Visual Representations of the Spatial Relationship Between Bermuda High Strengths and Hurricane Tracks

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The 2004 and 2005 hurricane seasons dramatically demonstrated the magnitude of the societal significance of hurricanes, negatively impacting on all scales from the personal to the national. Although definitive identification of the forcing mechanisms controlling hurricane tracks and landfall patterns remains elusive, increasing evidence supports the hypothesis that the increase in hurricane activity along the Gulf Coast is due to a southwestward shift in the position of the Bermuda High. This research uses multiple visualization techniques to explore the spatial correlation between Bermuda High strengths - as interpreted from the North Atlantic Oscillation (NAO) index - and hurricane tracks. Using hurricane vector data from the National Oceanic and Atmospheric Administration (NOAA) Hurricane Data set (HURRDAT) and NAO index data since 1947, the hypothesized spatial relationships were investigated. Due to the vast number of storm track segments (more than 17,000), displaying all segments in the same map failed to reveal any coherent spatial pattern. For this reason, storm track segments were converted into a point coverage, each point representing the mid-point of an original storm segment. Other visualization methods were applied to this new point coverage, including choropleth mapping and continuous 2-D and enhanced 3-D surface displays. The latter two methods were novel approaches for the visualization of large numbers of hurricane tracks and can be applied to any large data sets consisting of linear features. Results visually support a spatial relationship between hurricane tracks and Bermuda High strengths.

Keywords: Geographic visualization, kernel density estimation, Bermuda High Hypothesis, hurricane tracks

INTRODUCTION

Hurricanes play a significant role in the lives of the people living in high-risk areas, negatively impacting on all scales from the personal to the national. The ever-increasing concentration of people and properties in coastal areas has raised a serious question regarding hurricanes: Are there changes in the periodicity or return periods of hurricanes, and, if so, what is causing these changes? Paleotempestology, the study of prehistoric hurricane activity via the interpretation of proxy records (i.e., coastal lake sediments), allows us to look to the past to interpret long-term changes in hurricane landfall frequencies that far exceed the scope of modern instrumental data. By looking to the proxy record, paleotempestology allows for the interpretation of changes in hurricane landfall patterns spanning millennia.

"Paleotempestology is the study of prehistoric hurricane activity via the interpretation of proxy records."

Previous paleotempestological studies done on sediment cores taken from coastal lakes and marshes along the U.S. Gulf and Atlantic coasts show an anti-phase relationship in hurricane landfall frequencies between

Initial submission, July 11, 2006; revised submission, December 31, 2006; final acceptance, January 10, 2007.

the two coasts. U.S. Gulf Coast studies (Liu, 2004; Liu and Fearn, 1993; 2000a; 200b) have shown that there was a period of increased hurricane activity during approximately 1000-3400 yr BP and decreased activity from 6000-3400 yr BP, as evidenced by a dramatic increase in the frequency of hurricane-deposited sand layers found in the lake and marsh sediments (Figure 1). Studies completed along the Atlantic Coast (Scott *et al.*, 2003; Collins *et al.*, 1999; Donnelly *et al.*, 2001a; Donnelly *et al.*, 2001b; Donnelly *et al.*, 2004; Lu and Liu 2005) indicate the opposite, a period of increased hurricane activity during the last 1000 yr BP and a period of relative inactivity during 1000-3400 yr BP.

The hypothesis that seeks to explain this anti-phase relationship in hurricane landfall frequencies is termed the Bermuda High Hypothesis. Liu and Fearn (2000a) hypothesize that during the Gulf Coast's hyperactive period of the late Holocene (3400-1000 yr BP) the Bermuda High

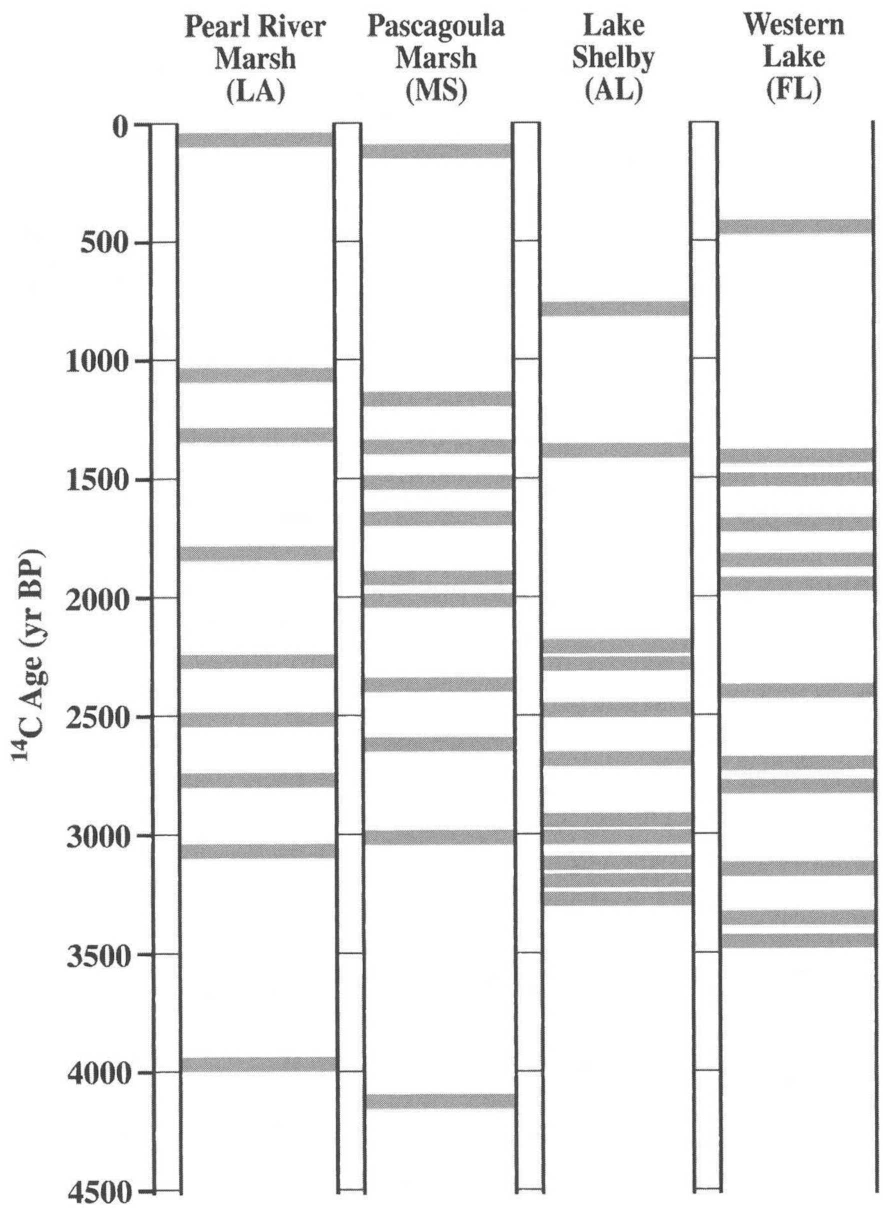

Figure 1. Chronology of catastrophic hurricane strikes along the U.S. Gulf Coast during the last 4,500 years (courtesy of Liu, 2004).

(also known as the Azores High or Atlantic Subtropical Anticyclone) was located southwest of its present position due to neo-glacial cooling and a southward shift in the jet stream. This southwesterly shift in the position of the Bermuda High would redirect the paths of hurricanes, leading to an increase in hurricane landfalls along the Gulf of Mexico Coast. Conversely, when the Bermuda High is in a more northeasterly position, closer to Bermuda, the Atlantic Coast experiences more hurricane strikes (Figure 2). The Bermuda High is thought to have a substantial influence on the direction and path of hurricanes (Elsner *et al.*, 2000; Elsner and Kara, 1999), but to date this relationship has not been tested visually or quantitatively.

The purpose of this research is to investigate the effect the Bermuda High has on hurricane tracks, testing the Bermuda High Hypothesis of Liu and Fearn (2000a). If the Bermuda High is indeed a factor in controlling the millennia-scale spatial shifts in hurricane landfall, a spatial relationship should be found between today's Bermuda High strengths and today's hurricane directions and tracks. Using different visualization techniques, this research seeks to explore, whether a spatial relationship exists between the modern-day Bermuda High strengths and the direction

"This research visually tests the Bermuda High Hypothesis."

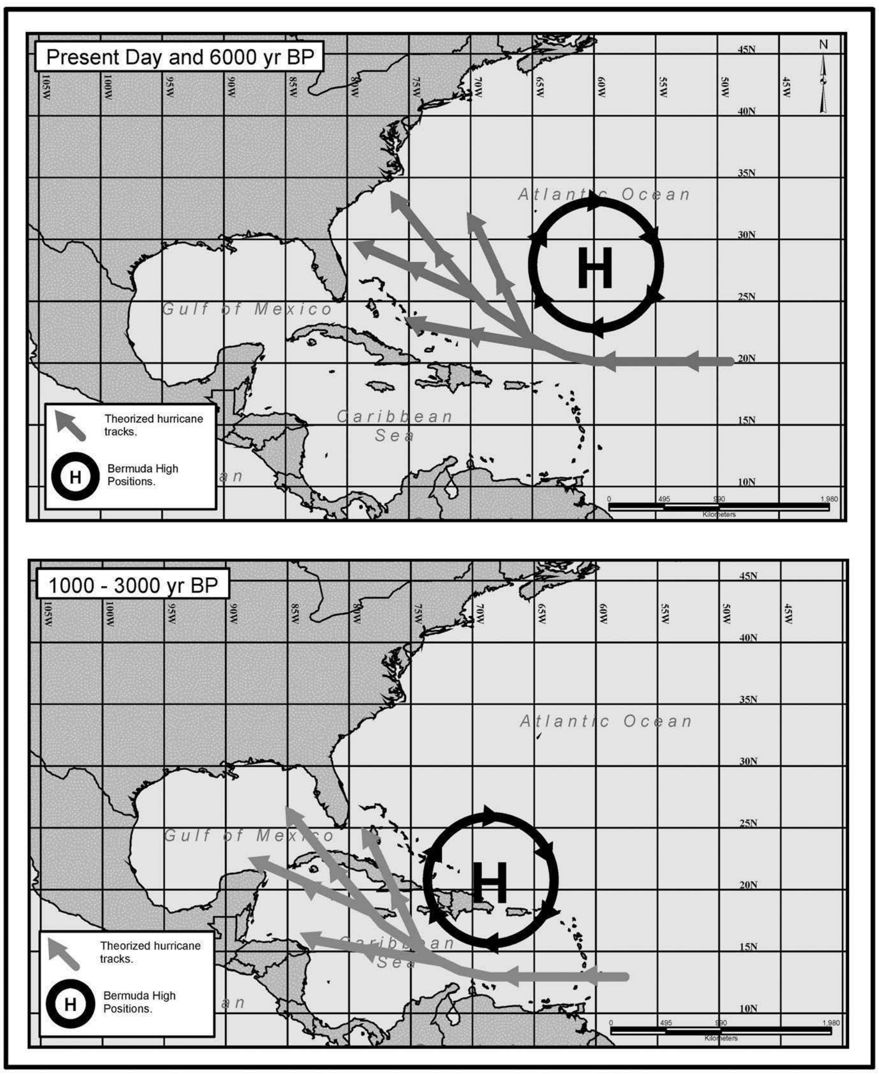

Figure 2. Relationship between the Bermuda High and hurricane tracks as expressed in the Bermuda High Hypothesis. (see page 76 for color version)

and path of modern-day hurricanes (Knowles, 2006). ArcView® GIS (ESRI, 1999), CrimeStat III (Levine, 2004), and Surfer (Golden Software, 2003) were used to visualize such possible relationships.

Background

Hurricane tracks are discrete linear features that have a starting and an end point. The logical map type to visualize such tracks is the so-called flow map, which shows linear movements between places. Hurricane tracks can be symbolized with flow lines of either uniform (no distinction is made between different hurricane strengths) or increasing line thickness to indicate differences in hurricane strengths (from tropical storms to category 5 hurricanes). Flow maps became especially popular in economic geography for mapping patterns of distribution of economic commodities, people (passengers), and any number of measures of traffic densities (Dent, 1999). Only recently has software for automated flow mapping become available. Examples include CrimeStat III (Levine, 2004), Tobler's Flow Mapper (Tobler, 1987), ArcGIS® (ESRI, 2005), and generatelines.dll, a tool that generates lines between locations. CrimeStat III (Levine, 2004) and Tobler's Flow Mapper (Tobler, 1987) can be downloaded from the following websites: http://www.icpsr.umich.edu/NACJD/crimestat.html/ and http://www.csiss.org/clearinghouse/FlowMapper/. The generatelines.dll tool is included in Groff and McEwen (2006), who also provide a detailed comparison of the three software packages. Unfortunately, flow maps are very poor at visualizing large amounts of flow lines that are spatially clustered, overlap, and criss-cross each other. Such a dense display of flow lines often masks any potential spatial patterns in the data.

"Flow maps are very poor at visualizing large amounts of flow lines that are spatially clustered, overlap, and criss-cross each other."

An alternative method to visualize hurricane tracks is first to split them into equally short segments and then replace each segment with a point placed at the center of each segment. Points can then be summarized for each cell of a regular grid placed on top of the study area. Such point densities can then be easily visualized with a choropleth map, which is defined by the International Cartographic Association as "a method of cartographic representation which employs distinctive color or shading applied to areas other than those bounded by isolines. These are usually statistical or administrative areas" (Meynen, 1973). In general, the choropleth map is easily understood by map readers and is therefore a popular visualization method. However, very "different-looking" choropleth maps can be derived from the same data depending on the classification method, areal symbolization, and size of administrative areas used. Any introductory cartographic textbook will provide a detailed discussion of the pitfalls of choropleth mapping (Dent, 1999; Slocum, *et al*., 2005; Campbell, 2001; Muehrcke, *et al*., 2001; Robinson, *et al*., 1995). In addition, the choropleth map assumes a uniform distribution within the same statistical area and can show rather abrupt density changes at the borders between an area and its neighbors. This latter drawback can be avoided when the center points of all hurricane segments are visualized using the kernel density interpolation method. This method creates smooth transitions between different density values.

The kernel density interpolation method has become a popular visualization method where the volume of incidents is relatively large and spatially clustered (Brunsdon, *et al*., forthcoming). It has, for example, been applied to investigate spatial and temporal changes in the retailing sector (Leitner and Staufer-Steinnocher, 2002); the dynamics of fire incidents (Corcoran *et al*., 2007); infant health analysis (Curtis and Leitner, 2006); crime hot spots (Eck *et al*., 2005); and concentrations of Foot and

Mouth Disease in South America (Curtis *et al.*, 2005). A detailed discussion of how the method works is provided below. In general, kernel density interpolation results can be visualized in the form of density maps (similar to choropleth maps but with smooth transitions between neighboring grid cells), isometric maps, or actual 3-D surfaces visualized with the popular fishnet (wire frame) structure. The isometric map is generated from data that occur at points and is one distinct form of the isarithmic map. Isarithmic mapping involves mapping a real or conceptual three-dimensional geographical volume with quantitative line symbols (Dent, 1999). Finally, an actual 3-D surface can be enhanced by draping additional information, such as the topography or shaded relief, over the original wire frame structure.

Data and Study Region

Hurricane data were downloaded from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center website (http://hurricane.csc.noaa.gov/hurricanes/index.html). The data set consisted of every storm (ranging from extra-tropical depression to category 5 hurricanes) that occurred during the last 150 years. Each storm consisted of a multi-vectored track, divided into 6hr segments (over 35,000 records). The attribute data associated with each 6hr segment included, among others: the storm's name, wind speed, category, and pressure; the day, month, and year of the storm segment's occurrence; and the segment's location, expressed as x- and y-coordinates. For this project, a subset that included only hurricanes after 1947 (over 17,000 records) was also collected, since 1947 is considered to be the onset of reliable measured data. The 17,000+ records represented a total of 577 hurricanes.

In addition to hurricane tracks, data measuring the strength of the Bermuda High needed to be collected. While no direct measure of the Bermuda High exists, its strength can be interpreted from the North Atlantic Oscillation (NAO) index. The NAO is a coherent north-to-south seesaw pattern in sea-level pressures between Iceland and the Azores, and when pressures are low over Iceland (Icelandic Low), they tend to be high over the Azores (Azores High) and vice versa. Simply put, when the Icelandic Low is strong (low pressures), the Bermuda High is strong (high pressures), resulting in a positive NAO index. NAO index data were taken from Portis *et al.* (2001), who calculated such data as the difference in the normalized sea-level pressure anomalies at the locations of maximum negative correlation between the sub-tropical and sub-polar North Atlantic Sea Level Pressure (SLP). This means that the stronger (more positive) the NAO index, the stronger the Bermuda High; and the weaker (more negative) the index, the weaker the Bermuda High. The Portis *et al.* (2001) NAO index values range from -3.51 to +3.51 and were manually added to the database of the 17,000+ hurricane vectors.

Visualization of Hurricane Tracks

Geographic visualization of all 17,000+ storm vectors as line segments in the same map resulted in a very dense display, which hid any potential spatial patterns in the data (Figure 3). For this reason, a subset of the NAO index data was created that separated a "weak" Bermuda High category, with NAO index values smaller than -2.51, from a "strong" Bermuda High category, with NAO index values larger than +2.51. This had the effect of removing any moderating data and leaving only storm tracks that were associated with very strong or very weak Bermuda High strengths. This

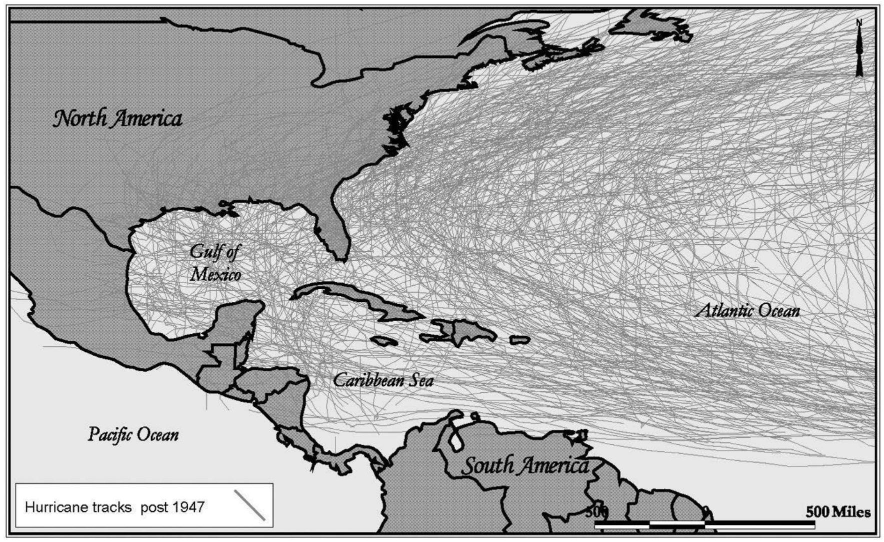

Figure 3. Visualization of all 577 hurricanes that have reached the Atlantic Ocean and the Gulf of Mexico since 1947. *(see page 77 for color version)*

subset resulted in 1,201 segments (47 hurricanes) associated with a "weak" and 825 segments (41 hurricanes) associated with a "strong" Bermuda High, respectively, for a total of 2,026 segments (88 hurricanes).

Geographic visualization of the subset of storm vectors associated with only the "weak" and "strong" Bermuda High categories resulted once again in a very dense map display that hid any spatial patterns. For this reason, each hurricane vector from this subset was converted into a point that was placed at the center of each 6hr storm vector. This resulting point coverage was used in all subsequent visualization efforts.

Choropleth Map

Visualizing the point coverage alone did not show any improvement over the previous two vector displays in terms of revealing any specific spatial patterns. However, overlaying a regular grid on top of the point coverage, counting the number of points falling into each grid cell, classifying the resulting "points-per-grid-cell" densities, and visualizing the densities with a sequential color scheme (Brewer, 1994), resulted in a much more useful visual display. This approach was carried out at three different grid cell sizes: 1° latitude/longitude, 2.5° latitude/longitude, and 5° latitude/longitude (Figure 4). While spatial patterns started to emerge using this choropleth method approach, maps still lacked smooth transitions between grid cells at all three resolutions. To further improve the smoothness of the visualization, the kernel density interpolation method was applied to the original point coverage.

Kernel Density Interpolation

The kernel density estimation is an interpolation technique that generalizes individual point locations or events, s_i, to an entire area and provides density estimates, $\lambda(s)$, at any location within the study region $\Re$ (Bailey and Gatrell, 1995; Burt and Barber, 1996; Fischer *et al*., 2001). Density estimates are derived by placing a symmetrical surface, called the kernel function, $\kappa(.)$, over each event and summing the value of all surfaces onto a regular reference grid superimposed over the study region (Figure 5).

Typically, a symmetrical kernel function falls off with distance from each event at a rate that is dependent on the shape of the kernel function and the chosen bandwidth, *b*. A number of different kernel functions have been used, including normal, triangular, quartic, negative exponential, and uniform. The bandwidth determines the amount of smoothing and, for the limited distance functions (triangular, quartic, negative exponential, and uniform), the size of the kernel's search area. In the case of the normal kernel function, the bandwidth is the length of the standard deviation of the normal distribution. The normal kernel function produces a density estimate over the entire region (i.e., it is an unlimited distance function), whereas the other four functions produce estimates only for the circumscribed bandwidth radius. Kernel density calculations can be carried out for events that are weighted or unweighted.

"Selecting an appropriate bandwidth is a critical step in kernel estimation . . ."

Selecting an appropriate bandwidth is a critical step in kernel estimation; bandwidth affects the results to a much greater extent than cell size or type of kernel function. A larger bandwidth expands the kernel at the cell center and results in a smoothed and generalized map with low-

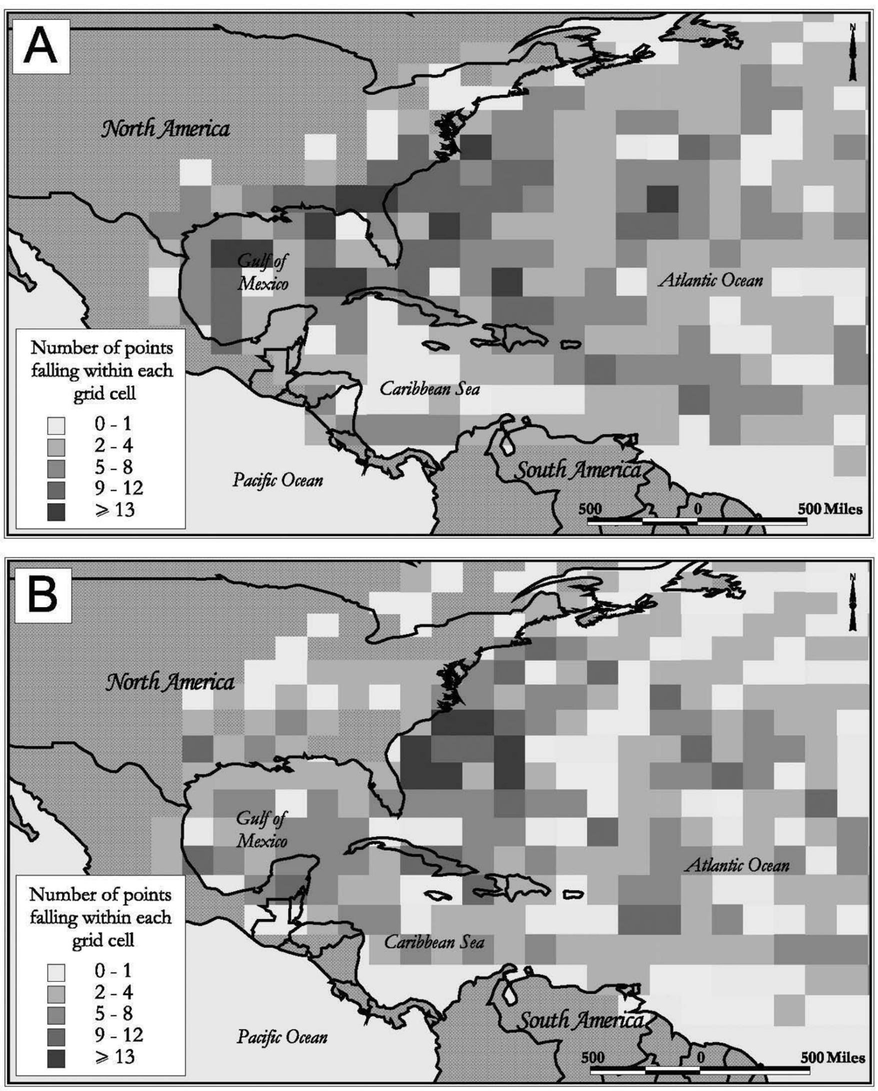

Figure 4. Choropleth mapping of hurricane density within a 2.5° latitude/longitude grid cell size based on a "weak" Bermuda High (4A) and a "strong" Bermuda High (4B). (see page 77 for color version)

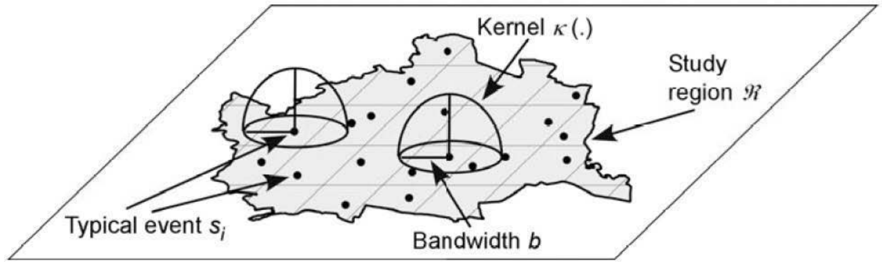

Figure 5. Kernel density estimation of a point pattern using the quartic kernel function (courtesy of Fischer et al.*, 2001).*

density values. In contrast, a small bandwidth results in less smoothing, producing a map that depicts local variations in point densities. A very small bandwidth almost reproduces the original point pattern and is spiky in appearance.

2-D Kernel Density Representation

"These results support a visual spatial correlation between modern-day Bermuda High strengths and modern-day hurricane tracks."

Using the mid-point for each 6hr section of the storm tracks, a kernel density interpolation was calculated using CrimeStat III (Levine, 2004). Density calculations were based on a normal kernel function with a fixed bandwidth of 195 miles. This bandwidth selection is fairly conservative, considering that hurricane diameters range from 125 to 800 miles (Elsner and Kara, 1999). The normal kernel function was chosen because it is the most commonly used (Kelsall and Diggle, 1995).

The results from the kernel density interpolations show the highest and lowest density of storm tracks in the darkest and lightest red, respectively. In contrast to the previously-discussed vector methods, spatial patterns now emerge more clearly. Hurricanes occurring during periods concurrent with a weak Bermuda High (highly negative NAO index) show little or no track re-curvature, with nearly all storm tracks showing east-west movement (Figure 6A). However, during periods concurrent with a strong Bermuda High (highly positive NAO index), hurricane tracks show large amounts of re-curvature along the western edge of the well-defined high pressure system (Figure 6B). These results support a visual spatial correlation between modern-day Bermuda High strengths and modern-day hurricane tracks.

3-D Kernel Density Representation

"The enhanced 3-D surface clearly distinguishes between regions of high activity concurrent with strong and weak Bermuda High strengths."

The final representation used the density values from the kernel interpolation method to create an enhanced 3-D display. This step was accomplished with the Surfer program (Golden Software, 2003). First, kernel density estimations were visualized in the form of a 3-D wire frame structure. This 3-D continuous surface was subsequently draped with (1) a simplified topographic map, showing only the outline of country boundaries and the land and water areas, (2) a shaded relief, and (3) an isometric map with hypsometric tints, but no contours (Figure 7).

The final, enhanced 3-D surface (Figure 8) is an improved visual representation compared to the 2-D display and clearly distinguishes between regions of high activity concurrent with strong and weak Bermuda High strengths. For periods with weak Bermuda Highs a general east-west trend of hurricane tracks is visible, indicative of a weak system exhibiting little or no control over the steering of the hurricanes. During periods

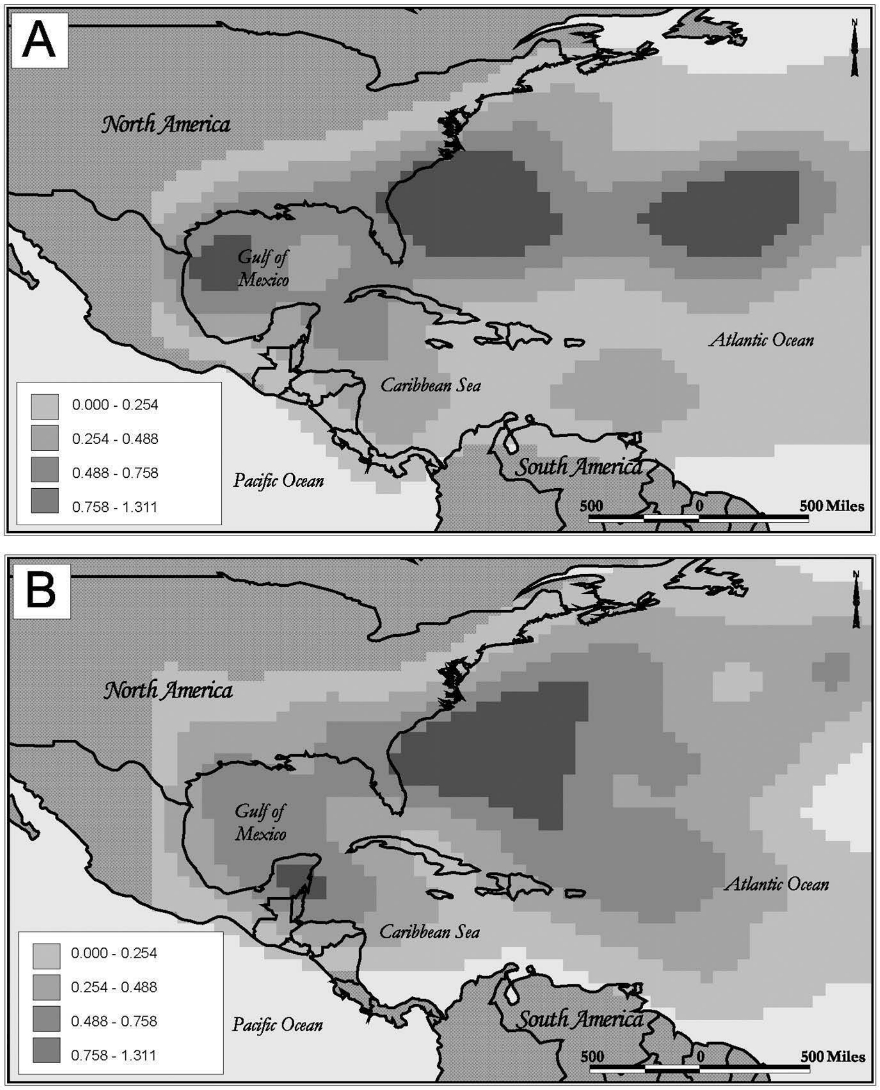

Figure 6. 2-D continuous surface display of hurricane tracks derived from kernel density estimations coinciding with a "weak" Bermuda High (6A) and a "strong" Bermuda High (6B). (see page 78 for color version)

when the Bermuda High is strong, hurricane tracks clearly exhibit a distinct pattern of re-curvature (Figure 8).

The 3-D enhanced surface representation is also compelling in that it illustrates changing risks associated with varying Bermuda High strengths. For example, according to the last 50+ years of data, when the Bermuda High is weak, the Caribbean Antilles (depicted with red circles in Figure 8) have a much lower occurrence of hurricane strikes. Alternatively, when the Bermuda High is strong, the same region's risk of hurricane strike increases dramatically.

Conclusions

The purpose of this research was to discover which visualization methods are best suited to detecting the spatial patterns of a large number of hurricane tracks collected for the Atlantic Ocean and the Gulf of Mexico since 1947. Specifically, the research visually tested the Bermuda High Hypothesis. The results indicate that, for periods concurrent with a strong Ber-

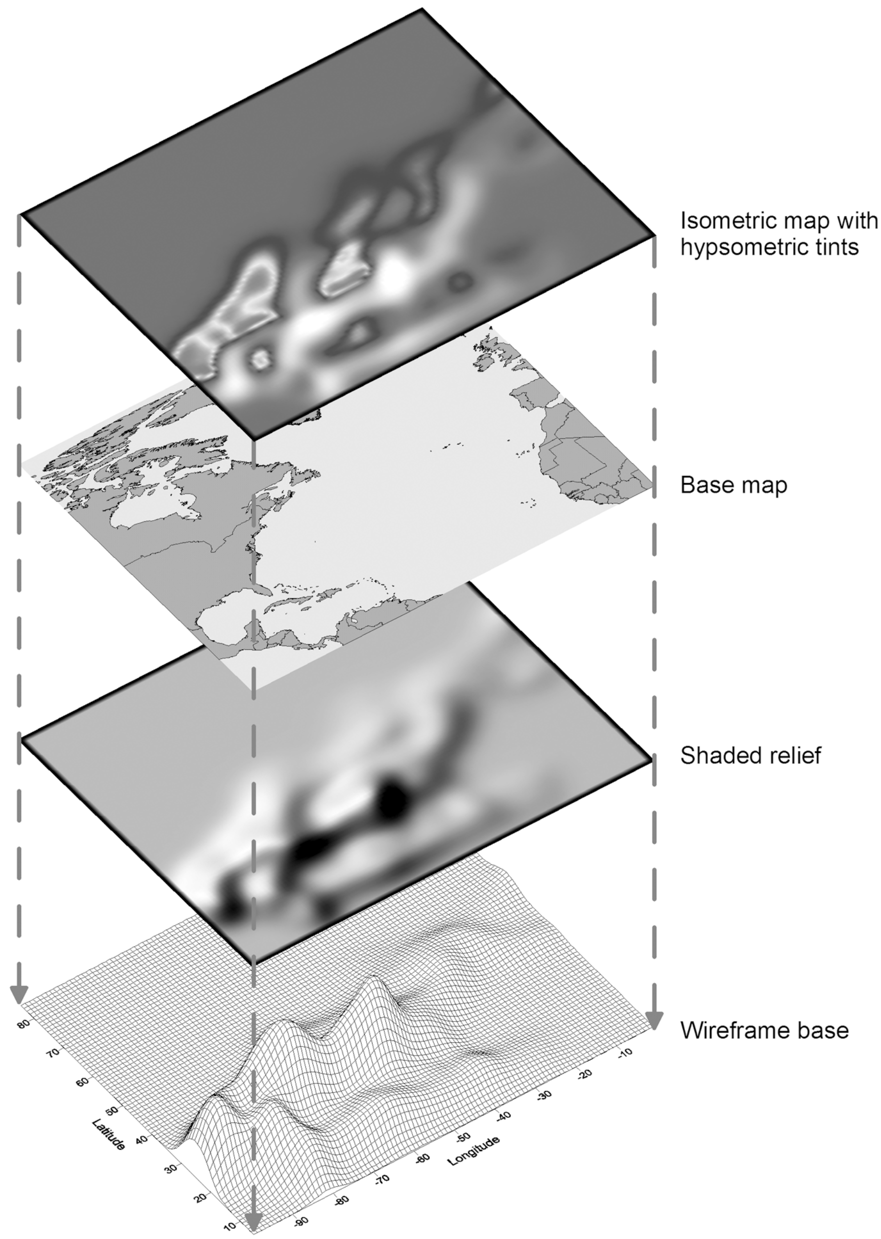

Figure 7. Schematic view of the components of the enhanced 3-D continuous surface display. (see page 79 for color version)

muda High, hurricane tracks show large amounts of re-curvature along the western edge of the well-defined (Bermuda High) pressure system, which is indicative of the Bermuda High as a controlling agent of hurricane tracks and is consistent with the stipulations put forth in the Bermuda High Hypothesis of Liu and Fearn (2000a). Hurricane tracks during periods concurrent with a weak Bermuda High are also in agreement with the Bermuda High Hypothesis, with hurricane tracks showing little or no track re-curvature but rather dominant east-west movement.

Among the different visualization methods tested, the 2-D and especially the enhanced 3-D representation, which are both based on kernel density interpolations, proved to be most useful. The spatial patterns exhibited by both visualization methods seem to be in agreement with the Bermuda High Hypothesis. To the best knowledge of the authors, this is

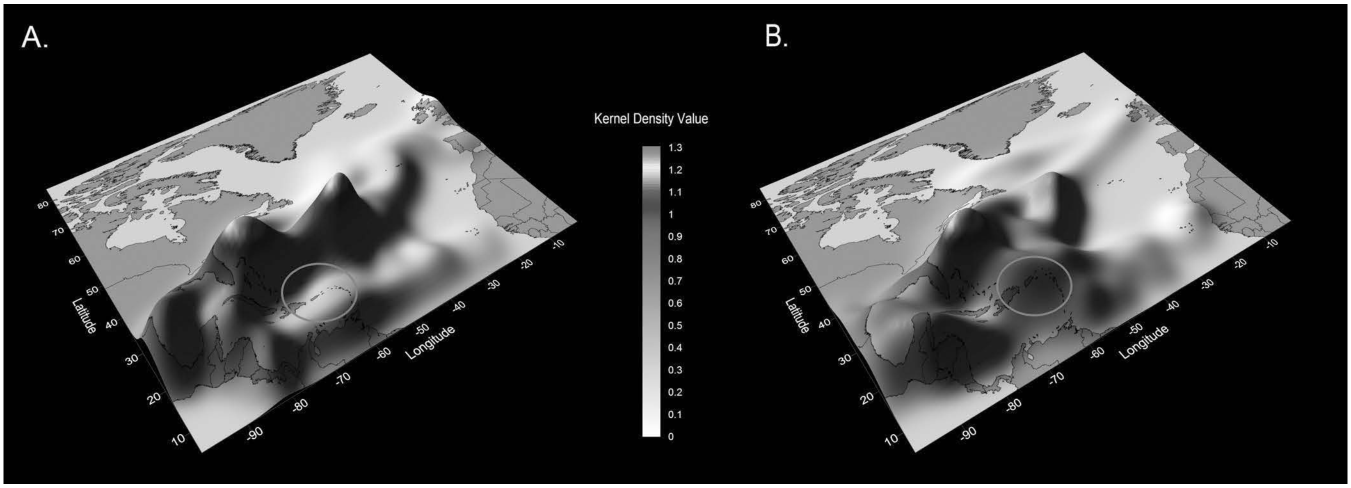

Figure 8. Enhanced 3-D continuous surface display of hurricane tracks derived from kernel density estimations coinciding with a "weak" Bermuda High (8A) and a "strong" Bermuda High (8B). Note: Red circles encompass the Caribbean Antilles and highlight changing risk associated with Bermuda High strength. *(see page 80 for color version)*

the first time that hurricane tracks have been represented in terms of their association with the strength of the Bermuda High using the kernel density estimation method. In general, the approach presented in this research should be useful for detecting spatial patterns in any large data sets that consist of linear features (e.g., migration patterns of birds or fish, urban traffic flows, patterns of drug trafficking or illegal immigration, and many others).

"This is the first time that hurricane tracks have been represented in terms of their association with the strength of the Bermuda High using the kernel density estimation method."

One drawback of the kernel density estimation is that its calculation is more complex and more time-intensive when compared to a traditional choropleth map that displays the density values for a regular grid. In addition, care must be taken when selecting the bandwidth used to calculate the kernel density values. Unfortunately, there is currently no agreement in the literature as to how wide a particular bandwidth should be (Environmental Systems Research Institute, 1999; Diggle, 1981; Williamson *et al.*, 1998).

An alternative approach to the fixed bandwidth is to use different bandwidths in different parts of the study area, an approach known as adaptive kernel estimation (Bailey and Gatrell, 1995). Adaptive kernel estimation is based on sampling theory, giving the choice of bandwidth a consistent level of precision over the entire study region. This is achieved by increasing the bandwidth until a fixed number of points (i.e., minimum sample size) are counted. Accordingly, in areas of high density, small bandwidths are used to show detailed local variation, whereas in areas of low density larger bandwidths smooth the point pattern (Bailey and Gatrell, 1995). Although adaptive kernel estimation solves the problem of determining a value for b, it still leaves open the question of how to set an appropriate minimum sample size. In general, the higher the minimum sample size, the larger the bandwidth and the more the density surface will be smoothed. Suggestions concerning the determination of the appropriate minimum sample size are lacking in the literature.

The main purpose of this research was to explore whether the Bermuda High Hypothesis could be tested using a series of geographic visualization methods. Results indicate that the 2-D and especially the enhanced 3-D display derived from kernel density interpolation seem to visually support the Bermuda High Hypothesis. This is in line with recent public safety (Eck *et al.*, 2005; Brunsdon *et al.*, 2007) and public health studies

(Curtis *et al*., 2005; Curtis and Leitner, 2006) that preferred to visualize large geospatial data sets of discrete (point or line) features that are spatially clustered with the kernel density interpolation method rather then with the choropleth or alternative methods. Although this is one indication that the kernel density interpolation method can "better" visualize large geospatial data sets, no human subject testing has ever been carried out to objectively validate this assumption. Such user studies become increasingly necessary as the kernel density interpolation method is implemented in spatial analysis software that becomes ubiquitously available (e.g., CrimeStat III).

"A more objective analysis is needed to verify the kernel density interpolation method's ability to visualize the relationship between Bermuda High strength and re-curvature of hurricane tracks."

With respect to this current study, a more objective analysis is needed to verify the kernel density interpolation method's ability to visualize the relationship between Bermuda High strength and re-curvature of hurricane tracks. Such an analysis would be the next logical step in this research and can be accomplished either through human subject testing or statistical analysis (e.g., correlation or spatial regression modeling). With regards to user studies, the two main assumptions that should be tested are (1) whether maps derived from kernel density interpolation are indeed "better" ("clearer," "more intuitive") at visualizing this specific relationship as compared to flow, dot, or choropleth maps; and (2) which parameter settings (i.e., bandwidth and kernel function) for the kernel density interpolation method would best visualize the relationship between Bermuda High strength and re-curvature of hurricane tracks. Human subject testing of this relationship would continue the recent resurgence of a long-standing tradition of empirical research in map design as a paradigm for eliciting and formalizing cartographic design knowledge (Leitner and Buttenfield, 2000; Aerts *et al*., 2003; Leitner and Curtis, 2004; Leitner and Curtis, 2006).

ACKNOWLEDGEMENTS

The authors would like to thank the National Science Foundation (Grant #-BCS-0623287) for supporting the continuation of this research. Additionally, the authors would like to express their gratitude to Terry McClosky for his assistance with this research.

REFERENCES

Aerts, J.C.J.H., Clarke, K.C. and Keuper, A.D., 2003. Testing popular visualization techniques for representing model uncertainty. *Cartography and Geographic Information Science*, 30(3):249-261.

Bailey, T.C., and Gatrell, A.C., 1995. *Interactive Spatial Data Analysis*. Essex, UK: Longman.

Brewer, C., 1994. Color use guidelines for mapping and visualization, In MacEachren, A.M. and Taylor, D.R.F. (Eds.) *Visualization in Modern Cartography*, 123-147. Oxford, New York, Tokyo: Elsevier Science.

Brunsdon, C., Corcoran, J. and Higgs, G., 2007. Visualizing space and time in crime patterns: A comparison of methods. *Computers, Environment and Urban Systems*, 31(1): 52-75.

Burt, J.E., and Barber, G.M., 1996. *Elementary Statistics for Geographers*. New York, NY: The Guilford Press.

Campbell, J., 2001. *Map Use and Analysis* (4th ed.). Dubuque, IA: McGraw-Hill.

Collins, E.S., Scott, D.B., and Gayes, P.T., 1999. Hurricane records on the South Carolina coast: Can they be detected in the sediment record? *Quaternary International*, 56:15-26.

Corcoran, J., Higgs, G., Brunsdon, C., Ware, A. and Norman, P., (under review). The use of spatial analytical techniques to explore patterns of fire incidence: A South Wales case study.

Curtis, A., Heath, S., and Hugh-Jones, M., 2005. GIS investigations of epizootics: The limitations of surveillance data, In Majumdar, S.K, Huffman, J., Brenner, F., and Panah, I.A. (Eds.) *Wildlife Diseases: Landscape Epidemiology. Spatial Distribution and Utilization of Remote Sensing Technology*. 459-474. Easton, PA: The Pennsylvania Academy of Science.

Curtis, A. and Leitner, M., 2006. *Geographic Information Systems and Public Health: Eliminating Perinatal Disparity*. Hershey, PA: Idea Group Inc.

Dent, B.D., 1999. *Cartography: Thematic Map Design* (5th ed.). Dubuque, IA: McGraw-Hill.

Diggle, P.J., 1981. Some graphical methods in the analysis of spatial point patterns, In Barnett, V. (Ed.) *Interpreting Multivariate Data*. New York, NY: Wiley.

Donnelly, J.P., Butler, J., Roll. S., Wengren, M., and Webb III, T., 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. *Marine Geology*, 210:107-121.

Donnelly, J.P., Bryant, S.S., Butler, J., Dowling, J., Fan, L., Hausmann, N., Newby, P., Shuman, B., Stern, J., Westover, K., and Webb III, T., 2001a. 700 yr sedimentary record of intense hurricane landfalls in southern New England. *Geological Society of America*, 113:714-727.

Donnelly, J.P., Roll, S., Wengren, M., Butler, J., Lederer, R., Webb III, T., 2001b. Sedimentary evidence of intense hurricane strikes from New Jersey. *Geology*, *29*(7):615-618.

Eck, J., Chainey, S.P., Cameron, J., Leitner, M. and R. Wilson (Eds.) 2005. *Mapping Crime: Understanding Hotspots*. Washington DC: National Institute of Justice.

Elsner, J.B., Liu, K.-b., and Kocher, B., 2000. Spatial variations in major U.S. hurricane activity: Statistics and a physical mechanism. *Journal of Climate*, 12:427-37.

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

Environmental Systems Research Institute, 2005. *ArcGIS, (v 9.0).* Redlands, CA: Environmental Systems Research Institute, Inc.

Environmental Systems Research Institute, 1999. *ArcView® GIS, (v 3.2).* Redlands, CA: Environmental Systems Research Institute, Inc.

Fischer, M.M, Leitner, M., and Staufer-Steinnocher, P., 2001. Spatial point pattern analysis - some useful tools for analyzing locational data. In Department of Geography and Regional Research, University of Vienna (Ed.) *Geographischer Jahresbericht aus Österreich*, Vol. 58:49-65. Vienna, Austria: Department of Geography and Regional Research.

Golden Software, 2003. *Surfer (v 8.03)*. Golden, CO: Golden Software, Inc.

Groff, E.R. and McEwen, T., 2006. *Visualization of Spatial Relationships in Mobility Research: A Primer*. Final Report (NCJ 214255). Alexandria, VA: Institute for Law and Justice.

Kelsall, J.E., and Diggle, P.J., 1995. Kernel estimation of relative risk. *Bernoulli*, 1:3-16.

Knowles, J.T., 2006. *Visual Representations of the Spatial Correlation Between Bermuda High Strengths and Tropical Cyclone Tracks*. Student Illustrated Paper Contest (3rd place). Chicago, IL: Association of American Geographers Annual Meeting.

Leitner, M. and Buttenfield, B.P., 2000. Guidelines for the display of attribute certainty. *Cartography and Geographic Information Science*, 27(1):3-14.

Leitner, M. and Curtis, A., 2006. A first step towards a framework for presenting the location of confidential point data on maps - results of an empirical perceptual study. *International Journal of Geographical Information Science*, 20(7):813-822.

Leitner, M. and Curtis, A., 2004. Cartographic guidelines for geographically masking the location of confidential point data. *Cartographic Perspectives*, 49:22-39.

Leitner, M. And Staufer-Steinnocher, P., 2002. Spatio-temporal changes in the Vienna food retailing market, In Strobl, J., Blaschke, T. and Griesebner, G. (Eds.) *Applied Geographic Information Technology XIV*, 308-317. Heidelberg, Germany: Herbert Wichmann Publishing.

Levine, N., 2004. *CrimeStat: A Spatial Statistics Program fop the Analysis of Crime Incident Locations (v 3.0)*. Houston, TX: Ned Levine & Associates and Washington, DC: The National Institute of Justice.

Liu, K.-b., 2004. Paleotempestology: Principles, methods, and examples from Gulf Coast lake sediments, In Murnane, R.J. and Liu, K.-b. (Eds.) *Hurricanes and Typhoons: Past, Present, and Future*, 13-57. New York, NY: Columbia University Press.

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

Liu, K.-b., and Fearn, M.L., 2000a. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. *Quaternary Research*, 54:238-245.

Liu, K.-b., and Fearn, M.L., 2000b. Holocene history of catastrophic hurricane landfalls along the Gulf of Mexico Coast reconstructed from coastal lake and marsh sediments, In Ning, Z.H. and Adbollahi, K.K (Eds.) *Current Stresses and Potential Vulnerabilities: Implications of Global Change for* *the Gulf Coast Region of the United States*, 38-47. Baton Rouge, LA: Franklin Press, Inc.

Lu, H.Y., and Liu, K.-b., 2005. Phytolith assemblages as indicators of coastal environmental changes and hurricane overwash deposition. *The Holocene*, 15(7):965-972.

Meynen, E. (Ed.) 1973. *Multilingual Dictionary of Technical Terms in Cartography*. International Cartographic Association, Commission II. Wiesbaden, Germany: Franz Steiner Publishing.

Muehrcke, P.C., Muehrcke, J.O., and Kimerling, A.J., 2001. *Map Use: Reading, Analysis, Interpretation* (4th ed., revised). Madison, WI: J.P. Publications.

Portis, D.H., Walsh, J.E, Hamly, M.E., and Lamb P.J., 2001. Seasonality of the North Atlantic Oscillation. *Journal of Climate*, 14:2069-2078.

Robinson, A.H., Morrison, J.L., Muehrcke, P.C., Kimerling, A.J., and Guptill, S.C., 1995. *Elements of Cartography* (6th ed.). New York, NY: Wiley.

Scott, D.B., Collins, E.S., Gayes, P.T., and Wright, E., 2003. Records of prehistoric hurricanes on the South Carolina coast based on micropaleontological and sedimentological evidence, with comparison to other Atlantic Coast records. *Geological Society of America*, 115(9):1027-1039.

Slocum, T.A., McMaster, R.B., Kessler, F.C. and Howard, H.H., 2005. *Thematic Cartography and Geographic Visualization* (2nd ed.). Upper Saddle River, NJ: Pearson/Prentice Hall.

Tobler, W.R., 1987. Experiments in migration mapping by computer. *The American Cartographer*, 14(2):155-163.

Williamson, D., McLafferty, S., Goldsmith, V., McGuire, P., Mollenkopf, J., 1998. Smoothing crime incident data: New methods for determining the bandwidth in kernel estimation. *Proceedings of the 18th Annual ESRI International User Conference*, http://gis.esri.com/library/userconf/proc98/PROCEED.HTM, last accessed 11/01/2006.