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1. Introduction

The study of past tropical cyclone activity by means of geological proxies and/or historical documentary records is known as paleotempestology. This scientific discipline has become prominent over the course of the last decade partially in response to the recent increase in tropical cyclone count and intensity in the North Atlantic basin witnessed since 1995. The field has also developed due to the socioeconomic impacts of tropical cyclones particularly along vulnerable coastal regions. During the twenty-five years prior to the start of the most recent increase in hurricane activity, major (Category 3, 4, or 5) hurricanes were less frequent than in previous decades. Yet, property losses from the hurricanes that did make landfall in the United States increased during this period due to development in damage prone areas (NOAA Paleoclimatology Program, 2000). Many researchers hence stress the importance of identifying historical tropical cyclones to understand long term trends in tropical cyclone climatology and to determine the influence of anthropogenic global warming on tropical cyclone activity and intensity. The North Atlantic Hurricane Database (HURDAT) has been one of the authoritative sources for examining North Atlantic tropical cyclone activity trends since 1850. However, some of the deadliest known hurricanes and potentially most active seasons in the North Atlantic basin occurred prior to the beginning of the HURDAT record (Table 1), including the Great Hurricane of 1780 that killed an estimated 22,000 people and was one of eight known tropical cyclones during that season. This chapter will provide a brief overview of some paleotempestology techniques and illustrate a methodology for identifying and reconstructing historical North Atlantic tropical cyclone tracks in the pre-HURDAT era employing a Geographic Information System (GIS) and utilizing readily accessible archival data.

2. Paleotempestology methods

2.1 Geological proxies

Some paleotempestological studies utilize evidence of tropical cyclones found in the physical landscape, such as sedimentary records, tree rings, and other geological proxies. When an ocean storm or tsunami produces a surge, coastal sediments are brought inland up to several miles away from the ocean. These sediments are preserved in lakes and marshes located near the ocean and are collected by scientists to estimate the dates of significant surge events generated from tropical cyclones, strong winter cyclones, or tsunamis. North

Atlantic sediment-based overwash reconstructions are limited yet extend geographically throughout major tropical cyclone impact zones within the basin, such as along the U.S. eastern and Gulf of Mexico coasts and the Caribbean. In a Rhode Island sedimentary record analysis, Donnelly et al. (2001) determined at least seven major hurricanes made landfall in New England in the last 700 years, with three occuring prior to the start of HURDAT (1635, 1638, and 1815) and two before European settlement. Basin-wide sediment analysis reconstruction over the past 1,500 years have shown Atlantic tropical cyclone activity to have peaked during medieval times (circa AD 1000) and decreased in the modern era (Mann et al. 2009), particularly during the 1970s and 1980s (Nyberg, et al., 2007). In the Gulf of Mexico, Belize sedimentary records of the past 5000 years show major hurricanes may have struck central America an average of once every decade with tropical cyclone activity being especially active about 2,500 to 4,500 years before present (McCloskey and Keller, 2009). Liu (2007) and Liu & Fearn (2009) note a similar period of hyper-hurricane activity along the central-eastern U.S. Gulf coast between 3,800 and 1,000 years ago based on the multiple sand layers found in sediment cores taken between Lousiana and western Florida.

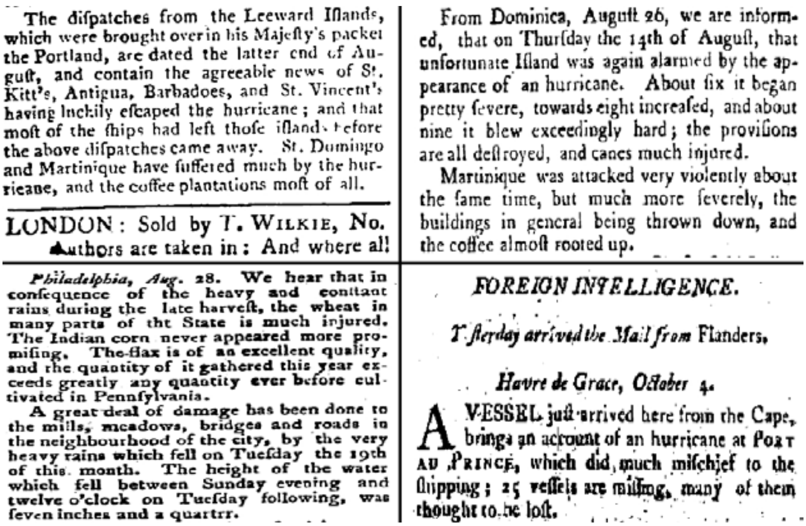
Rank	Year	Name	Deaths	Rank	Year	Name	Deaths
1	1780	The Great Hurricane	22,000+	16	1831	Great Barbados Hur.	2,500
2	1997	Mitch	19,325	17	1931	Unnamed	2,500
3	1900	Galveston Hurricane	12,000	18	1935	Unnamed	2,150+
4	1974	Fifi	10,000	19	1979	David	2,068+
5	1930	Hurricane San Zeon	8,000	20	1781	Unnamed	2,000+
6	1963	Flora	8,000	21	1893	Sea Islands Hurricane	2,000+
7	1776	Pointe a Pitre Bay Hur.	6,000+	22	1780	Solano's Hurricane	2,000
8	1775	Newfoundland Hurricane	4,000	23	1870	Hurricane San Marcos	2,000
9	1899	Hurricane San Ciriaco	3,433+	24	1893	Chenier Caminada Hurr.	2,000
10	1928	Okeechobee Hurricane	3,411+	25	1666	Unnamed	2,000
11	1932	Unnamed	3,107+	26	2005	Katrina	1,836
12	2004	Jeanne	3,025	27	2005	Stan	1,628
13	1813	Unnamed	3,000+	28	1767	Unnamed	1,600
14	1934	Unnamed	3,000+	29	1909	Unnamed	1,500
15	1791	Hurricane Las Puentas	3,000	30	1644	Unnamed	1,500

Table 1. The 30 deadliest recorded Atlantic hurricanes. Hurricanes that occurred prior to 1851 (the start of HURDAT) are highlighted. (Source: National Hurricane Center).

Tree ring analysis or dendrochronology is a relatively new tool for identification of pre-HURDAT tropical cyclones. Tree-ring cellulose store information on the oxygen isotopic composition (O^{18}) of source water around the time of growth, particularly in tree species with shallow root systems. Lower oxygen isotope water environments are common after extremely intense rainfall periods, such as after a tropical cyclone passage, and diminshed O^{18} levels are recorded in the cellulose in the weeks following an event. Miller et al. (2006) present a 220-year record of oxygen isotope values in longleaf pine tree rings in which they link anomalously low oxygen isotope values in the latewood portion of the ring (i.e., summer-early autumn growth) with tropical cyclones that impacted the southeastern United States. For example, tree ring samples from Valdosta, Georgia showed evidence of a 1780 hurricane, most likley Solano's Hurricane, that tracked from eastern Gulf of Mexico, made landfall in northwestern Florida, and then moved into Georgia before heading into the Atlantic.

2.2 Historical documents

Another aspect of paleotempestological research focuses on the examination of historical documents to reconstruct the tracks of tropical cyclones. When a strong tropical storm or hurricane makes landfall in a populated area, its impacts are typically recorded and can range from a qualitative description of the overall damage to detailed hourly observations pre- and post-impact. Most landfall accounts are in the form of newspapers, some of which simply reprint a story featured in another newspaper in the afflicted area and are reported often months after an event. For example, the impacts of an August 1788 Caribbean hurricane were not reported in London newspapers until more than two months after the event (Fig. 1). This introduces a potential error source on tropical cyclone landfall dates and impact times from newspapers and reports may need to be cross-referenced using government records and shipping logs. When tropical cyclones are over the open ocean, the logs of various merchant, transport, and naval ships are often our only information source in the pre-HURDAT era. The annual frequency of ship reports in the Atlantic varied according to the amount of trade between the Americas and the Old World and the level of conflict, if any. Based on ship track densities, Vecchi & Knutson (2011) suggest pre-satellite era Atlantic hurricane counts may be exceedingly underestimated and that increased hurricane activity in the late 20th century is a function of technological detection and not anthropogenic warming.



The diſpatches from the Leeward Iſlands, which were brought over in his Majeſty's packet the Portland, are dated the latter end of Auguſt, and contain the agreeable news of St. Kitt's, Antigua, Barbadoes, and St. Vincent's having luckily eſcaped the hurricane; and that moſt of the ſhips had left thoſe iſlands before the above diſpatches came away. St. Domingo and Martinique have ſuffered much by the hurricane, and the coffee plantations moſt of all.

LONDON: Sold by T. WILKIE, No.
Authors are taken in: And where all

From Dominica, Auguſt 26, we are informed, that on Thurſday the 14th of Auguſt, that unfortunate Iſland was again alarmed by the appearance of an hurricane. About ſix it began pretty ſevere, towards eight increaſed, and about nine it blew exceedingly hard; the proviſions are all deſtroyed, and canes much injured.

Martinique was attacked very violently about the ſame time, but much more ſeverely, the buildings in general being thrown down, and the coffee almoſt rooted up.

Philadelphia, Aug. 28. We hear that in conſequence of the heavy and conſtant rains during the late harveſt, the wheat in many parts of the State is much injured. The Indian corn never appeared more promiſing. The flax is of an excellent quality, and the quantity of it gathered this year exceeds greatly any quantity ever before cultivated in Pennſylvania.

A great deal of damage has been done to the mills, meadows, bridges and roads in the neighbourhood of the city, by the very heavy rains which fell on Tueſday the 19th of this month. The height of the water which fell between Sunday evening and twelve o'clock on Tueſday following, was ſeven inches and a quartrr.

FOREIGN INTELLIGENCE.

Yeſterday arrived the Mail from Flanders.

Havre de Grace, October 4.

A VESSEL juſt arrived here from the Cape, brings an account of an hurricane at PORT AU PRINCE, which did much miſchief to the ſhipping; 25 veſſels are miſſing, many of them thought to be loſt.

Fig. 1. A collection of 1788 London newspaper articles summarizing the impacts of an August Caribbean hurricane. From upper left to lower right: Oct. 23rd *Chronicle*; Oct. 18th *Bristol Journal*; Nov. 14th *Public Advertiser*; and Oct. 7th *Times* (Heritage Archives, Inc., Available at: www.newspaperarchive.com)

Historical data from the late 18th through the 19th centuries are frequently employed in individual Atlantic and Gulf of Mexico hurricane track reconstructions. Early station observations, marine log books, colonial government reports and *London Gazette* newspaper articles were used to reconstruct the track of a 1680 tropical cyclone that formed near the

Cape Verde Islands, impacted the Caribbean Lesser Antilles, and struck the British Isles as a powerful extratropical cyclone (Wheeler et al., 2009). During the onset of the American Revolution, the "Independence Hurricane" made landfall in North Carolina on September 2nd, 1775 and then was thought to have tracked northward into Newfoundland on September 12th, leaving approximately 4,000 dead. Historic document analysis showed two separate cyclones rather than a single hurricane track a more likely scenario (Rapport & Ruffman, 1999; Williams, 2008).

Hurricane track reconstructions are also useful for comparing with the modern record. Mock et. al. (2010) reconstructed the Great Louisiana Hurricane of 1812 track using largely qualitative descriptions of prevailing wind direction and strength, precipitation intensity, and damage reports from merchant and naval ship logs, personal diaries, and newspaper accounts. The resultant track highlighted a "worst case scenario" for New Orleans and mimicked aspects of 2005 Hurricane Katrina. The landfall of October 2005 Hurricane Vince in Spain was widely reported as the first European tropical cyclone; however, historical archives have suggested a storm with a similar genesis and track occurring in October 1842 (Vaquero et al., 2008).

2.3 Chronologies

Historians have used geological proxies, historical documents and other archival data to construct comprehensive chronologies of Atlantic tropical cyclones. A chronology is a sequential listing or timeline of tropical cyclone events by date and locations impacted. The foundation for many tropical cyclone chronologies written over the last century stems from a paper written by Andrés Poey (1855) that synthesized data from shipping logs and newspaper accounts to catalog 400 cyclones in the North Atlantic and Caribbean basins between 1493 and 1855. The Poey chronology contains several serious flaws, such as the inclusion cyclones of non-tropical origins and structure and multiple entries for a single cyclone; these unintentional errors persist in other uncorrected Poey-based chronologies, such as in Tannehill (1938).

Perhaps the most widely used chronology referenced, the Tannehill (1938) chronology was the first considerable update of the original Poey listing. In addition to increasing the tropical cyclone event timeline by over 80 years, Tannehill added qualitative information on hurricane events and removed many clearly non-tropical cyclones, particularly those occurring outside the traditional bounds of the Atlantic hurricane season (i.e., December-May). Tannehill also produced several hurricane track reconstructions (e.g., Fig. 2), a basis for the modern "best-track" data approach of the HURDAT database. However, the Tannehill chronology does not combine entries from a single cyclone that impacted multiple locations, thereby inflating the number of different tropical cyclones. Subsequent chronologies in the latter half of the 20th century have strived to amend these inaccuracies.

Significant improvements and renewed interest in tropical cyclone chronologies occurred in the 1960s, coinciding with technological innovations in weather monitoring (i.e., satellite and radar) and several active hurricane seasons during the previous decade. *Atlantic Hurricanes* (Dunn & Miller, 1960) was one of the first exclusively American chronologies, categorizing tropical cyclones by six coastal impact zones for a 400-year period. *Early American Hurricanes, 1492-1870* (Ludlum, 1963) and *Hurricanes of the Caribbean and Adjacent Regions, 1492-1800* (Millás, 1968) reexamined earlier chronologies, most notably Poey (1855) and Tannehill (1938), on a case-by-case basis and provided additional evidence supporting the decision to accept or reject a particular entry as a valid tropical cyclone. In particular, Ludlum (1963) examines historical documents from a meteorological perspective, estimating the location and movement of some of the more prominent tropical cyclones of the early American period.

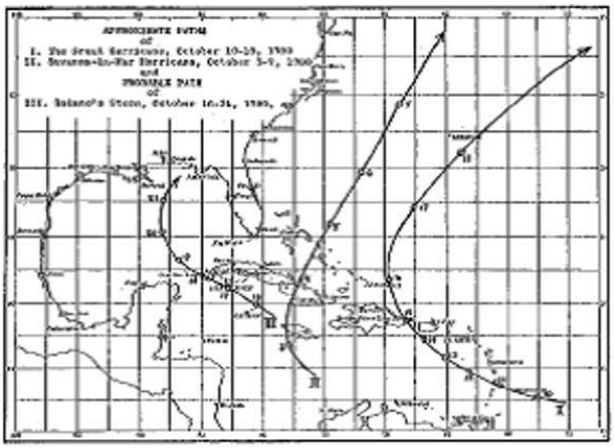


Fig. 2. The reconstructed tracks of three October 1780 hurricanes (Figure 70,Tannehill (1938))

Two notable modern chronologies incorporate, expand and correct earlier work and utilize newly available data sources and technological methods. Bossak & Elsner (2003) created the Historical Hurricane Information Tool (HHIT), a geographic information system (GIS) database that provides not only track data but supporting evidence for tropical cyclones of the early 19th century. The HHIT is publicly available database that uses historical archives (including previous chronologies, particularly Ludlum (1963)), knowledge of the behavior and structure of tropical cyclones, and GIS to document the impacts of 91 individual tropical cyclones that impacted the American coastline between 1800 and 1850. Modern technology has enabled easier accessibility of historical documents through online digital archives and language translation programs. Utilizing data sources not previously available, Chenoweth (2006) revises earlier chronologies, particularly that of Poey (1855) and Millás (1968), to create a comprehensive listing of historical Atlantic tropical cyclones with multiple supporting data sources. The data and methodologies defined in the Bossak & Elsner and Chenoweth studies serve as the foundation for the Atlantic tropical cyclone track reconstructions presented here.

3. Atlantic tropical cyclone track reconstruction

Prior to the start of HURDAT in 1851, a myriad of sources are needed to reconstruct hurricane frequencies and tracks, such as newspaper accounts, shipping logs, diaries, descriptive summaries, and chronologies. Taking these mostly qualitative, and occasionally conflicting or inaccurate, accounts of tropical cyclones and extracting information to develop a series of geographic coordinates is a significant challenge of historical hurricane database construction. The hurricane track reconstructions shown here are a result of identifying potential sources of quantitative and qualitative data, analyzing the historical archives, creating a tabular database for further data analysis, and finally creating the spatial dataset, including ArcGIS shapefiles (as outlined in LaVoie, 2011). This method advances other chronological or GIS based tropical cyclone reconstructions studies (e.g., Chenoweth, 2006; Bossak & Elsner, 2003) by utilizing multiple primary and secondary sources to determine the geographical locations impacted by a hurricane and presenting the resultant tracks in a visual medium. In addition to example track reconstructions, the long-term trends in tropical cyclone frequency is examined.

3.1 Data

3.1.1 Data sources: HURDAT and pre-HURDAT

The North Atlantic Hurricane Database (HURDAT) is considered one of the most comprehensive and authoritative databases for Atlantic hurricane track and landfall information currently available. Initially created in the 1960s to provide tropical cyclone forecasting guidance, the original database contained six-hourly "best track" and intensity information for all known tropical cyclones starting in 1886 (Jarvinen et. al, 1984). During the past decade, HURDAT has been going through an extensive reanalysis led by the Hurricane Research Division (United States) and Christopher Landsea to extend and correct the Atlantic hurricane database of individual cyclone tracks and intensities as well as U.S. landfalling storms. For example, 1992 Hurricane Andrew has since been upgraded from a Category 4 to Category 5 hurricane at Florida landfall and in August 2011 alone, about 20 different years have had alterations to the track and/or intensity of some tropical cyclones (AOML, accessed 2011). The current HURDAT extends from 1851 to present and is used to illustrate similarities in pre-HURDAT historical hurricane tracks with the modern era.

In order to conduct a temporal study of tropical cyclone activity prior to the start of HURDAT, data must first be extracted from historical archives containing mainly descriptive information and nominal level data. Quantitative measurements such as temperature and barometric pressure are very sparse in the pre-HURDAT era and measurements were limited to landfalls near larger population centers and to shipping lanes. Table 2 lists the data sources used in the pre-HURDAT analysis according to author, period of record, number of relevant tropical cyclone entries (i.e., confirmed tropical cyclones occurring during the analysis period from 1751-1850), and regional focus. These sources include many of the chronologies previously discussed (see Section 2.3) as well as several others with a more regional U.S. focus. Although some of these references are contemporaries of one another, each source provides a different type of information (e.g., quantitative data, qualitative descriptions, landfall impacts, track data, etc.).

In addition to the sources listed in Table 3.2, newspapers and shipping reports are used. In populated cities of the around the North Atlantic, newspapers would summarize accounts of hurricanes, both firsthand from their city as well as stories from sailors visiting their ports. Historical newspapers are acquired from those publicly available through the Heritage Archives, Inc. website (www.newspaperarchive.com). Shipping logs provide one of the few available sources of both wind speed and direction. These ship reports can help locate the center of circulation and are especially valuable over the open ocean. Unless specifically identified in one of the chronologies, ship reports are derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

Source Name	Record	Relevant Entries	Region
Poey (1855)	1492-1855	296	North Atlantic
Perley (1891)	1635-1890	8	New England
Tannehill (1938)	1492-1855	327	North Atlantic
Dunn & Miller (1960)	1559-1958	101	United States
Ludlum (1963)	1492-1870	76	United States
Millás (1968)	1492-1800	136	Caribbean
Barnes (2001)	1546-2006	35	Florida
Sandrik & Landsea (2003)	1565-1899	44	Georgia, NE Florida
Bossak & Elsner (2003)	1800-1850	91	United States
Chenoweth (2006)	1700-1855	308	North Atlantic
Barnes (2007)	1524-1999	15	North Carolina
Hairr (2008)	1775-1999	7	North Carolina

Table 2. Pre-HURDAT analysis data sources arranged by publication date. The number of relevant entries refers to tropical cyclone events occurring between 1750 and 1850 in the North Atlantic (including the Caribbean and Gulf of Mexico).

Despite the extensive range of resources for historical hurricane track reconstruction, each source has particular caveats that must be considered when extracting data from them. HURDAT is undergoing incessant revisions and it is likely that an average of three tropical cyclones are not accounted for in the database each year prior to 1966, the commencement of continuous satellite monitoring of the North Atlantic basin (Landsea, 2007). The HHIT database provides users with track information for recorded cyclones that impacted only the United States between 1800 and 1850 (versus the entire ocean basin) and does not account for potential error sources in the early chronologies used as the foundation for the track reconstructions. As noted in Section 2.3, the primary difficulty with utilizing chronologies is that most authors use previous chronologies as a foundation for their studies and as a result, some incorrect data is transferred into the updated listing. The disadvantage of many newspaper accounts is that many of them contain secondhand reproductions from other newspapers or sources which can result in a miscommunication of details. While shipping logs are our most likely data source for hurricane tracks at sea, anemometers were generally unavailable and wind speed was estimated using the Beaufort scale (i.e., the relative wave height) or qualitatively described as “hurricane force” winds. Each of these limitations is addressed on a case-by-case basis whereby a tropical cyclone is confirmed using multiple sources (as opposed to a single chronology) before being incorporated into the master database list.

3.1.2 Methodology

A master database of North Atlantic tropical cyclones from 1751-1850 was created using quantitative and qualitative information from the aforementioned data sources. Each tropical cyclone event was coded based on the number of data sources and information origin (e.g., chronology, newspaper, etc.). This included linking the HHIT database track positions for tropical occurring between 1800 and 1850. Each entry was then subsequently cross-referenced for spatial and temporal consistency among the data sources. A tropical cyclone from the 1788 Atlantic hurricane season is used to illustrate this process.

In mid-August 1788, the third known tropical cyclone of that season impacted the Caribbean and United States. Multiple data sources document the existence of an Atlantic tropical cyclone during this period, but disagree on whether or not the impacts in the Caribbean and United States are from a single tropical cyclone or are two separate events (Table 3). Locally known as “Hurricane San Rouge” in the Caribbean and the “Western New England Hurricane” in the northeastern United States, the Millás (1968), Chenoweth (2006), Poey (1855) and Tannehill (1938) chronologies list multiple events for the third (or fourth) 1788 tropical cyclone. Chenoweth (2006) lists this hurricane as two individual cyclones; Hurricane San Rouge dissipating after impacting Haiti on August 16th and a different tropical storm (not a hurricane) impacting the United States a few days later. In contrast, Ludlum (1963) identifies only a single tropical cyclone impacting both regions between August 14th and August 19th. Additional supporting evidence from newspapers, ship logs and overwash sediments in New Jersey (Donnelly et al., 2004) suggest that these cyclones should be classified as a single hurricane that made landfall in the Caribbean and the northeastern United States. Consequently, all entries related to a tropical cyclone impacting the Caribbean around August 14th and the northeastern United States by August 19th are merged into single event and are used to construct the tropical cyclone track positions.

After creation of the master database, six-hourly geographic positions for each storm are estimated. Six-hour intervals were chosen to coincide with the HURDAT format. Pre-HURDAT tropical cyclones often lack the quantitative data of modern-era storms; however the storm track and intensity can be estimated from reports detailing the damage extent, landfall time, wind direction shifts, and relative storm location observations. In addition, the observed tracks of similar tracking tropical cyclones can be used to estimate the likely cyclone trajectory in areas where data is sparse. The coordinates are then plotted using mapping software applications (e.g., Google Earth) or a geographic information system. The ESRI ArcGIS system enables the transfer and display of multiple sets of coordinates and manipulation of different storm attributes, including linking qualitative impact information.

Using the information presented in Table 3, the estimated track of the third 1788 Atlantic tropical cyclone is shown in Figures 3 and 4. The data indicates the hurricane center struck the island of Martinique shortly after midnight on August 15th and moved directly west since the islands of Antigua to the north and Trinidad to the south did not report any impacts from the hurricane. After damaging primarily the southwestern portion of Puerto Rico, the cyclone crossed the island of Hispaniola from southeast to northwest on August 16th and 17th before moving rapidly north towards New England. Based on Perley (1891) and contemporary newspaper accounts, the hurricane made landfall in southern New Jersey on August 19th and quickly transitioned into an extratropical storm, a typical pattern of poleward moving storms though the northeastern United States (Fig. 4).

The final master database for pre-HURDAT Atlantic tropical cyclones contained 408 entries for the 1751-1850 period. Each entry on average appeared in three or more primary sources. While sufficient information is not available to reconstruct tracks for all 408 entries with reasonable confidence, the process outlined here shows the potential for extending the HURDAT record. The reconstructed tracks for two example pre-HURDAT Atlantic tropical cyclones are presented in the following section. One example illustrates track reconstruction using archival documents and the other shows how the atmospheric environment during the hurricane life cycle can be approximated in cases when meteorological observations are sparse or non-existent.

Source	Data
Chenoweth (2006)	August 14-18th hurricane impacting central Leeward Is. and Haiti August 17-19th tropical storm impacting southeastern Pennsylvania and New England
Millás (1968)	Tropical cyclone near Martinique, Dominica and Guadeloupe on August 14-15th "Hurricane San Rouge" south and near Puerto Rico and Hispaniola August 16-17th
Ludlum (1963)	Tropical cyclone impacting Martinique, Puerto Rico, Pennsylvania (PA), New Jersey (NJ), New York (NY), Connecticut (CT), Massachusetts (MA), Vermont (VT), New Hampshire (NH), and Maine (ME) August 14-19th
Dunn and Miller (1960)	Minimal hurricane with six deaths in NH, MA, and CT Much hurricane damage in Eastern New York
Tannehill (1938)	Tropical cyclone near Martinique August 14-15th Tropical cyclone near Puerto Rico and Hispaniola August 16-17th Tropical cyclone impacting the United States August 19th
Poey (1855)	Tropical cyclone near Martinique, Puerto Rico and Hispaniola August 14-16th Tropical cyclone impacting the United States August 19th
Perley (1891)	During the afternoon of August 19th, a gale impacted portions of western New England and eastern NY. The event lasted from around noon until approximately 4pm. There were reports of damage in southwestern CT, western MA, southern VT, and southwestern NH. Winds during the event were variable.
Ship Log Summary	Available observations on August 14th suggest that a large area of high pressure dominated the eastern Atlantic. A ship located between St. Kitts and Antigua reports a NE wind at 20mph, the outer edge of the hurricane. The same ship, located north of the Lesser Antilles on the 16th, experiences a strong pressure gradient between the hurricane and the Bermuda-Azores high. A ship moving just off the east Florida coast reports northerly winds as the hurricane moves well to the east. A ship located to the east of Boston reports strong winds albeit below tropical storm force, from the south on August 19th.
Newspapers	From Millás (1968): Guadeloupe and Martinique suffered from a gale the night of August 14th. Dominica saw much damage to sugar canes and provisions but damage was much worse in Martinique. St. Lucia did not suffer much and the hurricane did not impact Antigua which was suffering from a drought. The hurricane passed south of Puerto Rico and crossed Hispaniola from southeast to northwest on August 16th and 17th. A Spanish ship sunk in the western Bahamas. From various London Newspapers: The islands of St. Kitts, Antigua, Barbados, and St. Vincent escaped the hurricane while Hispaniola and Martinique suffered much. 25 vessels are missing at Port au Prince. The hurricane started at Dominica at 6pm (on August 14th) and increased in violence throughout the night. The hurricane was more severe at Martinique. Much damage was done to crops in Pennsylvania (on the 19th).

Source	Data
Final Result	Tropical Cyclone 1788-3: Hurricane San Rouge/Western New England Hurricane August 14th: Landfall in Martinique moving West August 15th: Northeastern Caribbean Sea August 16th: Approaching Puerto Rico August 17th: Impacting Puerto Rico and Hispaniola August 18th: Moving rapidly towards the North-Northeast August 19th: US landfall; moving North rapidly

Table 3. Listing of available sources for the third 1788 tropical cyclone and the resulting entry used for track reconstruction.

Fig. 3. Estimated track of the 1788 Hurricane San Rouge/Western New England Hurricane. White dots are 0Z positions from August 15th through August 19th.

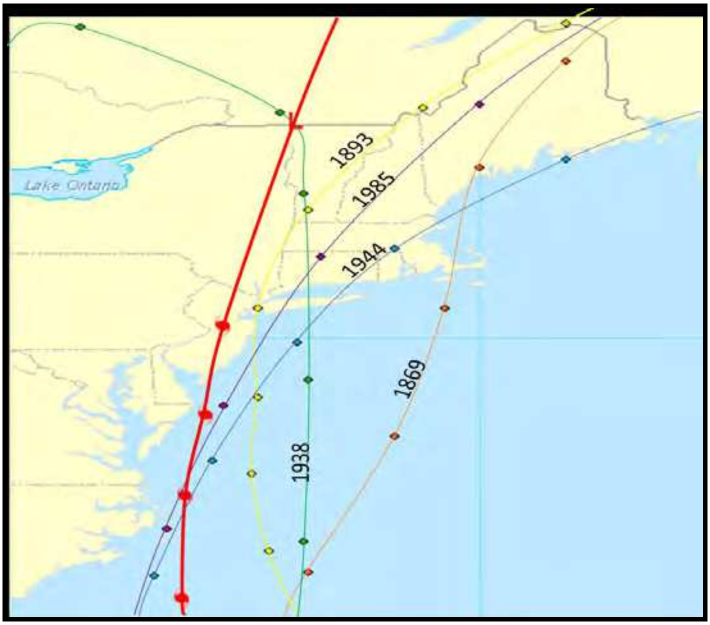


Fig. 4. The estimated United States impact track of 1788 Hurricane San Rouge/Western New England Hurricane and five other notable New England hurricanes with similar trajectories.

4. Pre-HURDAT data analysis: Individual track reconstructions

4.1 Analysis of the Great Hurricane of 1780

The deadliest known Atlantic hurricane on record occurred in October 1780, impacting primarily the eastern Caribbean and resulting in an estimated 22,000 deaths (Table 1). Known simply as the "Great Hurricane", the tropical cyclone is a prominent entry in nearly all archival data sources, including the Ludlum (1963) chronology that does not focus on areas outside the United States. Although most sources depict a track beginning in the Lesser Antilles and culminating in the vicinity of Bermuda, there are several key differences.

Figures 5 and 6 depict the "best track" of the Great Hurricane of 1780 (solid red line) analyzed using the master database sources (see Section 3.1) compared with five alternative tracks produced by previous authors (Norcross, 2007; Millás (1968); Ludlum (1963); Tannehill (1938); and Reid (1838)). Each storm description indicates a hurricane formed far southeast of the Lesser Antilles and made landfall (or very near) Barbados at nearly peak intensity before heading northwestward within the vicinity of St. Lucia and Martinique. Ship reports indicate that the hurricane moved very slowly in the eastern Caribbean before passing over or very near the small island of Mona located between Puerto Rico and Hispaniola. The storm then recurved northeastward around 70º W longitude and passed some distance to the southeast of Bermuda before moving into the open Atlantic. The track variations among different authors may be a result of different interpretations of wind information and reports of damage on land. In particular, the lack of damage reports from certain locations is an important component to understanding the actual track of this hurricane.

The Great Hurricane of 1780 appears to have taken a track that is more unusual than depicted by previous historians (Fig. 5 and 6). Sources agree the hurricane took an unusually long time to traverse the eastern Caribbean, taking nearly a week to go from Barbados to eastern Hispaniola. Local weather reports throughout the Caribbean indicate the rate of storm motion was not constant and the hurricane may have stalled and/or changed direction after passing into the Caribbean Sea. Both Reid (1838) and Tannehill (1938) assumed that the hurricane did not deviate significantly from a northwesterly track through the Caribbean but this fails to explain the high death toll (>> 1,000) recorded from St. Eustatius in the northern Lesser Antilles. In contrast, Ludlum (1963) and Norcross (2007) believe that the hurricane did pass close to the northern Lesser Antilles, with a track suggesting direct impacts to Antigua, St. Croix, and Montserrat; however, Antigua, located only 75 miles (120 kilometers) to the east of St. Eustatius, received only minor damages and Montserrat and St. Croix reported none. Millás (1968) compensated for the disparities in damage reports but the track of the hurricane still does not pass close enough to St. Eustatius and St. Kitts to cause the level of destruction reported on these islands.

The "best track" of the Great Hurricane proposed here (Fig. 5 and 6) modifies the previously discussed track positions by incorporating qualitative information from newspaper accounts and several key ship observations from military vessels throughout the region. The log of the HMS Albemarle, stationed off the southwestern coast of Barbados, indicates that the hurricane passed just north of its location where northeasterly winds eventually shifted to the west and then south. The HMS Alcmene, located off the southwestern coast of Martinique, reported a gradual change in the wind direction as the eye of the hurricane

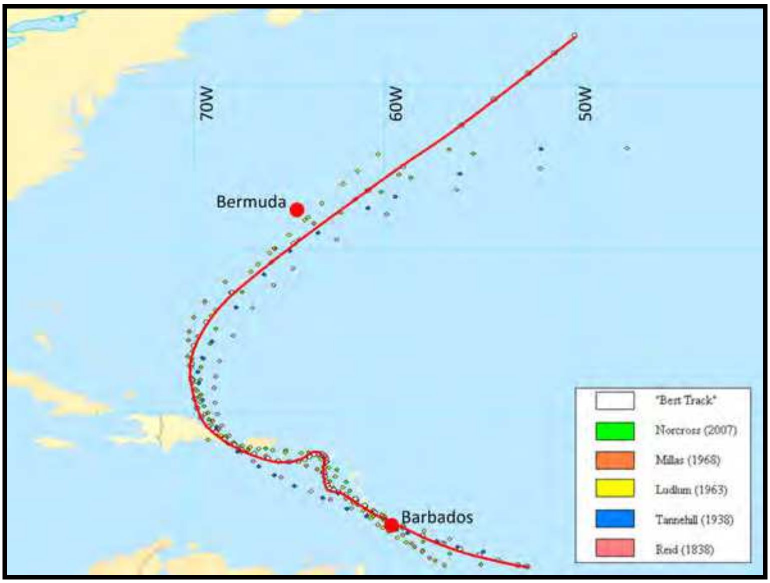


Fig. 5. The "best track" of the Great Hurricane of 1780 (solid red line) compared with five alternative tracks suggested by previous authors (Norcross, 2007; Millás (1968); Ludlum (1963); Tannehill (1938); and Reid (1838)).

passed very close to that island. Finally, the HMS Star located near Antigua reported four days of winds out of the east before shifting to the southeast on the 14th of October. Land reports show the most severe storm damage came from Barbados, St. Lucia, St. Vincent, Martinique, southern Guadeloupe, St. Kitts, St. Eustatius, southwestern Puerto Rico, and southeastern St. Domingo (Hispaniola). This information suggests that after the hurricane passed Martinique and Dominica, the cyclone turned north towards St. Kitts before abruptly shifting west/southwest and eventually northwest across extreme southeastern Hispaniola (Fig. 6). While this is an atypical track for any tropical cyclone in the North Atlantic, similar behavior has been observed in other hurricanes (e.g., Hurricane Marilyn in 1995).

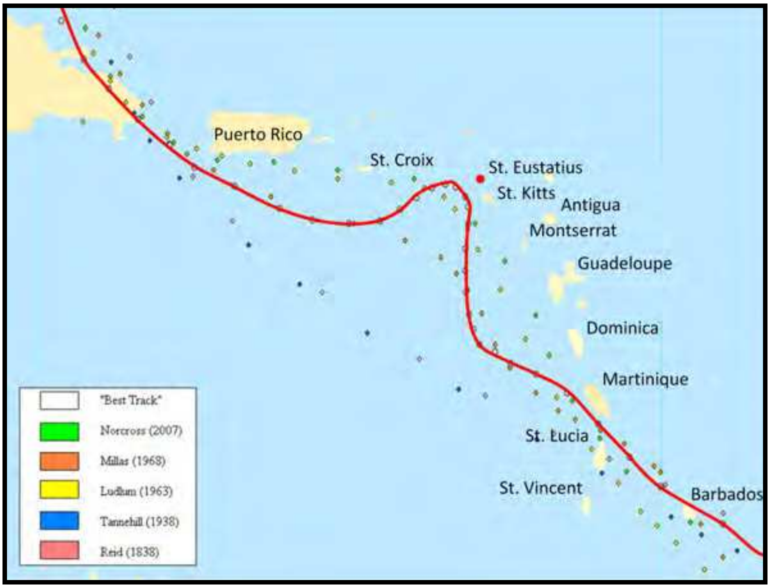


Fig. 6. Same as Figure 5 except enlarged and focused on the Eastern Caribbean.

4.2 The 1821 New England hurricane

The 1821 New England hurricane, also known as the "Norfolk and Long Island Hurricane", was the first tropical cyclone of that season. First detected north of Puerto Rico on September 1st, this fast moving and powerful hurricane passed north of the Bahamas, turned towards the north, and made the first of several landfalls about 20 miles east of Moorehead City, North Carolina late on September 2nd. The center then stayed within 30 miles of the East Coast of the United States. This 1821 hurricane was the only major hurricane to directly impact the modern limits of New York City, making landfall on September 3rd. Following a brief passage over Long Island, the hurricane made its final landfall in Connecticut on September 4th and passed through New England and into Canada.

4.2.1 An analysis of the 1821 Hurricane using 20th century data

While meteorological observations during the pre-HURDAT era are scarce, the analogs of modern tropical cyclones can be used to visualize the general synoptic weather pattern that prevailed when a hurricane made landfall. The track of the 1821 New England hurricane (and hurricanes in the 1820s and 1830s in general) followed the hurricane track patterns of many storms of the 1950s and 1960s that featured similar number of landfalls along the eastern United States. In particular, the tracks of Hurricanes Carol (1954), Edna (1954), Donna (1960) and Gerda (1969) display a comparable U.S. landfall trajectory, stretching from Cape Hatteras through New England (Fig. 7). Hurricanes Carol, Edna and Donna are used to create a composite of the overall synoptic environment around the time of landfall, thus serving as a proxy for meteorological conditions during the 1821 New England Hurricane; Hurricane Gerda was excluded from the final composite analysis since the hurricane center did not cross into New England.

Fig. 7. Reconstructed track of the 1821 New England Hurricane (thick white line) and similar track hurricanes used for the synoptic environment composite analysis (Hurricanes Carol (1954); Edna (1954); Donna (1960); and Gerda (1969)).

Using the three selected 20th century tropical cyclones, composites of the 500-hPa geopotential heights (in meters) and mean sea level pressure (SLP) (in hPa) were generated for five time periods: two days, one day, and twelve hours prior to landfall; during landfall; and twelve hours after landfall. The composites were generated using six-hourly data from the NCEP/NCAR Reanalysis dataset (Kalnay, et. al, 1996) and images generated from the NOAA/ESRL Physical Sciences Division website. The composite analysis highlights the rapid alteration of the synoptic environment surrounding the time of landfall (Fig. 8a-e).

Two days prior to a hurricane making landfall in New England (Fig. 8a), the Bermuda-Azores High dominates the eastern and central Atlantic, centered around 45° W. In the mid-latitudes, a generally zonal pattern quickly becomes increasingly meridional as the hurricane moves up the eastern United States coast (Fig. 8b-d). The ridge over the central

Atlantic strengthens in response to a deepening trough over the eastern Great Lakes region. By twelve hours prior to landfall (Fig. 8c), a strong geopotential height gradient is developed and the hurricane follows this southwest to northeast orientated gradient which continues to intensify even after the hurricane has made landfall.

The composite presented in Figure 8 represents the likely synoptic environment for the 1821 New England Hurricane that followed a similar trajectory to its mid-20th century counterparts. During the time the hurricane was rapidly approaching New York City from the southwest (September 3rd at 22Z), wind direction observations and weather conditions from ICOADS ship reports indicate a hurricane along the northeast U.S. coast and also suggest the presence of a geographically extensive high pressure system in the north-central Atlantic (Fig. 9). The wind behavior of the ten meteorological observations in the northeastern United States clearly indicates the counterclockwise rotation around the hurricane center (Fig. 10). These observations confirm the results of the composite analysis.

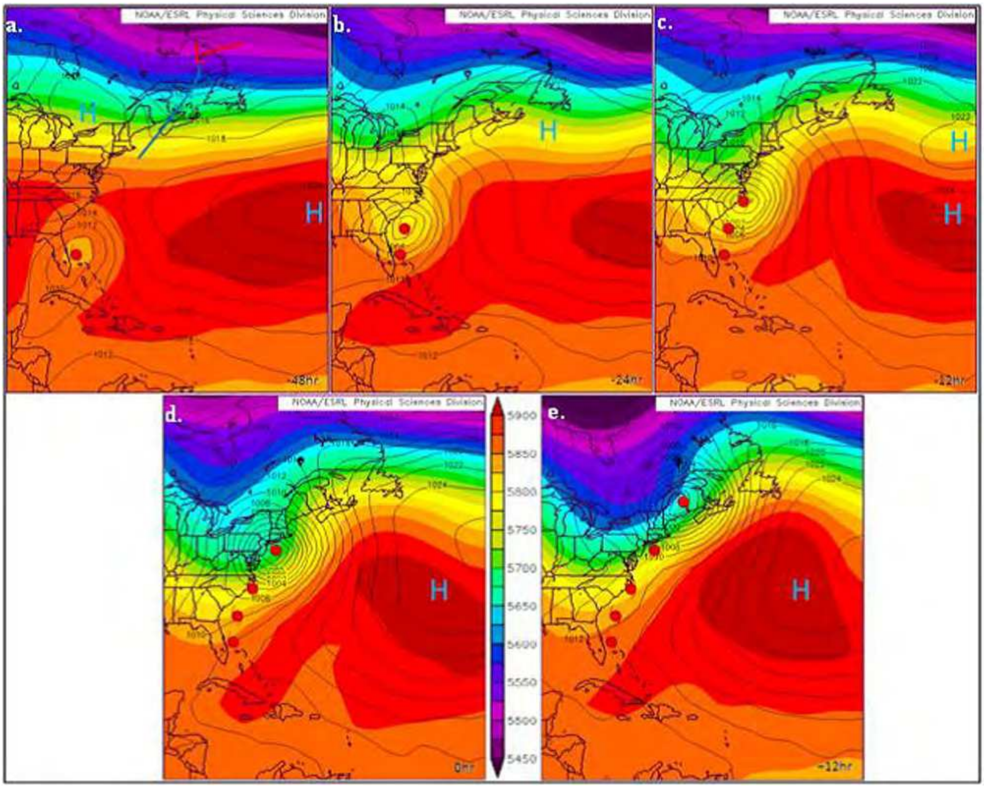


Fig. 8. Composite time series for Hurricanes Carol (August 31, 1954 at 12Z), Edna (September 11, 1954 at 18Z), and Donna (September 12, 1960 at 18Z). Solid contours are SLP (2 hPa intervals) and shaded contours are 500-hPa geopotential heights (50 m intervals). Time series from top left to bottom right are: (a) 48 hours, (b) 24 hours, and (c) 12 hours prior to landfall; (d) during landfall; and (e) 12 hours after landfall.

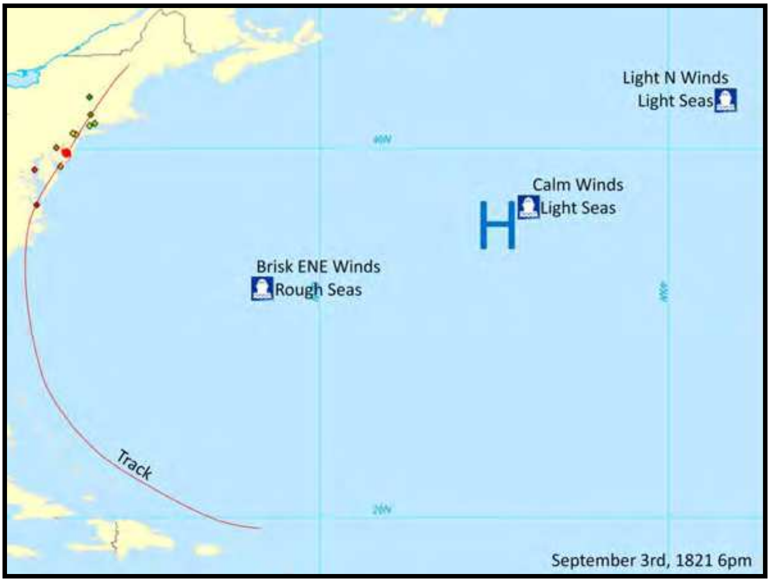


Fig. 9. The estimated 1821 New England Hurricane track and the locations of the available meteorological and ship report observations for September 3rd at approximately 22Z.

Fig. 10. The approximate location of the 1821 New England Hurricane (New Jersey) and wind direction at ten land locations taken around 22Z on September 3rd.

5. Pre-HURDAT era analysis: Long-term trends

In the past decade much attention has been given to the potential relationship between climate variability and change and relative tropical cyclone activity over time. The debate centers on whether or not the dramatic increase in the number of tropical cyclones observed since 1995 is due to natural variability in conjunction with our increasing ability to detect tropical cyclones or simply due to anthropogenic effects (e.g., Mann and Emanuel, 2006; Knutson et al., 2010; Holland and Webster, 2007). Many studies analyzing this issue analyze only post-satellite era data, which may not accurately reflect long-term trends or cycles in tropical cyclone activity.

Tropical cyclone and subtropical counts for the period 1851-2010 were derived from the official HURDAT "best track" database (AOML, accessed 2011) and combined with the pre-HURDAT era (1751-1850) count estimates derived from the master database. Based on the 1751-2010 time frame a gradual increase in the Atlantic tropical cyclone counts is apparent, with the largest increase beginning in the late 1990s that continues into the 21st century (Fig. 11). The most named tropical cyclones observed in the Atlantic basin occurred in 2005 (n = 28); however, several other peak years are apparent. The hurricane seasons that show the most robust signal are 2005, 1969 (n = 18), 1933 (n = 21), 1887 (n = 19), and 1837 (n = 12) with an average 42 years between these peak events. The record 2005 year (and the higher tropical cyclone activity in the past two decades in general) may not be an unusual occurrence, especially if pre-satellite era counts are adjusted for non-landfalling tropical cyclones that may have gone undetected.

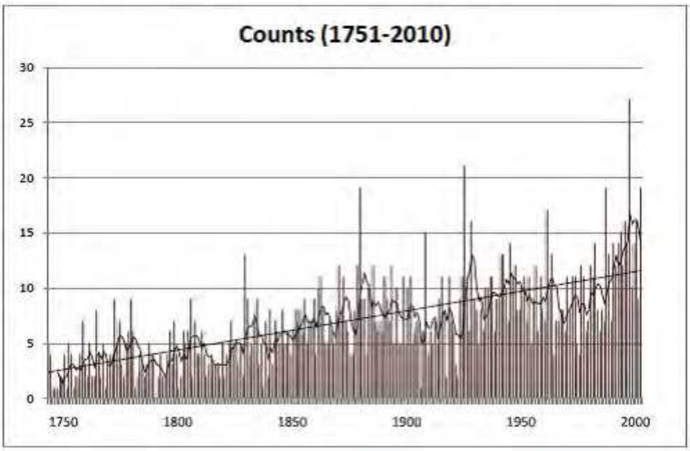


Fig. 11. Tropical cyclone frequencies by year for the period 1751-2010 with trend line and five-year moving average.

Periods of "hyperactivity" are often followed by a phase of subdued tropical cyclone activity (Fig. 12). During the 20th century two periods of below normal Atlantic tropical cyclone counts (1900 to 1931 and 1972 to 1995) were followed by sudden extended increases (1932-1971 and 1995 to present). The pre-HURDAT era shows a similar cyclical, multi-decadal pattern in tropical cyclone frequency, albeit shorter in duration than in the past century. Guan and Nigam (2009) note four leading modes of Atlantic sea surface temperature (SST) variability in the North Atlantic (the Atlantic Multidecadal Oscillation; a two-mode, El Niño-like pattern in the tropical eastern Atlantic; and an SST tripole resembling the North Atlantic Oscillation) that can produce warm and cold Atlantic temperature phases with seasonal to multi-decadal time scale. These modes may be important for explaining the cyclical and linear trend in the number of Atlantic tropical cyclones, but not necessarily any changes in the intensity (Briggs, 2008).

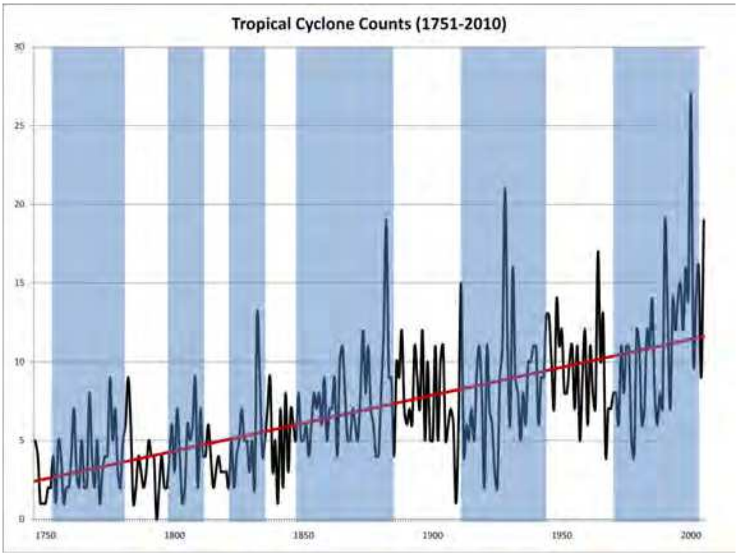


Fig. 12. Tropical cyclone frequencies by year for the period 1751-2010 with trend line and five-year moving average with period of increasing tropical cyclone activity highlighted.

6. Conclusion

In addition to a broad overview of paletempestology methods, a simplistic methodology for taking mainly qualitative archival information and reconstructing the tracks of historical tropical cyclones is presented. This paper shows analysis of North Atlantic hurricane seasons prior to the start of the HURDAT database (before 1851) is feasible using readily available public data. Furthermore, historical hurricane tracks need to be continually analyzed if new data sources become available, as shown in the case of the Great Hurricane of 1780. A comparison of landfall patterns associated with similar landfalling east coast hurricanes in the pre-HURDAT period and the modern record highlights the potential for using historical hurricane track patterns for real-time hurricane track forecasting.

By extending the North Atlantic tropical cyclone record back to 1751 using basic historical documents alone, the frequency of tropical cyclones in the Atlantic appears to be increasing. A cyclical pattern in activity also emerges, alternating by periods of 10-20 years of active and non-active seasons. Further research needs to be done to confirm whether or not these trends are a product of anthropogenic induced climate change or are a natural response to shifts in long-term atmospheric-oceanic patterns, such as the Atlantic Multidecadal Oscillation (AMO).

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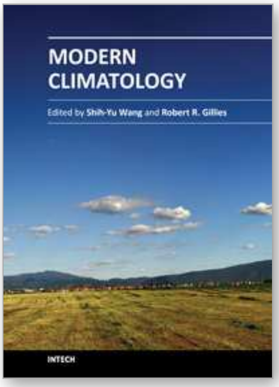

Modern Climatology

Edited by Dr Shih-Yu Wang

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Climatology, the study of climate, is no longer regarded as a single discipline that treats climate as something that fluctuates only within the unchanging boundaries described by historical statistics. The field has recognized that climate is something that changes continually under the influence of physical and biological forces and so, cannot be understood in isolation but rather, is one that includes diverse scientific disciplines that play their role in understanding a highly complex coupled "whole system" that is the earth's climate. The modern era of climatology is echoed in this book. On the one hand it offers a broad synoptic perspective but also considers the regional standpoint, as it is this that affects what people need from climatology. Aspects on the topic of climate change - what is often considered a contradiction in terms - is also addressed. It is all too evident these days that what recent work in climatology has revealed carries profound implications for economic and social policy; it is with these in mind that the final chapters consider acumens as to the application of what has been learned to date.