ELSEVIER

Marine Geology 210 (2004) 7–15

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Spatial and temporal variability of coastal storms in the North Atlantic Basin

Barry D. Keim[a,b,*], Robert A. Muller[b], Gregory W. Stone[c]

[a] *Southern Regional Climate Center, Louisiana State University, Baton Rouge, LA 70803, USA*
[b] *Department of Geography and Anthropology, Louisiana State University, Baton Rouge, LA 70803, USA*
[c] *Department of Oceanography and Coastal Sciences, Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803, USA*

Received 10 June 2002; received in revised form 24 November 2003; accepted 3 May 2004

Abstract

Over the past three to four decades, there has been a growing awareness of the important controls exerted by large-scale meteorological events on coastal systems. For example, definitive links are being established between short-term (timescales of 5–10 years) beach dynamics and storm frequency. This paper assesses temporal variability of coastal storms (both tropical and extratropical) and the wave climatology in the North Atlantic Basin (NAB), including the Gulf of Mexico. With both storm types, the empirical record shows decadal scale variability, but neither demonstrates highly significant trends that can be linked conclusively to natural or anthropogenic factors. Tropical storm frequencies have declined over the past two or three decades, which is perhaps related to recent intense and prolonged El Niños. Some forecasts predict higher frequencies of tropical storms like that experienced from the 1920s to the 1960s to occur in coming decades. Results from general circulation models (GCMs) suggest that overall frequencies of tropical storms could decrease slightly, but that there is potential for the generation of more intense hurricanes. These data have important implications for the short-term evolution of coastal systems.

There is strong suggestion that extratropical systems have declined overall over the past 50–100 years, but that there is an increase in frequency of very powerful storms, especially at higher latitudes. Both ENSO and the North Atlantic Oscillation (NAO) are shown to have associations with frequencies and tracking of these systems. These empirical results are in general agreement with GCM forecasts under global warming scenarios. Analyses of wave climatology in the NAB show that the last two to three decades have been rougher at high latitudes than several decades prior, but this more recent sea state is similar to conditions from about 100 years ago. The recent roughness at sea seems to be related to high NAO index values, which are also expected to increase with global warming. Thus, when coupled to an anticipated continued rise in global sea level, this trend will likely result in increasing loss of sediment from the beach-nearshore system resulting in widespread coastal erosion.

Keywords: temporal variability; tropical storms; extratropical storms; wave climatology

1. Introduction

In recent years, there has been a concerted effort to establish definitive links between large-scale me-

* Corresponding author.
E-mail address: keim@lsu.edu (B.D. Keim).

0025-3227/$ - see front matter
doi:10.1016/j.margeo.2003.12.006

teorological events and the short-term (decadal scale) evolution of coasts (Stone et al., 1997; Muller and Stone, 2001; Ranasinghe et al., 2004; Stone et al., 2004; Pepper and Stone, 2004). In terms of environmental and economic impacts, coastal storms are among the most significant on earth. Although wind speeds in coastal storms are less than the most severe tornadoes, the scale and duration of these events are much larger, which are compounded by the generation of damaging waves that propagate far beyond the region of wind stress. Along low-lying coastal zones, storm surges can extend damage even further inland. As a result, impacts of these storms are significant to both the coastal morphodynamics and the large population base that inhabit the coastal zone. This paper will assess the spatial and temporal variability of coastal storms in the North Atlantic Basin (NAB), including the Gulf of Mexico. It will include examination of tropical and extratropical storms, both of which occur in this region, as well as the wave climatology of the basin. Empirical studies over the past century, as well as recent modeled results of future climates, are both addressed. Implications for coastal systems are assessed for the areas under study.

2. Observed trends in tropical cyclones

Tropical cyclones are storms that generally form and intensify over warm tropical water surfaces and then frequently travel poleward. In the NAB, these events can occasionally have their origins traced back to the coast of northwestern Africa, where clusters of thunderstorms begin to take on cyclonic circulations. These thunderstorms initially become tropical waves, which can then intensify to tropical storm or hurricane strength under particular atmospheric and oceanic conditions. A tropical cyclone can be defined as a low-pressure, synoptic-scale system that is warm-cored and nonfrontal (Neumann et al., 1993), occurring from June to November, with a peak in September. During development in the NAB, these storms drift westward at tropical latitudes within the easterly trade winds, then often turn northward, tracking around the Atlantic Subtropical High (Davis et al., 1997) to affect the eastern United States and occasionally even western Europe (Fig. 1), e.g., Tropical Storm Andrew in 1986 and Hurricane Bob in 1991 (Neumann et al., 1993). Along this trajectory, it is common for tropical cyclones to transform into extratropical systems, especially north of 35°N latitude. Although these transformed cyclones rarely regain their former strength, over half of these systems undergo posttransition intensification and are most likely to impact the northeastern United States and Canadian Maritimes (one to two storms per year) and western Europe (once every 1–2 years) (Hart and Evans, 2001). Fig. 1 depicts all the tropical storm tracks from 1886 to 1992 during the latter part of August (August 21–31). The classic parabolic curved path is clearly evident here as storms drift from east to west in the trade winds, then drift poleward until steered by the westerlies, where they travel from west back to east at higher latitudes.

Empirical analyses of tropical storm and hurricane strikes along the coasts of the United States over the past century show that particular coastal segments are exposed to recurring strikes, e.g., southeastern Louisiana, southern Florida, and eastern North Carolina (14–17 events over the 100-year record), and that other coastal segments rarely experience direct hurricane strikes, e.g., the Sea Islands of Georgia (1 in 100 years) and the northeastern margin of the Gulf of Mexico in the vicinity of Cedar Keys, Florida (3 in 100 years) (Muller and Stone, 2001). For the NAB, multidecadal variability in frequencies is more characteristic than linear trends (Landsea et al., 1999). For example, Bove et al. (1998a,b) found no trends in hurricane frequencies and intensities in the Gulf of Mexico basin from 1886 to 1995. However, regarding total NAB hurricane activity, the early 1900s to the 1920s was a relatively quiet period, the late 1920s to the 1960s was active, and the 1970s through the early 1990s was relatively quiet again (Landsea et al., 1992). Muller and Stone (2001) also showed that the Cape Hatteras region, southern Florida, the northern Gulf Coast, and southern Texas all experienced different clusters of years and even decades with frequent or infrequent storm strikes. Gray (1990) attributed these decadal and geographical scale oscillations to shifts in sea surface temperatures (SSTs), where above-normal SSTs in the NAB, coupled with below-normal SSTs in the South Atlantic, are most conducive to intense hurricane formation in the NAB.

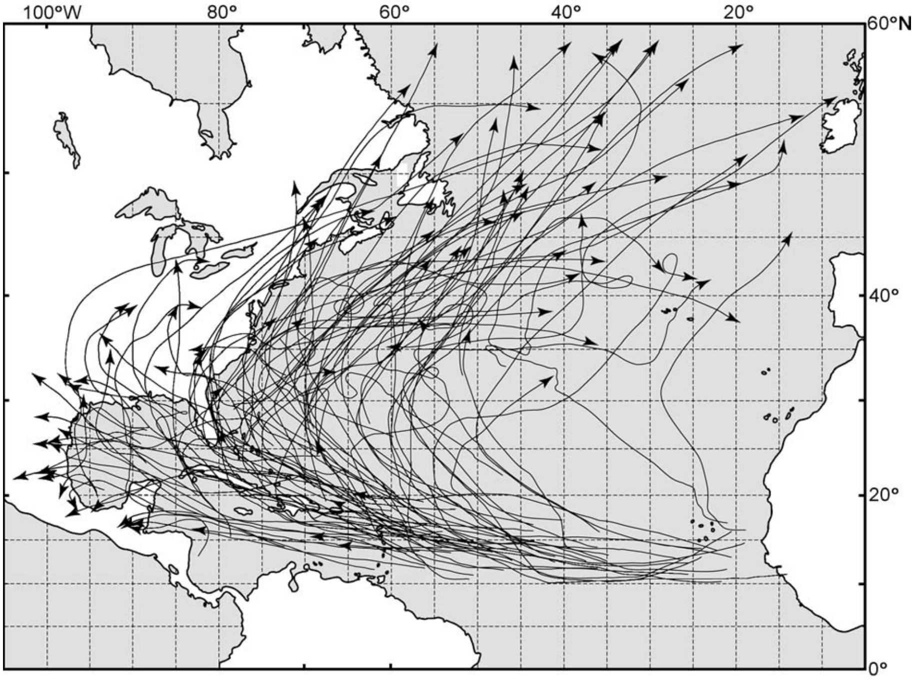

Fig. 1. Tracking of all tropical storms and hurricanes from August 21 to 31 for the years 1886–1992. Adapted from Neumann et al. (1993).

Zhang et al. (2000) analyzed storm surge data along the U.S. East Coast and also found similar decadal scale variability, but also reported that sea-level rise over the past century has exacerbated impacts of these events over time.

The El Niño Southern Oscillation is also linked to frequencies of NAB tropical cyclone activity. Goldenberg and Shapiro (1996) demonstrated that warm phase (El Niño) conditions in the eastern Pacific Ocean coupled with drought in the African Sahel operate together to increase potential for westerly vertical wind shear. This creates unfavorable conditions for hurricane formation in the NAB. Furthermore, Bove et al. (1998a,b) showed that the annual probability of a major hurricane landfall in the United States is 23% during a (warm phase) El Niño season, 58% during neutral conditions, and 63% during cold-phase (La Niña) conditions. Similarly, Pielke and Landsea (1999) found that hurricane-induced damage is associated with ENSO, with La Niña hurricane seasons exhibiting significantly more damage than during hurricane seasons occurring with an El Niño.

3. Model studies of tropical storms

Modeled studies of tropical cyclone activity may give us some indication as to how these storms may change in frequency and magnitude as the overall global climate changes. For example, Hobgood and Cerveny (1988) used the Goddard Institute for Space Studies general general circulation model (GCM) run of the last glacial maximum conditions of 18,000 years BP. They concluded that this atmosphere had potential to support tropical cyclone development, but such tropical storms would have been weaker than modern tropical storms. Using this same concept of implementation of GCMs, there have been several studies that attempted to assess the impacts of potential global warming on tropical cyclone activity. Emanuel (1987) used a GCM to simulate global warming conditions in August and concluded that there may be up to a 40–50% increase in the destructive potential of hurricanes at that time of year. Bengtsson et al. (1996) concluded that a doubling of CO_2 on earth would not likely change the geographical patterns and seasonality of storms, but that the overall number of events was significantly reduced in their model run. Despite this conclusion, they also suggested that more powerful storms could result, which is in general agreement with Emanual (1987). Similarly, Haarsma et al. (1992) found an increase in the frequency and magnitude of the most intense tropical cyclones in their GCM run, although they did caution that GCMs do not resolve tropical cyclones adequately. They found that GCM-simulated tropical cyclones are generally weaker in intensity and have larger horizontal extent than modern storms, but the simulated storms do display the basic physics of tropical cyclones.

Broccoli and Manabe (1990) raised the question as to how useful GCM results are when used to predict future tropical cyclone activity. Although they admit that their model resolution is insufficient to reproduce the fine structures exhibited by tropical cyclones, they concluded that given the models' ability to qualitatively simulate tropical storm climatologies, the answer is yes. However, Henderson-Sellers et al. (1998) argued that the coarse resolution of modern GCMs greatly limits their results. In lieu of GCMs, they instead analyzed recent thermodynamical estimation of tropical cyclone maximum potential intensities (MPI). The MPI is an estimation of the possible strength of a hurricane resulting from available energy from both atmosphere and ocean. Modern estimates are made from monthly mean atmospheric temperature soundings at radiosonde sites, combined with sea surface temperatures, whereas forecasts are informed with GCM input. Recent studies suggest that hurricane MPI will remain the same or increase modestly (up to 10–20%) with global warming (Henderson-Sellers et al., 1998).

4. Observed trends in extratropical cyclones

Whereas tropical cyclones develop over warm tropical oceans, extratropical cyclones, also called mid-latitude cyclones, evolve along the polar front, which is defined as a semicontinuous boundary in the mid-latitudes that separates cold polar air masses from warm subtropical air masses (Ahrens, 2000). Three-dimensional interactions between these contrasting air masses provide the needed dynamics for development of extratropical storms. Cyclogenesis takes place in regions of baroclinicity, where winds blow across isothermal patterns to produce temperature advection. In other words, a baroclinic zone has warm air transport into a region that is colder, while adjacent cold air is transported into a region that is warmer. The polar front resides below the baroclinic zone, separating cold polar air from warm tropical air at the surface, while the jet stream resides aloft. This type of atmospheric setting is conducive to the formation of extratropical cyclones (cyclogenesis) and occurs frequently during colder months on the lee side of the Rocky Mountains, over the northwestern Gulf of Mexico along the Texas Coast, and especially off Cape Hatteras, North Carolina where colder air from the continent meets much warmer air over the warmer ocean (Fig. 2). Along the East Coast of North America, there are noteworthy secondary points of cyclogenesis off of Cape Cod, Massachusetts, and Nova Scotia, Canada (Fig. 3) (Bradbury et al., 2003).

Mather et al. (1964) were the first to classify storms along the East Coast of the United States. They developed eight classes of storms, of which one represented tropical events, while the remaining seven classes were all extratropical cyclonic systems. Coastal storms of moderate intensity or greater should be expected once every 1.4 years in New York and New Jersey and once every 4.2 years in Georgia. Mather et al. (1967) also reported a high number of damaging storms along the East Coast of the United States in late 1950s and early 1960s as compared to the 1930s through early 1950s. Davis and Dolan (1993a) have also examined United States East Coast storm frequencies. They concluded that storm frequencies

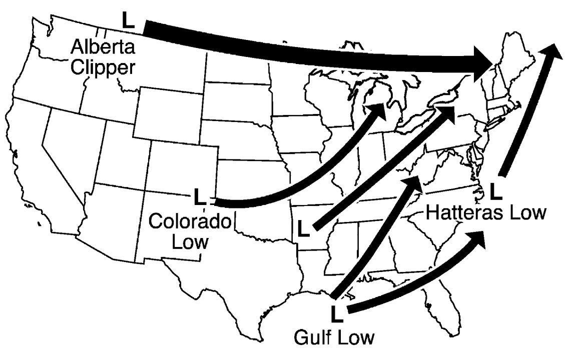

Fig. 2. Primary areas of cyclogenesis in North America. Adapted from Ahrens (2000).

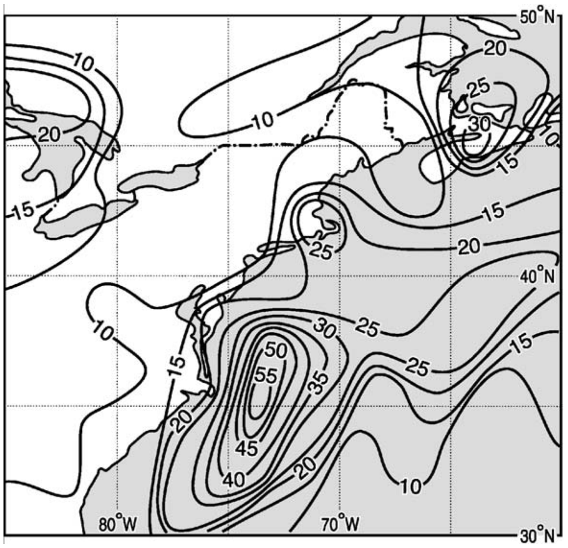

Fig. 3. Total cyclogenesis occurrences (1958–2000) along the northeastern coast of the United States. Adapted from Bradbury et al. (2003).

declined from the mid-1960s to mid-1970s, then increased through 1984, but the frequency of the most severe damaging storms had increased throughout the period of record (1942–1992). The overall decrease in storm frequencies was also observed by Reitan (1979) and Zishka and Smith (1980), who reported a general trend toward decreasing cyclone frequencies over the continent of North America. However, somewhat contradictory results were reported by Agee (1991), who found that there was a positive correlation between northern hemisphere temperature and cyclone frequencies, citing higher frequencies during the warming period from 1905 to 1940 (at least in the United States) and reduced frequencies during the cooler period from 1940 to 1977.

Hirsch et al. (2001) reported that, on average, 12 East Coast winter storms occur per winter season, with a maximum in January. Significant trends (1951–1995) were not evident. However, a marginally significant (alpha = 0.10) decrease in average storm minimum pressure was noted. They also concluded that the average monthly winter storm frequency anomalies are significantly higher during El Niño months over the October–April storm season. Winter storms showed little or no change in frequencies during La Niña months. DeGaetano et al. (2002) took this research a step further and noted that United States East Coast storms are related to both El Niño and the North Atlantic Oscillation (NAO) phases, as heightened storm activity tends to occur during the positive phase of the NAO in conjunction with El Niño conditions. However, Joyce (2002) cautioned that the recent (post-1960) associations between the NAO and climate in the eastern United States may be overestimated because the relationship was not as robust earlier in the 20th century and was nonexistent in the latter portion of the 19th century.

McCabe et al. (2001) concluded that cyclones in the middle latitudes (30–60°N) in the northern hemisphere have significantly declined in frequency, but have increased significantly at higher latitudes (60–90°N), suggesting that extratropical cyclonic activity has shifted poleward due to hemispheric warming (Fig. 4). In addition, they reported that severe storm intensity has increased at both middle and high latitudes, which corroborated results of Davis and Dolan (1993a).

Schmith et al. (1998) studied winter storminess using mean sea level pressure data over the Northeast Atlantic. They reported decadal scale variations and large geographical variability in storms. They concluded that a modest increase in storminess over the

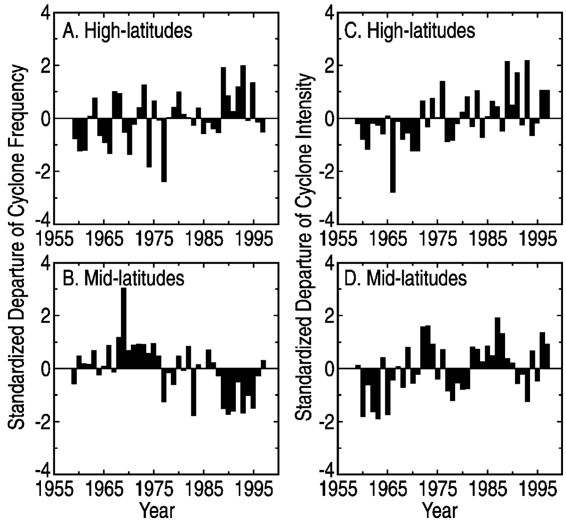

Fig. 4. Northern hemisphere standardized departures of winter (November–March) cyclone counts at (A) high latitudes and (B) mid-latitudes, as well as for intensity (C) high latitudes and (D) mid-latitudes. Adapted from McCabe et al. (2001).

past two to three decades occurred in the region of Scandinavia, but this was less detectable in and near the United Kingdom, supporting results of McCabe et al. (2001). Overall, they found modest increases in winter storminess over the Northeast Atlantic from 1875 to 1995. Andrade et al. (2004) examined storms in the Azores and found high frequencies of storms from about 1875 to 1905, very low frequencies in the 1920s to the early 1940s, then returning to a regime of higher frequencies, peaking around 1980.

Although a few studies have actually analyzed wind data, Siegismund and Schrum (2001) reported a substantial increase in average annual wind over the North Sea: about a 10% increase from 1958 to 1997. Pirazzoli et al. (2004) also examined wind data in western France and found increasing occurrences of strong winds in western Brittany, but decreasing trends in Normandy and Pays de Loire.

5. Model studies of extratropical cyclones

In agreement with Schmith et al. (1998), GCM simulations of increasing CO_2 indicated heightened storminess in the Northeast Atlantic, as well as in northwestern Europe because of a potential intensification and eastward extension of the North Atlantic storm track (Carnell et al., 1996). Schrum (2001) also demonstrated that a high North Atlantic Oscillation (NAO) Index results in an intensification of cyclonic circulation in both the Baltic and North Seas and that under a global warming scenario, the NAO index values are expected to rise. Furthermore, Lambert (1995) reported that in a $2 \times CO_2$ GCM simulation, there is a reduction in the total number of winter cyclones in both hemispheres, but the frequency of intense cyclones increases, especially in the Northern Hemisphere, which is clearly in general agreement with the empirical record. Lozano et al. (2004) further support these findings by reporting that the Ireland–Scotland region may experience fewer, but more powerful storms in a future dominated by global warming.

6. Wave climatology of the North Atlantic Basin

Most significant ocean waves are generated from wind stress, either from tropical or extratropical storms. There is a body of literature that places primary focus on the waves and may or may not address the storms that generated the waves. Dolan and Davis (1992), for example, devised a rating system for northeasters based on significant wave heights (SWH) and storm duration. The scale is similar to the Saffir/Simpson hurricane scale ranging from Dolan/Davis 1 (minor beach erosion) to a Dolan/Davis 5 (extreme beach erosion). Although their dataset ends in 1992, they concluded that Class 4 and 5 northeasters appeared to be increasing in frequency (Davis and Dolan, 1993a), though this result was not statistically significant (Keim and Cruise, 1998). Davis and Dolan (1993b) also classified northeasters into eight types based on the origins of the storms. Bahamas Lows and Florida Lows were found to be rare, but produced the greatest wave heights along the East Coast of the United States. Kushnir et al. (1997) reported an increasing trend in significant wave heights (SWH) at several Northeast Atlantic locations since 1960. They believe this trend is related to the systematic deepening of the Icelandic low and intensification of the Azores high over the last three decades, leading to high positive NAO values. The analysis suggests that wave height south of 40°N has decreased during the same period.

Wang and Swail (2001) concluded that over the past four decades, statistically significant changes in the seasonal extremes of SWH in the North Atlantic (NA) were evident, but only for the winter (January–March) season. The geographical pattern of these findings was that the northeastern North Atlantic had significant increases in SWH, while significant decreases were found in the subtropical North Atlantic. The temporal patterns were also associated with phases and intensity of the North Atlantic Oscillation (NAO). Wang and Swail (2002) confirmed their previous results and showed that the northeast North Atlantic Ocean has experienced significant multidecadal variations in wave height activity over the last century, and it has indeed roughened in winters of the last four decades. This detailed Atlantic hindcast shows more significant increases in wave heights in the region off the Canadian coast in summer and fall; and in winter, it shows higher rates of increases in the region northwest of Ireland, but less significant changes in the North Sea and in the region off the Scandinavian coast.

The WASA Group (1998) pointed out that inhomogeneities in the empirical data are a major methodological obstacle in wave hindcasting. However, their main conclusions in this research were that decadal scale variations are evident in the record, the northeastern Atlantic has indeed roughened in recent decades, but that recent wave climates are comparable to the climatology around the turn of the 20th century, and that at least part of this variability is associated with the NAO.

7. Discussion and summary

With both tropical and extratropical storms, the empirical record shows decadal scale variability, but data for both of these storm systems tend to lack highly significant trends that can be linked conclusively to natural or anthropogenic factors. Tropical storm frequencies have shown decadal variability, whereas the past two or three decades have had reduced frequencies. This is probably the result of recent intense and prolonged El Niños, which create environments that are not conducive to the formation of tropical systems in the NAB. However, there are signs that hurricanes may be increasing in frequency again, and some forecasts for the next few decades are predicting higher frequencies like that experienced from the 1920s to the 1960s (Gray, 1999). Results from GCMs about future tropical cyclone climatologies are mixed, but there is a suggestion that overall frequencies of tropical storms could decrease slightly, but that there is potential for the generation of more intense hurricanes. Broccoli and Manabe (1990) concluded that GCMs are qualitatively appropriate tools to assess anthropogenic changes in tropical systems, though there is no general agreement in the literature.

There is strong suggestion that extratropical systems in the NAB have declined overall over the past 50–100 years, but that there is an increase in frequency of really powerful storms. Some geographical variability is apparent in these trends, whereas higher latitudes in the northern hemisphere are experiencing upward trends in cyclone frequencies, including the regions off of the eastern Canadian coast, Iceland, and Scandinavia, while decreasing trends are more evident at middle latitudes. Both ENSO and the NAO have impacts on frequencies and tracking of these systems. These empirical results are in general agreement with GCM forecasts under global warming scenarios, as extratropical storms are expected to displace northward along with the jet stream and regions of baroclinicity. Analyses of wave climatology in the NAB show that the last two to three decades have been rougher at high latitudes than several decades prior, but this more recent sea state is similar to conditions about 100 years ago. The recent roughness at sea seems to be related to high NAO index values, which are also expected to increase with global warming.

These findings have important implications for the short-term evolution of coasts particularly if an increase in the frequency and/or intensity of hurricanes occurs. As an example, barrier and beach ridge coasts along the northeast Gulf of Mexico have demonstrated stability over periods approximating two decades when tropical cyclone activity was very low (from the 1970s to the mid-1990s). This sand-rich stretch of coast offsets rises in sea level during that period. However, with the onset of a pronounced period of storminess, which occurred post-1995 (Stone et al., 2004), a significant erosional trend was observed. The same response would be anticipated along the NAB where an increase in frequency of very powerful storms may occur. Over longer timescales (millennia), the incidence and intensity of storms will play an increasingly important role in the morphodynamic evolution of coasts during periods of 'stillstands' in sea level, particularly in the transgressive evolution and migration of coasts across the shelf.

References

Agee, E.M., 1991. Trends in cyclone and anticyclone frequency and comparison with periods of warming and cooling over the Northern Hemisphere. Journal of Climate 4, 26–263.

Ahrens, C.D., 2000. Meteorology Today, 6th ed. Brooks/Cole Thomson Learning, Pacific Grove, CA.

Andrade, C., Freitas, M.C., Moreno, J., Craveiro, S.C., 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. Mar. Geol. 210, 339–362.

Bengtsson, L., Botzet, M., Esch, M., 1996. Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? Tellus 48A, 57–73.

Bove, M.C., Elsner, J.B., Landsea, C.W., Niu, X., O'Brien, J.J., 1998a. Effect of El Niño on U.S. landfalling hurricanes revisited. Bulletin of the American Meteorological Society 79, 2477–2482.

Bove, M.C., Zierden, D.F., O'Brien, J.J., 1998b. Are Gulf landfalling hurricanes getting stronger? Bulletin of the American Meteorological Society 79, 1327–1328.

Broccoli, A.J., Manabe, S., 1990. Can existing climate models be used to study anthropogenic changes in tropical cyclone climate. Geophysical Research Letters 17, 1917–1920.

Bradbury, J.A., Keim, B.D., Wake, C.P., 2003. The influence of regional storm tracking and teleconnections on winter precipitation in the northeastern United States. Annals of the Association of American Geographers 93 (3), 544–556.

Carnell, R.E., Senior, C.A., Mitchell, J.F.B., 1996. An assessment of measures of storminess: simulated changes in the Northern Hemisphere winter due to increasing CO_2. Climate Dynamics 12, 467–476.

Davis, R.E., Dolan, R., 1993a. Nor'easters. American Scientist 81, 428–439.

Davis, R.E., Dolan, R., 1993b. Synoptic climatology of Atlantic Coast northeasters. International Journal of Climatology 13, 171–189.

Davis, R.E., Hayden, B.P., Gay, D.A., Phillips, W.L., Jones, G.V., 1997. The North Atlantic subtropical anticyclone. Journal of Climate 10 (4), 728–744.

DeGaetano, A.T., Hirsch, M.E., Colucci, S.J., 2002. Statistical prediction of seasonal east coast winter storm frequency. Journal of Climate 15, 1101–1117.

Dolan, R., Davis, R.E., 1992. Rating northeasters. Mariners Weather Log, Winter, 4–11.

Emanuel, K.A., 1987. The dependence of hurricane intensity on climate. Nature 326, 483–485.

Goldenberg, S.B., Shapiro, L.J., 1996. Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. Journal of Climate 9, 1169–1187.

Gray, W.M., 1990. Strong association between West African rainfall and US landfall of intense hurricanes. Science 249, 1251–1256.

Gray, W.M., 1999. On the causes of multi-decadal climate change and prospects for increased Atlantic Basin hurricane activity in coming decades. 10th Symposium on Global Change Studies. American Meteorological Society, pp. 183–186. Preprint.

Haarsma, R.J., Mitchell, J.F.B., Senior, C.A., 1992. Tropical disturbances in a GCM. Climate Dynamics 8, 247–257.

Hart, R.E., Evans, J.L., 2001. A climatology of the extratropical transition of Atlantic tropical cyclones. Journal of Climate 14, 546–564.

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P., McGuffie, K., 1998. Tropical cyclones and global climate change: a post-IPCC assessment. Bulletin of the American Meteorological Society 79, 19–38.

Hirsch, M.E., DeGaetano, A.T., Colucci, S.J., 2001. An east coast winter storm climatology. Journal of Climate 14, 882–899.

Hobgood, J.S., Cerveny, R.S., 1988. Ice-age hurricanes and tropical storms. Nature 333, 243–245.

Joyce, T.M., 2002. One hundred plus years of wintertime climate variability in the eastern United States. Journal of Climate 15, 1076–1086.

Keim, B.D., Cruise, J.F., 1998. A technique to measure trends in the frequency of discrete random events. Journal of Climate 11, 848–855.

Kushnir, Y., Cardone, V.J., Greenwood, J.G., Cane, M.A., 1997. The recent increase in North Atlantic wave heights. Journal of Climate 10, 2107–2113.

Lambert, S.J., 1995. The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. Journal of Climate 8, 1447–1452.

Landsea, C.W., Gray, W.M., Meilke Jr., P.W., Berry, K.J., 1992. Long-term variations of West Sahelian monsoon rainfall and intense U.S. landfalling hurricanes. Journal of Climate 5, 1528–1534.

Landsea, C.W., Pielke Jr., R.A., Mestas-Nunez, A.M., Knaff, J.A., 1999. Atlantic basin hurricanes: indices of climate changes. Climatic Change 42, 89–129.

Lozano, I., Devoy, R.J.N., May, W., Andersen, U., 2004. Storminess and vulnerability along the Atlantic coastlines of Europe: analysis of storm records and greenhouse gases induced climate scenario, Mar. Geol. 210, 205–225 (this issue).

Mather, J.R., Adams III, J., Yoshioka, G.A. 1964. Coastal storms of the Eastern United States. Journal of Applied Meteorology 3, 693–706.

Mather, J.R., Field, R.T., Yoshioka, G.A., 1967. Storm damage hazard along the East Coast of the United States. Journal of Applied Meteorology 6, 20–30.

McCabe, G.J., Clark, M.P., Serreze, M.C., 2001. Trends in Northern Hemisphere surface cyclone frequency and intensity. Journal of Climate 14, 2763–2768.

Muller, R.A., Stone, G.W., 2001. A climatology of tropical storm and hurricane strikes to enhance vulnerability prediction for the southeast US coast. Journal of Coastal Research 17, 949–956.

Neumann, C.J., Jarvinen, B.R., McAdie, C.J., Elms, J.D., 1993. Tropical Cyclones of the North Atlantic Ocean, 1871–1992. Historical Climatology Series, vol. 6–2. National Climatic Data Center, Asheville, NC.

Pepper, D.A., Stone, G.W., 2004. Hydrodynamic and sedimentary responses to two contrasting winter storms on the inner shelf of the northern Gulf of Mexico, USA. Marine Geology 210, 43–62 (this issue).

Pielke Jr., R.A., Landsea, C.N. 1999. La Niña, El Niño, and Atlantic hurricane damages in the United States. Bulletin of the American Meteorology Society 80, 2027–2033.

Pirazzoli, P.A., Regnauld, H., Lamasson, L., 2004. Changes in storminess and surges in western France during the last century. Mar. Geol. 210, 307–323 (this issue).

Ranasinghe, R., McLoughlin, R., Short, A., Symonds, G., 2004. The Southern Oscillation Index, wave climate, and beach rotation. Marine Geology 204, 273–287.

Reitan, C.H., 1979. Trends in the frequencies of cyclone activity over North America. Monthly Weather Review 107, 1684–1688.

Schmith, T., Kaas, E., Li, T.-S., 1998. Northeast Atlantic winter storminess 1875–1995 re-analysed. Climate Dynamics 14, 529–536.

Schrum, C., 2001. Regionalization of climate change for the North Sea and Baltic Sea. Climate Research 18, 31–37.

Stone, G.W., Grymes, J.M., Dingler, J.R., Pepper, D.A., 1997. Overview and significance of hurricanes on the Louisiana coast USA. Journal of Coastal Research 13 (3), 656–669.

Stone, G.W., Liu, B., Pepper, D.A., Wang, P., 2004. The importance of extratropical and tropical cyclones on the short-term evolution of barrier islands along the northern Gulf of Mexico, USA. Marine Geology 210, 63–78 (this issue).

Siegismund, F., Schrum, C., 2001. Decadal changes in the wind forcing over the North Sea. Climate Research 18, 39–45.

Wang, X.L.L., Swail, V.R., 2001. Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. Journal of Climate 14, 2204–2221.

Wang, X.L.L., Swail, V.R., 2002. Trends in Atlantic wave extremes as simulated in a 40-year wave hindcast using kinematically reanalyzed wind fields. Journal of Climate 15, 1020–1035.

WASA Group, 1998. Changing waves and storms in the Northeast Atlantic. Bulletin of the American Meteorological Society 79, 741–760.

Zhang, K., Douglas, B.C., Leatherman, S.P., 2000. Twentieth-century storm activity along the U.S. East Coast. Journal of Climate 13, 1748–1761.

Zishka, K.M., Smith, P.J., 1980. The climatology of cyclones and anticyclones over North America and Surrounding Ocean Environs for January and July, 1950–1977. Monthly Weather Review 108, 387–401.