JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D03108, doi:10.1029/2009JD012424, 2010

Toward increased utilization of historical hurricane chronologies

K. N. Scheitlin,[1] James B. Elsner,[1] J. C. Malmstadt,[1] R. E. Hodges,[1] and T. H. Jagger[1]

Received 4 May 2009; revised 31 July 2009; accepted 14 September 2009; published 5 February 2010.

[1] The record of past tropical cyclones provides an important means to evaluate the hurricane hazard. Historical chronologies are a source of information about tropical cyclones prior to the modern era. Chenoweth (2006) describes an archive of 383 tropical cyclones occurring during the eighteenth and nineteenth centuries, largely before the official hurricane record. The present study demonstrates a novel way this archive can be used to articulate historical tropical cyclone activity across space. First, an event in the archive is assigned a series of latitude/longitude coordinates approximating the descriptive locations of the cyclone's affect. Second, tropical cyclones from the modern record that approach these locations (modern analogs) are mapped. Third, a probable pathway and a realistic track of the archived event is created by averaging the modern analog tracks. As an example, the procedure is used to generate a map showing the tracks of the Atlantic tropical cyclones of 1766. Sensitivity of the methodology to changes in event location and event timing are considered. The study shows that historical hurricane chronologies when combined with a history of cyclone tracks can provide useful information about the older events that is not directly related to where the original information was gathered. When this information is available for all cyclones it should help climatologists better understand long-term variations in tropical cyclone activity.

Citation: Scheitlin, K. N., J. B. Elsner, J. C. Malmstadt, R. E. Hodges, and T. H. Jagger (2010), Toward increased utilization of historical hurricane chronologies, *J. Geophys. Res.*, *115*, D03108, doi:10.1029/2009JD012424.

1. Introduction

[2] Recent destructive hurricane seasons have led to an increased awareness of the field of hurricane climatology. While the comprehension of hurricane climatology grows with each related research publication, there are arguments as to the accuracy of long-term variability assessment due to temporal brevity of hurricane records [*Chenoweth and Divine*, 2008]. Since these long-term trends provide a basis for understanding the climate change–tropical cyclone relationship, it is important that strides be made toward improving the quality and temporal extent of the North Atlantic tropical cyclone data set. In fact, the record of past hurricanes is among the most important means to evaluate the hurricane hazard, so extending the database of hurricanes by several hundred years is valuable.

[3] The data set used most often by hurricane researchers is the Hurricane Database (HURDAT), maintained by the National Hurricane Center. HURDAT contains data for all observed tropical cyclones from the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea since 1851. The HURDAT record (also known as the best track record) is continually updated and reanalyzed in order to make it consistent and accurate. However, the relatively short time period of tropical cyclone data sets limits the ability of climatologists to determine long-term (50–100 years) variability. In response to this challenge researchers have begun using methods to uncover hurricanes from the eighteenth and nineteenth centuries.

[4] The purpose of this paper is twofold: (1) to provide a digitized version of the *Chenoweth* [2006] historical tropical cyclone list (Chenoweth archive) and (2) to illustrate a procedure for estimating the likely pathway of cyclones in the archive. The work is an extension of *Elsner et al.* [2008] where geological records of prehistorical hurricanes at a single location over time are compared with the record of modern cyclones. Here it is shown how historical archives of spatial locations affected by tropical cyclones can be summarized across space with the help of a record of modern cyclones.

[5] Section 2 provides a brief description of the Chenoweth archive and places it in the context of other methods for uncovering past tropical cyclone activity. Section 3 lists the methods for digitizing the archive and gives details on how to determine a cyclone path from digitized locations and tropical cyclone analogs from the modern record. Section 4 examines the active 1766 hurricane season, and section 5 explains how the methods can incorporate "unusual" historical cyclones as is the case for the fourth cyclone of 1766. Section 6 answers questions about the

[1]Department of Geography, Florida State University, Tallahassee, Florida, USA.

0148-0227/10/2009JD012424$09.00

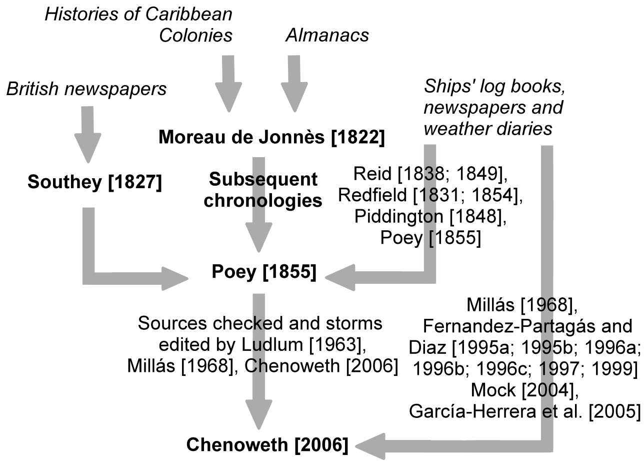

Figure 1. Major contributors leading to the Chenoweth archive. Words in italics denote a source, while bold names represent published tropical cyclone chronologies.

sensitivity of the methodology. Section 7 summarizes the research efforts.

2. Early Tropical Cyclones

[6] Evidence of early hurricanes come from proxy data and historical documents. Proxies in the form of coral cores, tree rings, and overwash sediments in coastal lakes can be used to detect hurricanes back through the middle Holocene [*Liu and Fearn*, 1993, 2000]. These proxies are useful in providing information pertaining to centennial- and millennial-scale tropical cyclone variations [*Murnane and Liu*, 2004]. While these proxies may reveal long-term variability in tropical cyclone occurrences, smaller-scale fluctuations are difficult to discern due to lack of temporal precision.

[7] While proxy approaches provide a glimpse of hurricane activity locally through time, historical documents can sometimes provide clues about the path of hurricanes across space. This paper focuses on data about early hurricanes uncovered from historical documents. The available time span and overall quality of these data vary for different regions of the world, with China having the longest history of written documents, spanning the last 3500 years [*Louie and Liu*, 2003]. While written history in North America and the Caribbean begins much later, the additional evidence of tropical cyclone occurrence from written records provides a larger data set for understanding long-term hurricane trends than is provided by HURDAT. Historical archives are largely qualitative in nature, consisting of descriptions of cyclone location and intensity. However, *Chenoweth* [2007] does provide quantitative interpretations of tropical cyclone intensity for storms affecting the Lesser Antilles and Jamaica. For example, "wind very high" is interpreted as an approximate wind speed of 17 ms^{-1} (35 kt).

[8] This paper examines one way a historical archive of North Atlantic tropical cyclones [*Chenoweth*, 2006] can be used to give more information about tropical cyclone tracks. Examination of historical documents to uncover Atlantic basin tropical cyclones began centuries ago, with researchers putting in countless hours of work looking through hundreds of thousands of ship logs, almanacs and newspapers [*García-Herrera et al.*, 2004]. A schematic of the research that went into the Chenoweth archive is shown in Figure 1. The first attempt toward a chronological list of hurricanes is attributed to Moreau de Jonnès in 1822 [*Chenoweth*, 2006]. Using almanacs and written histories of the Caribbean colonies, *Moreau de Jonnès* [1822] documented observed hurricanes in the West Indies back to the year 1495. Meanwhile, *Southey* [1827] created a chronology using information from British newspapers, and *Reid* [1838, 1849], *Redfield* [1831, 1854], and *Piddington* [1848] uncovered additional cyclones using ship's log books, weather diaries, and other newspapers.

[9] Subsequent chronologies followed, and by combining his own research with the aforementioned studies, *Poey* [1855] provides a chronological list of 348 Atlantic basin tropical cyclone occurrences from 1493 to 1855. This list is considered the foundation of historical hurricane chronologies and was constantly analyzed, improved, and updated in subsequent publications in order to create more accurate lists (most notably by *Ludlum* [1963] and *Millás* [1968]). The practice of uncovering cyclones through historical documents has a rich history, and it is interesting to note that Poey and fellow researchers of his time were uncovering past hurricanes during a time period that is still under investigation today.

[10] In 2006, Michael Chenoweth produced a list of tropical cyclones (inclusive of hurricanes and tropical storms) from 1700 to 1855 by taking into account all previous historical archives and research. This includes the edited Poey list and additional cyclones later uncovered by *Millás* [1968], *Fernandez-Partagás and Diaz* [1995a, 1995b, 1996a, 1996b, 1996c, 1997, 1999], *Mock* [2004], and *García-Herrera et al.* [2005]. Table 4 of *Chenoweth* [2006] is a list of the most widely accepted tropical cyclone accounts, and is what we consider here as the Chenoweth archive. Chenoweth's chronology begins in 1700 because logbook records and newspapers are abundant by this time, and most of the tropical cyclones on the Poey list occur after 1700 [*Chenoweth*, 2006]. The archive contains 383 published and independently confirmed tropical cyclones that traversed the Atlantic basin between 1700 and 1855. The Chenoweth archive is available at www.aoml.noaa.gov/hrd/hurdat/Chenoweth/index.html [*Chenoweth*, 2006].

[11] A few caveats are in order. This archive is a comprehensive chronology of all previously uncovered tropical cyclones after careful edits and source checking. It does not contain more recently uncovered cyclones by Chenoweth himself. Moreover, although here Table 4 of *Chenoweth* [2006] is referred to as the Chenoweth archive, it does not represent all that is known about these historical events. More information is available with Michael Chenoweth on individual events, especially for some of the later cyclones on the list, but this additional information is not in a digital format at this time.

[12] Table 1 lists a portion of the Chenoweth archive corresponding to the 1766 season. Each cyclone is listed chronologically with a start and end date (referring to the first and last observation of the cyclone), and an associated location of the region affected. Not present in Table 1, the Chenoweth archive also lists whether the cyclone was included in previous chronologies (e.g., the *Poey* [1855] archive), the number of log books and newspapers checked

Table 1. A Portion of the Chenoweth Archive Pertaining to the 1766 Hurricane Season[a]

Event Month	Event Day	CA Storm Number	Location	Method	Latitude (°N)	Longitude (°E)
8	13	93	Martinique	4	14.65	−61.01
8	16	93	south of Jamaica	6	16.74	−77.27
9	1	94	Gulf of Mexico	5	24.82	−90.14
9	4	94	Texas	3	28.40	−96.38
9	8	95	Atlantic	9	31.36	−35.09
		95	off Virginia	6	37.29	−74.58
9	13	95	west of NYC	6	40.70	−75.00
9	17	96	Lesser Antilles	9	13.90	−60.97
		96	23°45′N 64°03′W	1	23.75	−64.05
		96	33°N 57°W	1	33.00	−57.00
9	24	96	Azores	9	38.65	−27.22
10	5	97	Lesser Antilles	9	13.90	−60.97
		97	Puerto Rico	4	18.23	−66.48
10	13	97	off South Carolina	6	32.77	−78.92
10	15	98	south of Haiti	6	16.52	−74.04
10	24	98	Pensacola, FL	2	30.42	−87.22
10	29	99	Havana	2	23.12	−82.35
11	1	99	east of Florida	6	28.50	−79.53

[a]CA, Chenoweth archive. The dates of the first and last events are listed for each cyclone. Location refers to the localities listed in the archive. Method refers to the methods used in this study to digitize the event location (see text). Most cyclones have more than one location.

for validity, and an estimate of whether the affect was likely due to a hurricane or tropical storm for each location.

3. Adding a Spatial Dimension

[13] The Chenoweth archive provides a glimpse into North Atlantic tropical cyclone activity prior to the Industrial Revolution. This is important in the context of climate change as related to anthropogenic greenhouse gas increases. Here we describe an attempt to digitize the Chenoweth archive for the purpose of making it more useful for researchers. We then use this digitized archive together with the HURDAT record to generate a pathway for each tropical cyclone in the archive, giving a spatial dimension to cyclones that began as newspaper accounts.

[14] The procedure is performed in two steps. First, the Chenoweth archive locations are digitized. The digitization is done using nine different methods depending on the locational information provided in the archive. Second, modern tropical cyclone tracks are used as location analogs and a likely pathway is found based on the distance of the analog to the archive's locations.

3.1. Digitizing the Chenoweth Locations

[15] Each tropical cyclone in the archive is defined by as few as one to as many as four observation locations (events), resulting in a total of 742 events. The average is 2.1 events per cyclone. Since events consist of reports from recurring locales (e.g., Jamaica), less than half of the event locations are unique. The descriptions of the locations range from specific (e.g., latitude and longitude coordinates), to broad (e.g., "New England"). In order to provide a spatial version of the Chenoweth archive, each of the events are assigned approximate latitude/longitude coordinates (digitized). The following methods were used to digitize the coordinates depending on the specificity of the description given in the archive.

[16] In method 1 latitude/longitude coordinates are given. If coordinates are given, these exact coordinates are used to represent the event location. For example, according to the Chenoweth archive, the second event of storm 96 affected the location 17°11′N, 69°49′W. Most of these locations are coordinates recorded in ship log books and are therefore located over the ocean. Thirteen percent of all event locations in the archive require this type of digitization.

[17] In method 2 city name is given. If the name of a city is given, either in the United States or international, the latitude and longitude of that city are found using a valid source, such as the United States Geological Survey. For example, according to the Chenoweth archive, the third event of storm 98 affected Pensacola, Florida. Eight percent of all event locations in the archive require this type of digitization.

[18] In method 3 state or country names are given. Most states or countries given are coastal areas, likely representing where the tropical cyclone made landfall. Therefore, if a coastal state or country is named, the center of the coastline is used to represent the location. For example, according to the Chenoweth archive, the second event of storm 94 affected Texas. Fourteen percent of all event locations in the archive require this type of digitization. If an inland state or country name is given, the event is considered a "special case" (see method 9).

[19] In method 4 island name is given. If the event location is an island, the coordinates of the geographic center of the island are used. For example, according to the Chenoweth archive, the second event of storm 97 affected Puerto Rico. Twenty-six percent of all event locations in the archive require this type of digitization.

[20] In method 5 water body is given. If a water body such as a sea, gulf, or bay is listed, the coordinates of the approximate geographic center of the water body are used. For example, according to the Chenoweth archive, the first event of storm 94 affected the Gulf of Mexico. Two percent of all event locations in the archive require this type of digitization. Since an ocean is large, it is considered a special case (e.g., the first event of storm 95 is listed as affecting the Atlantic.)

[21] In method 6 directional description is given. For some events the location description includes a direction from a landmass, such as "west of," "off the coast of," or "near" a given area. For example, according to the Chenoweth archive, the second event of storm 93 affected south of Jamaica. We assume that for most of these event types, the effects were felt and reported at the location listed, but the eye of the tropical cyclone did not traverse the area. Instead the cyclone struck a nearby location, which is being described by direction from the area reporting the storm. The average North Atlantic tropical cyclone radius is 3° of latitude as defined by the circular area encompassing relative vorticity values less than 1×10^{-5} s^{-1} [*Liu and Chan*, 1999]. Therefore, a location listed as "south of Jamaica" is assumed to be within 333 km (approximately 3° of latitude) of the most south-central point of Jamaica. For the purposes here, a directional description is defined as 1° of latitude (approximately 111 km) away from the base point, as farther distances could imply the cyclone is closer to a different landmass that could instead be defined as a distance away from that landmass. Twelve percent of

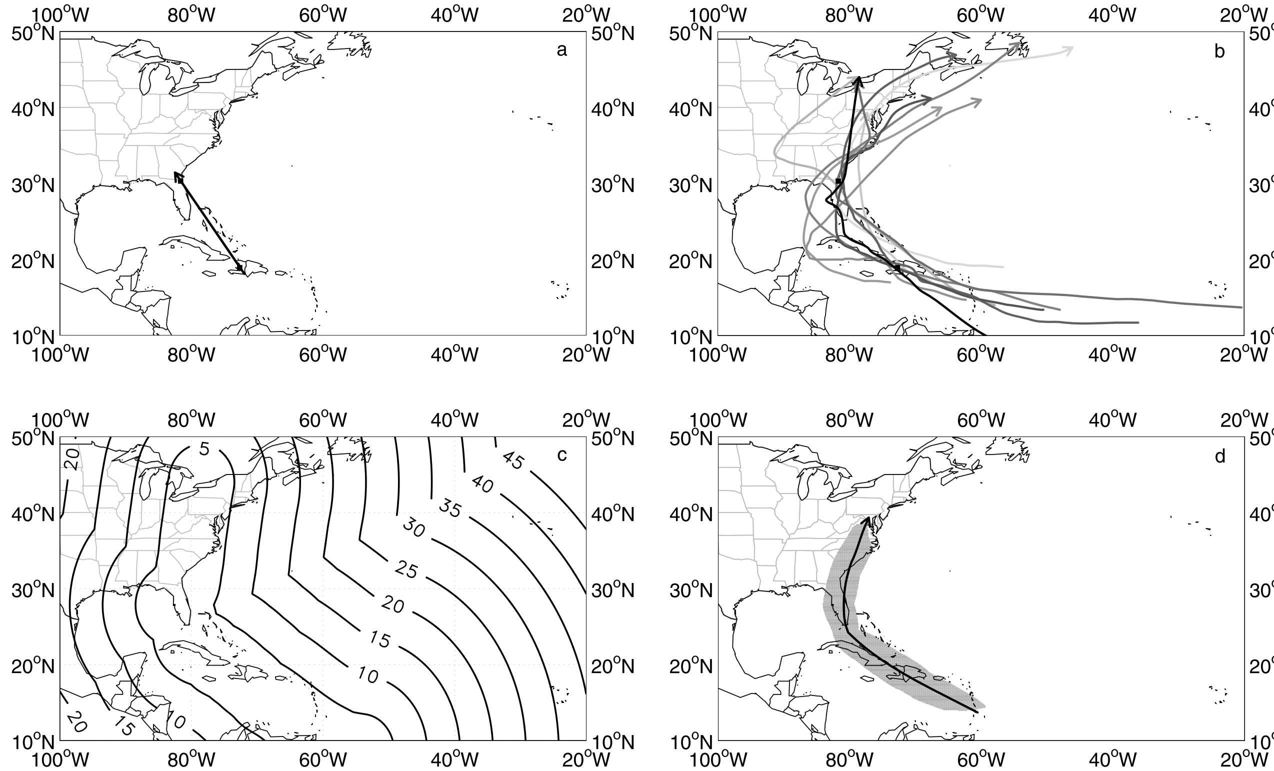

Figure 2. Storm 275 in the Chenoweth archive. (a) The two locations mentioned in the archive for storm 275 and a straight line through them (first-order track). (b) The 10 closest tracks (track analogs) to the locations of storm 275 shaded by average distance to the locations (km) with the darker shading indicating a closer track. (c) Distance from any location across the basin to the closest track analog in degrees of latitude. (d) Tropical cyclone pathway constructed by a weighted average of the distance grids of all track analogs. The shaded area encompasses a weighted average distance of less than or equal to 2.25° of latitude. A curve through the shaded area represents a possible (second-order) track for storm 275.

all event locations in the archive require this type of digitization.

[22] In method 7 coastline is given. If a coastline is listed, the coordinates of the geographic center of the coastline are used. For example, according to the Chenoweth archive, the fourth event of storm 55 affected the U.S. Gulf Coast. Two percent of all event locations in the archive require this type of digitization.

[23] In method 8 portion of an area is given. Many events are described as a specific portion of a political or geographic area. Methods used in this case are similar to those above; the coordinates of the geographic center of the portion of the area are used. For example, according to the Chenoweth archive, the second event of storm 129 affected western Haiti, and is therefore represented by the coordinates of the center of the western quadrant of Haiti. Similarly, if the area listed is part of a coastline, the coastline is portioned off and the coordinates of the center of the appropriate quadrant are used. For example, according to the Chenoweth archive, the second event of storm 315 affected the southeast U.S. Coast. Eight percent of all event locations in the archive require this type of digitization.

[24] Method 9 is for special cases. If the location does not fit one of the cases above, it is considered a special case. Some examples include broad areas (e.g., storm 4 affecting New England) or island chains (e.g., storm 11 affecting the Lesser Antilles). The coordinates for these locations are chosen following as closely as possible to the methods described in the above cases. Fifteen percent of all event locations in the archive require this type of digitization.

3.2. Determining a Probable Pathway

[25] The above methods are applied to all 742 events listed in the Chenoweth archive. Figure 2a shows the digitized locations for storm 275 in the archive, described as affecting Haiti and the northeast coast of Florida. A complete list of all events by date and spatial coordinates is available from myweb.fsu.edu/jelsner/extspace/ChenowethArchive.csv. While the locations are not the exact coordinates of the center of the cyclone, one can assume that these locations felt its direct affects, and in most cases the cyclone's eye passed nearby. The coordinates serve as event locations to assist in determining a pathway of the archived cyclones. A straight line connecting the event locations provides what we call a first-order approximation to a possible track.

[26] Additional information about tropical cyclones in the archive can be gained with the help of a track climatology. Previous research has shown tropical cyclones move across the Atlantic in a somewhat predictable manner [*Elsner and Kara*, 1999; *Brettschneider*, 2008]. However, track patterns fluctuate on annual and decadal timescales [*Elsner et al.*,

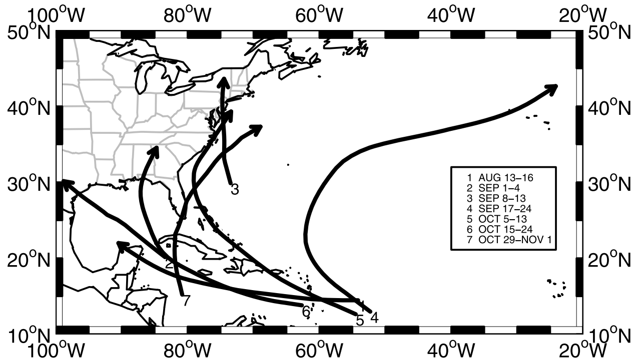

Figure 3. Tropical cyclone tracks for the 1766 North Atlantic hurricane season. The tracks are based on the cyclones listed in the Chenoweth archive (storms 93–99) and the method described in section 4 using the thresholds listed in Table 2.

2000]. Indeed a seasonal forecast of U.S. hurricane probability requires not only knowing how many cyclones will form, but where they will track [*Elsner and Jagger*, 2006]. Here it is assumed that the same steering flows have influenced hurricanes throughout the centuries and that hurricane tracks have had a similar response to those influences, making it possible to create pathways for historic hurricanes based on known tracks in the modern record. It is further assumed that the data set used here contains a large enough sample of cyclone tracks to represent most possible climate scenarios.

[27] Hourly interpolated track data [*Jagger and Elsner*, 2006] are used to find modern tropical cyclones that have passed near the Chenoweth event locations. The higher temporal resolution ensures that cyclones traveling quickly past the event location are not missed. The data are interpolated from the 6 hourly HURDAT data based on splines described by *Jagger and Elsner* [2006]. The code used to select modern tracks (and other routines used in this study) is developed within the R package for statistical computing [*R Development Core Team*, 2007].

[28] Figure 2b shows the 10 closest tracks (analogs) to the event locations of storm 275, which was the third known tropical cyclone of 1825, occurring during late September. The 10 tracks are ranked according to their average great circle distance from the event locations (analog rank). While the historical cyclone almost surely did not follow any of these specific tracks, it likely traversed a similar pathway, which can be represented by a ‘‘probable’’ pathway.

[29] There are various ways to determine a pathway, the one presented here being an inverse distance weighting (IDW) approach. This method is preferred because it weights the modern cyclone tracks based on their inverse distance to the event locations. The IDW approach also has the advantage that it is easy to understand and has relatively few free parameters. Here the 10 closest modern tracks are used. As shown in section 5, the larger the analog rank, the larger the average distance from the locations so the less weight it has on determining the pathway.

[30] The IDW approach begins by converting each of the modern analogs into a distance grid, the values of each grid point representing the closest distance that point is from the track (Figure 2c). The track itself has a value of zero where it intersects the grid. Distance grids (D_k) for all 10 modern analogs are then averaged using IDW, so that the average distance grid is weighted toward the modern analog tracks that are closest to the historical storm. The formula for the IDW is given by

$$D(\mathbf{s}) = \frac{\sum_{k=1}^{10} w_k D_k(\mathbf{s})}{\sum_{k=1}^{10} w_k},$$

where

$$w_k = \frac{1}{d(e, t_k)}$$

and $d(e, t_k)$ is the nearest great circle distance from the event location (or locations) to the track. Then, from the average distance grid $D(\mathbf{s})$ a maximum threshold value is chosen that provides an area encompassing the tracks of the closest cyclones on their closest approach to the event locations.

[31] Figure 2d shows the tropical cyclone pathway for storm 275. The pathway is constructed by determining the area enclosing a 2.25° latitude threshold. The threshold indicates that average distances are less than this value within the region. The threshold distance is a tuneable parameter, but here is chosen to provide a small, but spatially continuous corridor that likely includes the event locations. A line is manually drawn down the center of the pathway provides what we call a second-order approximation to a track.

[32] Storm 275 provides a good example where the second-order track provides a realistic depiction of the hurricane's movements. While the hurricane was only reported in Haiti and northwest Florida, it could have had additional affects over a larger portion of Florida and possibly the Carolinas. Despite this evidence, it would not be surprising if there is no record of storm 275 affecting the peninsula of Florida, as most of the state was not settled until the early twentieth century [*Landsea et al.*, 2004].

4. The 1766 Hurricane Season

[33] The procedure outlined in section 3.2 produces a probable pathway and a realistic track for a hurricane listed as a set of events in a historical archive. While this track is almost certainly not the actual track of the archived cyclone, the probable pathway defines a corridor that bounds an area for realistic tracks based on past climate scenarios.

[34] Figure 3 shows the tropical cyclone tracks for the 1766 season based on the method described above. The minimum distances and the threshold for the pathway are listed in Table 2. The third cyclone of the season and has the smallest minimum distance (22 km), while the fourth cyclone has the largest minimum distance (509 km). The track is manually drawn through the center of the pathway. Longer tracks result from either event locations being dispersed more widely across the region, and/or relatively more similarities between the modern analog tracks. The start and end points of the track are placed just outside the objectively determined pathway to make them easier to see.

Table 2. Parameters Used to Determine Tracks for the 1766 North Atlantic Hurricane Season[a]

Season Sequence Number	CA Storm Number	Minimum Distance (km)	Threshold (deg latitude)
1	93	69	2.00
2	94	48	2.00
3	95	22	2.00
4	96	509	4.00
5	97	178	3.00
6	98	24	2.75
7	99	24	2.75

[a]The number of analogs is the number of tropical cyclones from the HURDAT used to determine the track. The minimum distance is the average distance to the Chenoweth locations for the closest analog. The threshold is the minimum distance in the weighted average distance grids that enclose a continuous pathway.

[35] This particular season consisted of one tropical storm and six hurricanes, and would be considered average (in terms of the number of hurricanes) by today's standards. While it is possible there were additional weaker tropical cyclones that remained unobserved, the Chenoweth archive represents a sample of historical tropical cyclones, especially for areas such as Jamaica and the Caribbean, where historical records are more numerous. In addition to the number of tropical cyclones in 1766, constructed tracks for this season highlight possible uses of the data set.

[36] The seventh recorded tropical cyclone of the 1766 season (Figure 3) could have made an additional landfall in central or south Florida. As previously alluded to, Florida tropical cyclone records are scarce prior to the twentieth century. Thus it would not be surprising if a storm striking Florida in 1766 went unreported. As the cyclone continued, it is less likely to have hit South Carolina at tropical storm strength or greater, as South Carolina archives are more prevalent and have been examined in detail with no signs of a storm in 1766 [*Mock*, 2004]. Therefore, the probable pathway based on the modern analogs is a good depiction of where the hurricane likely went.

5. Unusual Archived Cyclones

[37] While the procedures outlined here can provide pathways for a large portion of historical tropical cyclones in an automated way, a climatologically based track might not be the most appropriate for cyclones with only a few or no close modern analogs. An example is the fourth tropical cyclone of the 1766 season (storm 96 in the Chenoweth archive), described as affecting the Lesser Antilles, 23°45′N 64°03′W, 33°00′N 57°00′W, and finally the Azores. The event is unusual in that it affected both the Lesser Antilles and the Azores. Also, the event is defined by four locations fairly evenly spaced across the North Atlantic. The unusualness of the cyclone is verified by a search for modern analogs. No recorded modern cyclone hit both the Lesser Antilles and the Azores, and the closest approach of any modern track averages 509 km to the event locations. Figure 4 depicts the distance of the 15 closest analogs for the cyclones in the 1766 season, showing that not only does storm 96 have no close analogs, but the average distance to the location increases relatively rapidly as a function of analog rank.

[38] The first-order track approximation of the Chenoweth events of storm 96 (Figure 5) depicts a reasonable hurricane path, with the missing piece being the curvature of the cyclone. Using the automated procedure and 10 analog tracks results in a pathway and track depicted in Figure 5b. Note the pathway does not include the Chenoweth event location over the Lesser Antilles (although it does include a portion of these islands). Thus, while some tropical cyclones will be well represented by their second-order track approximation, others need to take into account the actual event locations when creating the pathway. In fact it might make sense to blend the pathways created by connecting the Chenoweth event locations with the pathway generated by the modern analog climatology. This blend represents what we call a third-order track approximation.

[39] Figure 5c shows a new pathway, calculated using the second-order track as 50% of the input and the first-order track as the remaining 50% percent. This approximation provides a better fit to the Chenoweth archive locations as the pathway now includes all four of the Chenoweth locations. Another option, shown in Figure 5d, uses the first-order track as 75% of the input and the second-order track as 25%. This pathway seemingly depicts the most appropriate rendition of the historic event, with the track down the center of the pathway passing all of the event locations within a reasonable distance. The weight ratio of the first-order and second-order tracks used in the third-order approximation will vary depending on the specific event. Thus in cases where the modern climatology provides less information relative to the historical event locations the procedure can be modified to include a direct track between the event locations and a "tuning" parameter that weights the analog tracks relative to the direct track.

6. Sensitivity of the Methodology

[40] Here the performance of the above methodology (second-order approximation) is examined under three

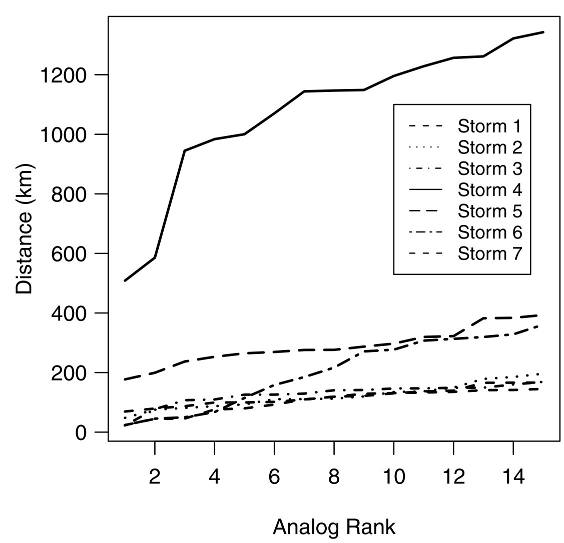

Figure 4. Distances (km) of the 15 closest modern analogs to the Chenoweth locations for the seven cyclones of the 1766 hurricane season. Distances increase with analog rank and relatively rapidly for some cyclones (storm 4).

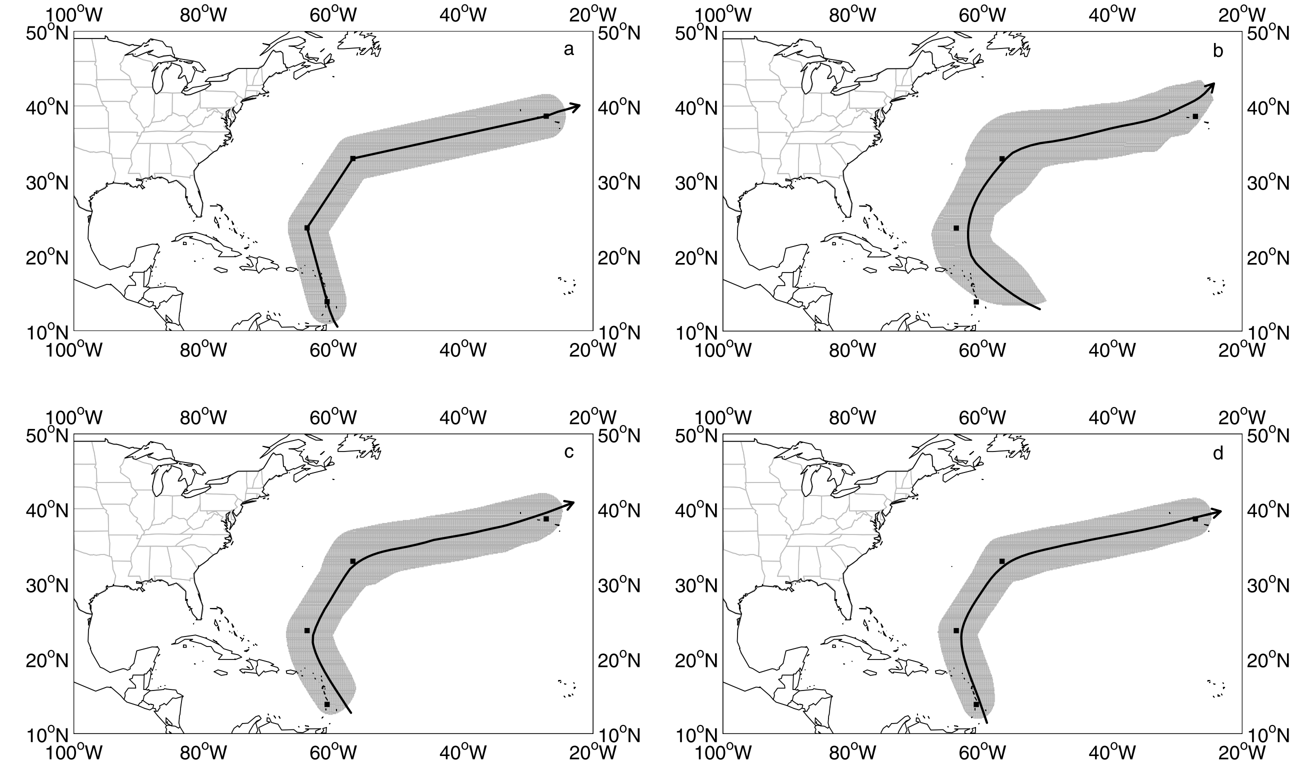

Figure 5. Storm 96 in the Chenoweth archive. (a) Connecting the event locations provides a first-order approximation to the track. (b) Using the event locations together with 10 modern analogs provides a second-order approximation. (c) A third-order approximation to the track is obtained by blending the first- and second-order approximations in a 1 to 1 ratio. (d) Another third-order approximation using a blend in a ratio of 3 to 1 in favor of the direct track.

experiments. First, pathways are constructed for the same event by leaving out a location in the archive. Second, the methodology is applied to a few known hurricanes where the information about the hurricane is degraded to the level available in the archive and a comparison of the pathway is made with respect to the known track. Third, a pathway is constructed using only hurricanes that correspond in time (within a month or so) of the event time and compared with a pathway constructed using hurricanes over a different part of the season.

6.1. Omitting an Event Location

[41] Here the sensitivity of the methodology is examined by omitting event locations. The archived cyclones are associated with one to four event locations, each location being a part of the methodology to construct the probable pathway. The number of locations for each cyclone affects the construction of pathways. For example, here four different pathways for storm 96, the fifth storm of the 1766 hurricane season, are considered.

[42] Figure 6a shows the pathway created using all three localities provided in the Chenoweth archive (Lesser Antilles, Puerto Rico, and off the South Carolina coast). The pathway in Figure 6b is created using only the first two locations, omitting the point off South Carolina. This pathway is shorter and does not contain the final event location. The third attempt, shown in Figure 6c, utilizes the first and third locations, omitting Puerto Rico. The pathway created here, however, still contains Puerto Rico and resembles the pathway in Figure 6a which uses all three points. Finally, Figure 6d depicts a pathway constructed using only the Puerto Rico locality. This pathway does not contain either of the omitted locations, although it does contain part of the Lesser Antilles and leaves open the possibility that the historical cyclone approached South Carolina. The best case scenario comes from a pathway with the largest number of localities for the particular cyclone. However, when data are especially limited, the most productive localities in terms of creating a realistic track are those farther separated across space.

6.2. Applying the Methodology to Recent Hurricanes

[43] Here the sensitivity of the methodology is examined by how well known tracks fit the estimated pathway. First, a known recent hurricane track is marked only by three locations based on its actual track and common locations in the Chenoweth archive. These locations are then used to construct a pathway following the above methodology, excluding the track of the particular cyclone of interest from the analog search.

[44] Figure 7a shows the pathway created for Hurricane Charley of 2004 using the event locations of west of Jamaica, western Cuba, and off the South Carolina coast. The actual track of Charley is also shown. The methodology does well as there appears to be a good spatial correspondence between the pathway and the track. On the other hand, Figure 7b shows the same for hurricane Dennis of 2005. The event locations used to create the pathway are

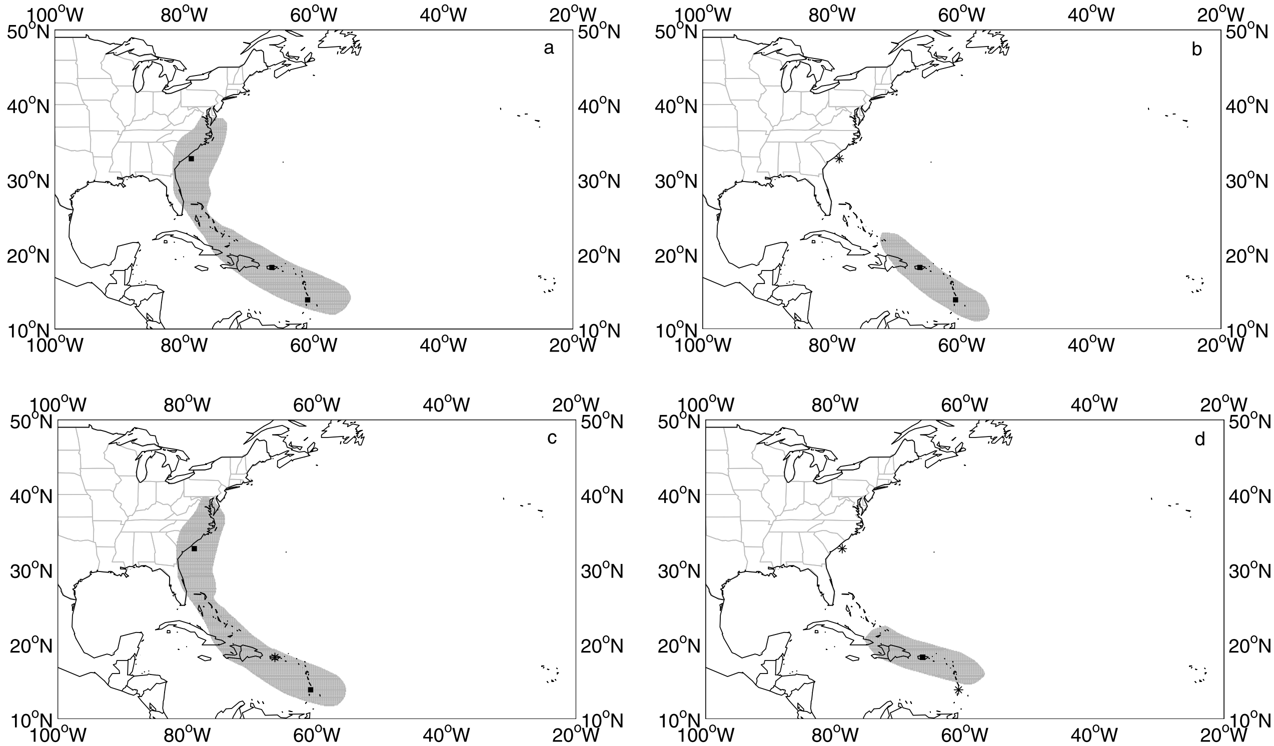

Figure 6. Pathways constructed for storm 97 by using some localities (marked by a square) and omitting others (marked by an asterisk). (a) Using all three localities: Lesser Antilles, Puerto Rico, and off South Carolina. (b) Omitting the location off South Carolina. (c) Omitting the Puerto Rico location. (d) Using only the Puerto Rico location.

north of Jamaica, western Cuba, and Pensacola, Florida. The spatial correspondence in this case is less precise as the pathway runs through the Greater Antilles and across the northern Gulf coast, while the track of Dennis is south of Puerto Rico and Hispaniola.

6.3. Filtering the Analogs by Time of Year

[45] It is well known that tropical cyclones track in varying directions depending on the time of year [*Elsner and Kara*, 1999]. A hurricane originating over the Gulf of Mexico or the western Caribbean during the early or later part of the season will tend to have a considerably greater northward component to its track compared to one originating over the central Atlantic during September. Thus it may be beneficial to restrict the search for analogs to those cyclones that occur near the same time of year as the historical hurricane. This may be especially helpful for those historical cyclones with less data, since the time of year may give more information about the storm's behavior.

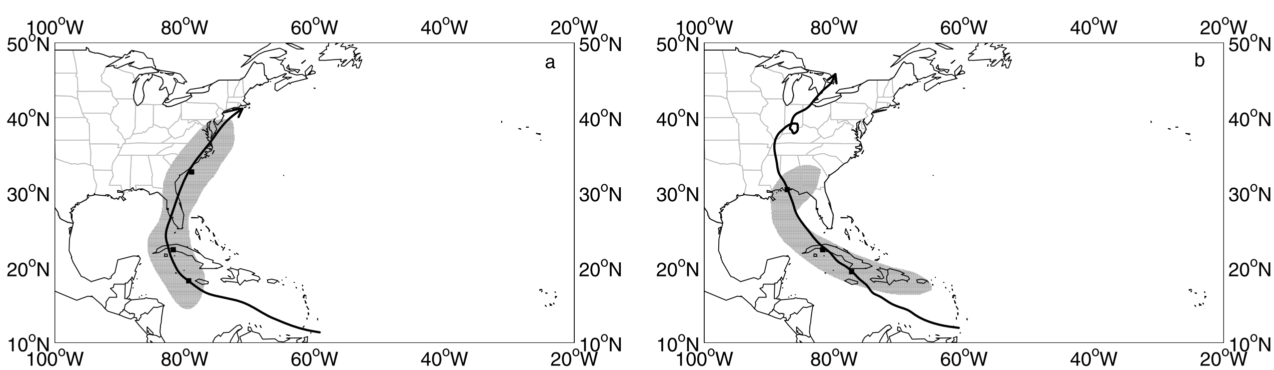

Figure 7. (a) Pathway and track for Hurricane Charley (2004). The pathway is constructed by using event locations: west of Jamaica, western Cuba, and off the South Carolina coast. Charley's track is not used to construct the pathway. The spatial correspondence between the probable pathway and actual track is quite good. (b) Pathway and track for Hurricane Dennis (2005). The pathway is constructed by using event locations: north of Jamaica, western Cuba, and Pensacola, Florida. Here the spatial correspondence between the pathway and track is less precise.

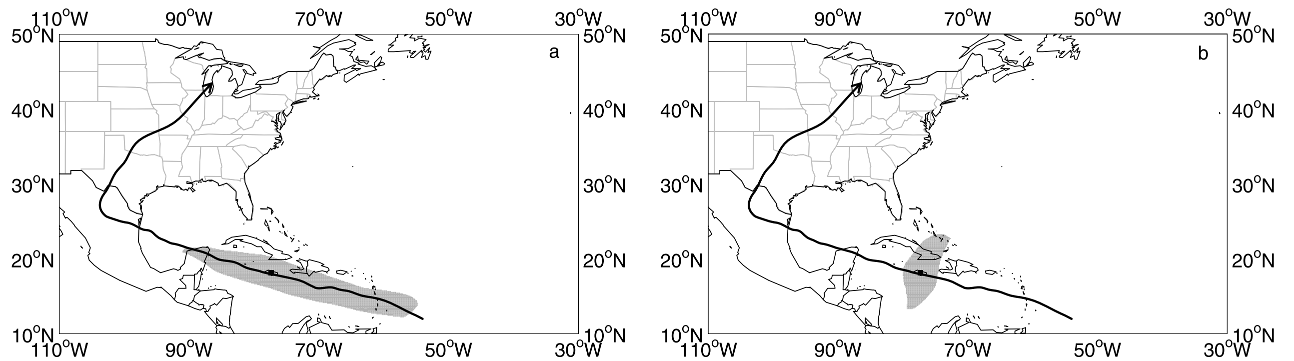

Figure 8. The track of Hurricane Gilbert and pathways created using analogs restricted to the months of (a) August and September and (b) October and November.

[46] Figure 8 provides an example using Hurricane Gilbert of 1988. The only location used to create the pathway is the island of Jamaica. Since Gilbert occurred during September, Figure 8a shows the pathway constructed using only analogs from the months of August and September (middle two months of the season). In contrast, Figure 8b shows the pathway using analogs from October and November. As expected, the pathway corresponding to the midseason analogs better resembles the cyclone's actual path, depicting the westward component common in this part of the basin during this part of the season. The pathway corresponding to the late season analogs shows a pathway directed to the north, and is not representative of this cyclone's actual track. Thus, the most appropriate rendition of the pathway of Hurricane Gilbert is created when the search of analogs is restricted based on the month of occurrence. It should be noted that pathway sensitivity will be considerably less severe when more than one event location is given in the archive, as the additional locations will better fix the direction of motion.

7. Summary

[47] A long record of past hurricane occurrences is the best way to assess future risk. While a complete and comprehensive record of all past hurricanes will remain elusive, information about previously undocumented cyclones is being uncovered through historical document searches and geological proxies. The present work is an initial attempt to make greater use of the limited information from historical hurricane archives. The major conclusion is that it is relatively straightforward to create a probable pathway for archived tropical cyclones based on a few event locations and a climatology of modern analog tracks. The pathway encompasses an area of possible tracks capable of improving information about tropical cyclone strikes in areas lacking extensive records or geologic proxy information. In turn, the pathway can be used to help uncover additional information about historical tropical cyclones. For instance, it might be worthwhile to examine historical documents from south Florida during late September or early October of 1825 for evidence of a cyclone corresponding to storm 275 in the Chenoweth archive.

[48] Although the methods discussed here rely largely on a climatology of modern hurricane tracks, not all event-specific characteristics are lost. The seventh storm of the 1766 season is evidence that it is possible to discover unusual tropical cyclone tracks relative to the set of modern records. Tropical cyclones such as these could result in additional insight into temporal variations in hurricane track patterns. Ultimately, this paper provides a digitized version of the *Chenoweth* [2006] historical hurricane chronology and a methodology for depicting a probable pathway based on the event locations and modern tracks. Once pathways and tracks are created for all of the tropical cyclones by *Chenoweth* [2006] they can be used by climatologists to better understand long-term hurricane variability.

[49] The methodology can be improved in a couple of ways. The certainty associated with localities in the Chenoweth archive varies based on the description given. Thus, weighting the modern analogs toward the more certain locations might give a more accurate depiction of the historical cyclone's pathway. Second, a distribution of cyclone intensities at locations along the constructed historical track could be added to the historical track database. Finally, the method could be used in concert with other specific information about the cyclone's path to generate an even more realistic track. An alternative approach would be to determine the posterior probability distribution that the historical track came within a specified distance of any location in the basin. This Bayesian approach would provide a statistical framework for understanding the behavior of tropical cyclones in historical hurricane chronologies.

[50] **Acknowledgments.** We acknowledge the National Hurricane Center for HURDAT. The work is supported by the U.S. National Science Foundation (ATM-0738172) and the Risk Prediction Initiative (RPI08-2-002) of the Bermuda Institute for Ocean Sciences. The speculation and opinions expressed here are those of the authors and do not reflect those of the funding agencies.

References

Brettschneider, B. (2008), Climatological hurricane landfall probability for the United States, *J. Appl. Meteorol. Climatol.*, *47*, 704–716.

Chenoweth, M. (2006), A reassessment of historical Atlantic basin tropical cyclone activity, 1700–1855, *Clim. Change*, *76*, 169–240.

Chenoweth, M. (2007), Objective classification of historical tropical cyclone intensity, *J. Geophys. Res.*, *112*, D05101, doi:10.1029/2006JD007211.

Chenoweth, M., and D. Divine (2008), A document-based 318-year record of tropical cyclones in the Lesser Antilles, 1690–2007, *Geochem. Geophys. Geosyst.*, *9*, Q08013, doi:10.1029/2008GC002066.

Elsner, J. B., and T. H. Jagger (2006), Prediction models for annual U.S. hurricane counts, *J. Clim.*, *19*, 2935–2952.

Elsner, J. B., and A. B. Kara (1999), *Hurricanes of the North Atlantic: Climate and Society*, Oxford Univ. Press, New York.

Elsner, J. B., T. H. Jagger, and X. Niu (2000), Changes in the rates of North Atlantic major hurricane activity during the 20th century, *Geophys. Res. Lett.*, *27*, 1743–1746.

Elsner, J. B., T. H. Jagger, and K. Liu (2008), Comparison of hurricane return levels using historical and geological records, *J. Appl. Meteorol. Climatol.*, *47*, 368–374.

Fernandez-Partagás, J., and H. F. Diaz (1995a), *A Reconstruction of Historical Tropical Cyclone Frequency in the Atlantic From Documentary and Other Historical Sources: 1851 to 1880. Part I: 1851–1870*, Clim. Diagn. Cent., Environ. Res. Lab., NOAA, Boulder, Colo.

Fernandez-Partagás, J., and H. F. Diaz (1995b), *A Reconstruction of Historical Tropical Cyclone Frequency in the Atlantic From Documentary and Other Historical Sources: 1851 to 1880. Part II: 1871–1880*, Clim. Diagn. Cent., Environ. Res. Lab., NOAA, Boulder, Colo.

Fernandez-Partagás, J., and H. F. Diaz (1996a), *A Reconstruction of Historical Tropical Cyclone Frequency in the Atlantic From Documentary and Other Historical Sources. Part III: 1881–1890*, Clim. Diagn. Cent., Environ. Res. Lab., NOAA, Boulder, Colo.

Fernandez-Partagás, J., and H. F. Diaz (1996b), *A Reconstruction of Historical Tropical Cyclone Frequency in the Atlantic From Documentary and Other Historical Sources. Part IV: 1891–1900*, Clim. Diagn. Cent., Environ. Res. Lab., NOAA, Boulder, Colo.

Fernandez-Partagás, J., and H. F. Diaz (1996c), Atlantic hurricanes in the second half of the nineteenth century, *Bull. Am. Meteorol. Soc.*, *77*, 2899–2906.

Fernandez-Partagás, J., and H. F. Diaz (1997), *A Reconstruction of Historical Tropical Cyclone Frequency in the Atlantic From Documentary and Other Historical Sources. Part V: 1901–1908*, Clim. Diagn. Cent., Environ. Res. Lab., NOAA, Boulder, Colo.

Fernandez-Partagás, J., and H. F. Diaz (1999), *A Reconstruction of Historical Tropical Cyclone Frequency in the Atlantic From Documentary and Other Historical Sources. Part VI: 1909–1910*, Clim. Diagn. Cent., Environ. Res. Lab., NOAA, Boulder, Colo.

García-Herrera, R., F. Rubio Durán, D. Wheeler, E. Hernandéz Martín, M. Rosario Prieto, and L. Gimeno (2004), The use of Spanish and British document sources in the investigation of Atlantic hurricane incidence in historical times, in *Hurricanes and Typhoons: Past, Present and Future*, edited by R. J. Murnane and K. Liu, pp. 149–176, Columbia Univ. Press, New York.

García-Herrera, R., L. Gimeno, P. Ribera, and E. Hernández (2005), New records of Atlantic hurricanes from Spanish documentary sources, *J. Geophys. Res.*, *110*, D03109, doi:10.1029/2004JD005272.

Jagger, T. H., and J. B. Elsner (2006), Climatology models for extreme hurricane winds near the United States, *J. Clim.*, *19*, 3220–3226.

Landsea, C. W., C. Anderson, N. Charles, G. Clark, J. Dunion, J. Fernández-Partagás, P. Hungerford, C. Neumann, and M. Zimmer (2004), The Atlantic hurricane database reanalysis project: Documentation for 1851–1910 alterations and additions to the HURDAT database, in *Hurricanes and Typhoons: Past, Present and Future*, edited by R. J. Murnane and K. Liu, pp. 177–221, Columbia Univ. Press, New York.

Liu, K., and M. L. Fearn (1993), Lake-sediment record of late Holocene hurricane activities from coastal Alabama, *Geology*, *21*, 793–796.

Liu, K., and M. L. Fearn (2000), Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records, *Quat. Res.*, *54*, 238–245.

Liu, K. S., and J. C. Chan (1999), Size of tropical cyclones as inferred from ERS-1 and ERS-2 data, *Mon. Weather Rev.*, *127*, 2992–3001.

Louie, K., and K. Liu (2003), Earliest historical records of typhoons in China, *J. Hist. Geogr.*, *29*, 299–316.

Ludlum, D. M. (1963), *Early American Hurricanes, 1492–1870*, Am. Meteorol. Soc., Boston, Mass.

Millás, C. J. (1968), *Hurricanes of the Caribbean and Adjacent Regions, 1492–1800*, Acad. of the Arts and Sci. of Am., Miami, Fla.

Mock, C. J. (2004), Tropical cyclone reconstructions from documentary records: Examples for South Carolina, United States, in *Hurricanes and Typhoons: Past, Present and Future*, edited by R. J. Murnane and K. Liu, pp. 121–148, Columbia Univ. Press, New York.

Moreau de Jonnès, A. (1822), Sur les ouragans des Antilles, avec un tableau chronologique de ceux qui eurent lieu, in *Histoire Physique des Antilles Françaises*, vol. 1, p. 346, Impr. de Migneret, Paris.

Murnane, R. J., and K. Liu (Eds.) (2004), *Hurricanes and Typhoons: Past, Present and Future*, 462 pp., Columbia Univ. Press, New York.

Piddington, H. (1848), *The Sailor's Horn-Book for the Law of Storms: Being a Practical Exposition of the Theory of the Law of Storms, and Its Uses to Mariners of all Classes in all Parts of the World, Shown by Transparent Storm Cards and Useful Lessons*, 2nd ed., John Wiley, New York.

Poey, A. (1855), A chronological table, comprising 400 cyclonic hurricanes which have occurred in the West Indies in the North Atlantic within 1493 to 1855, *J. R. Geogr. Soc.*, *25*, 238–291.

R Development Core Team (2007), R: A language and environment for statistical computing, R Found. for Stat. Comput., Vienna.

Redfield, W. (1831), Remarks on the prevailing storms of the Atlantic coast of the North American states, *Am. J. Sci. Arts*, *20*, 17–51.

Redfield, W. (1854), On the first hurricane of September 1853, in the Atlantic; with a chart; and notice of other storms, *Am. J. Sci.*, *18*, 1–18.

Reid, W. (1838), *An Attempt to Develop the Law of Storms by Means of Facts, Arranged According to Place and Time; and Hence to Point Out a Cause for the Variable Winds, With a View to Practical Use in Navigation*, J. Weale, London.

Reid, W. (1849), *The Progress of the Development of the Law of Storms, and of the Variable Winds: With the Practical Application of the Subject to Navigation*, J. Weale, London.

Southey, T. (1827), *Chronological History of the West Indies*, vol. 3, *Cass Libr. West Indian Stud.*, vol. 4, Frank Cass, London.

J. B. Elsner, R. E. Hodges, T. H. Jagger, J. C. Malmstadt, and K. N. Scheitlin, Department of Geography, Florida State University, Bellamy Bldg. Room 323, Tallahassee, FL 32306, USA. (kscheitlin@fsu.edu)