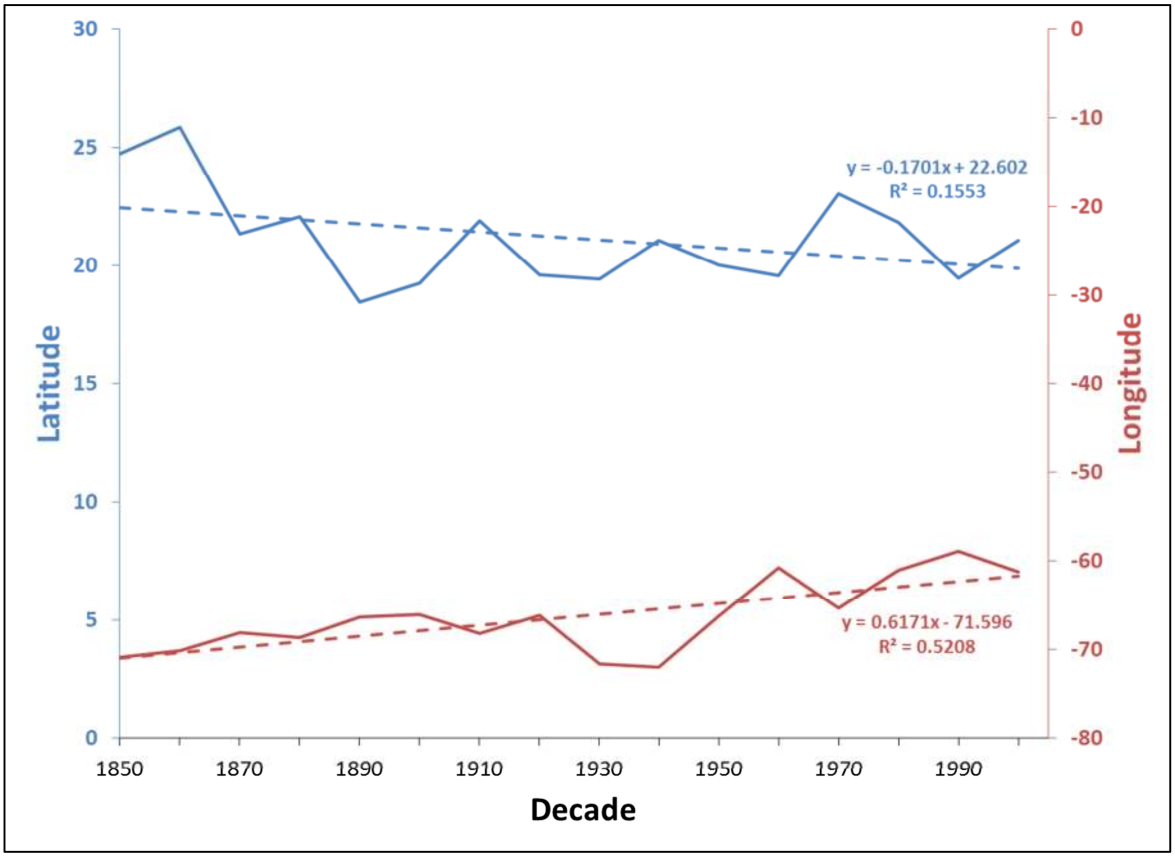

Figure 5: First 24 hour period observations method with latitude and longitude averaged over all the first four points, 1851-2009.

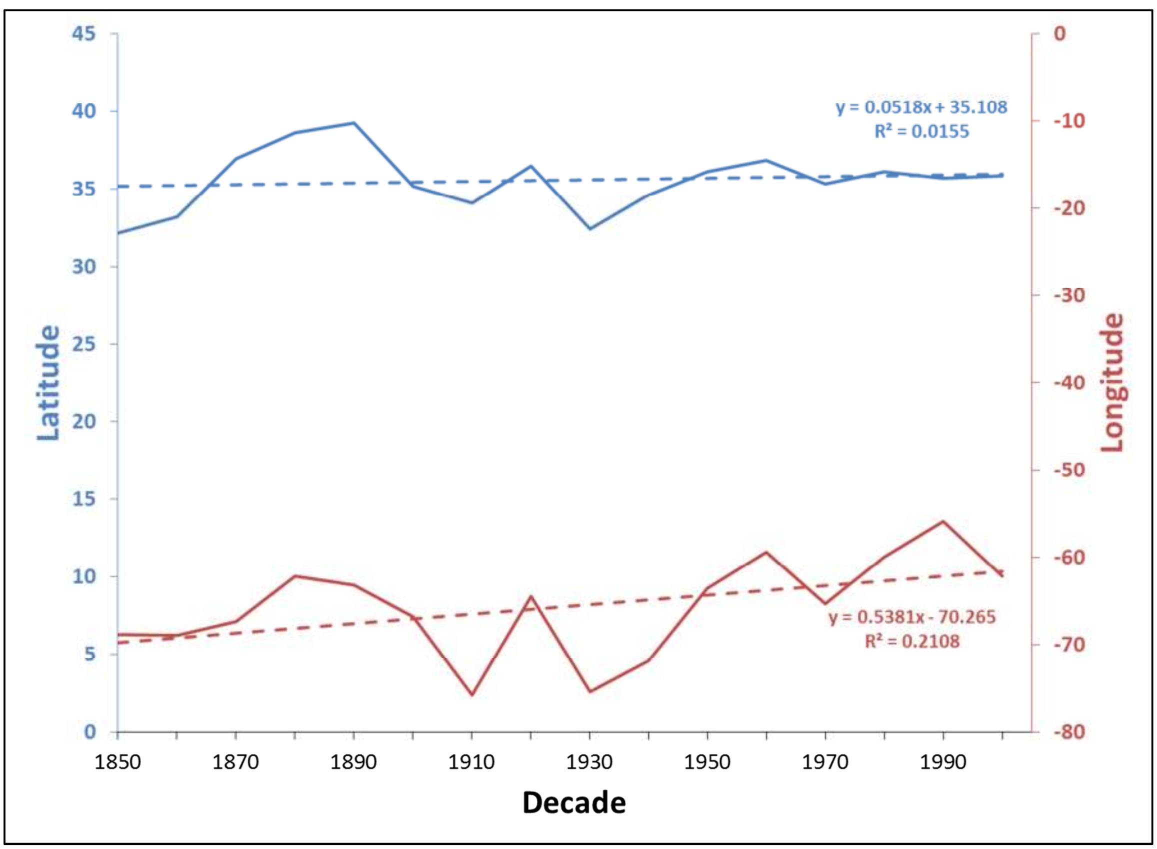

Figure 6: Last 24 hour period observations method with latitude and longitude averaged over all the last four points, 1851-2009.

Type	Category	Pressure (mb)	Winds (knots)	Winds (mph)
Depression	TD	-----	< 34	< 39
Tropical Storm	TS	-----	34-63	39-73
Hurricane	1	> 980	64-82	74-95
Hurricane	2	965-980	83-95	96-110
Hurricane	3	945-965	96-112	111-130
Hurricane	4	920-945	113-135	131-155
Hurricane	5	< 920	>135	>155

Figure 7: Saffir-Simpson Hurricane scale. Pressures are in millibars and winds are in knots where one knot is equal to 1.15 mph.