Caribbean coral tracks Atlantic Multidecadal Oscillation and past hurricane activity

Steffen Hetzinger*
Miriam Pfeiffer
Wolf-Christian Dullo
Leibniz Institut für Meereswissenschaften, IFM-GEOMAR, Wischhofstrasse 1-3, 24148 Kiel, Germany
Noel Keenlyside
Mojib Latif
Leibniz Institut für Meereswissenschaften, IFM-GEOMAR, Düsternbrooker Weg 20, 24105 Kiel, Germany
Jens Zinke Vrije Universiteit Amsterdam, FALW, De Boelelaan 1085, 1081 HV, Amsterdam, Netherlands

ABSTRACT

It is highly debated whether global warming contributed to the strong hurricane activity observed during the last decade. The crux of the recent debate is the limited length of the reliable instrumental record that exacerbates the detection of possible long-term changes in hurricane activity, which naturally exhibits strong multidecadal variations that are associated with the Atlantic Multidecadal Oscillation (AMO). The AMO, itself a major mode of climate variability, remains also poorly understood because of limited data. Here, we present the first coral-based proxy record (δ^{18}O) that clearly captures multidecadal variations in the AMO and the hurricane activity. Our record, obtained from a brain coral situated in the Atlantic hurricane domain, is equally sensitive to variations in sea surface temperature (SST) and seawater δ^{18}O, with the latter being strongly linked to precipitation, by this means amplifying large-scale climate signals in coral δ^{18}O. The SST and precipitation signals in the coral provide the longest, thus far, continuous proxy-based record of hurricane activity that interestingly exhibits a long-term increase over the last century. As multidecadal SST variations in this region are closely related to the AMO, this study raises new possibilities to extend the limited observations and to gain new insights into the mechanisms underlying the AMO and long-term hurricane variations.

Keywords: oxygen isotopes, Caribbean Sea, corals, Atlantic Multidecadal Oscillation, hurricane activity.

INTRODUCTION

The 2005 hurricane season gave a dramatic outlook on the extreme socioeconomic consequences of above-normal hurricane years. Improved knowledge of long-term changes in hurricanes is of great importance, since the population of coastal areas affected directly by landfalls of major hurricanes is increasing. Some studies have argued that the recent changes in hurricane activity are only part of natural multidecadal cycles (e.g., Goldenberg et al., 2001), while others suggest that anthropogenic climate change may play a substantial role in this increase (Emanuel, 2005; Mann and Emanuel, 2006; Webster et al., 2005). It is well established that hurricanes form over the tropical oceans in regions where SSTs exceed 26 °C (Gray, 1968). Theory and observations indicate that hurricane activity is most sensitive to small increases in SST between 26 and 29 °C (DeMaria and Kaplan, 1994). In the Atlantic region, SSTs and hurricane activity display strong variations on interannual to multidecadal time scales (Goldenberg et al., 2001). Recent studies suggest that decadal to multidecadal SST variability in the North Atlantic, which has been referred to as Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000), affects the number of hurricanes forming in the northern tropical Atlantic (Goldenberg et al., 2001).

Observations show a nonlinear upward trend in tropical Atlantic SST over the twentieth century. The trend, which is superimposed on natural multidecadal variability, has been linked to human-induced global warming (Houghton et al., 2001). However, it is still under debate how much of the observed warming in the tropical Atlantic can be attributed to the influences of anthropogenic climate change (Mann and Emanuel, 2006). This is largely because temporal and spatial resolution of observed SST decreases rapidly in the early historical record.

Despite the SST trend, no evidence for a secular increase in hurricane activity has been found when examining the frequency of hurricane occurrence solely (Pielke, 2005b). A different picture unfolds for storm intensity. Model simulations indicate a tendency for more intense hurricanes in greenhouse gas–induced climate change scenarios (Knutson and Tuleya, 2004), although the magnitude and timing of the expected change in hurricane intensity remain unclear. It has been suggested that tropical cyclone intensity is correlated with multidecadal fluctuations of North Atlantic SST (Gray, 1990; Latif et al., 2007), and several recent studies (Hoyos et al., 2006; Webster et al., 2005) provide evidence for a direct link between hurricane intensity and SST changes in the hurricane formation regions. Unfortunately, the record of Atlantic hurricane activity is not considered very reliable before 1944, when routine aircraft reconnaissance in the Atlantic started (Goldenberg et al., 2001). Therefore, the length of this record is too short to detect long-term changes in hurricane behavior.

In this context, the most important and highly controversial issue is whether the recent upward trend in hurricane activity lies outside the range of natural variability (Landsea et al., 2006; Pielke, 2005a). Longer records are needed that help to extend the history of Atlantic hurricane activity back in time and shed light onto the causes of the recent upward trend. Long-lived corals from the tropical oceans can provide accurate records of key climatic parameters with a fidelity and temporal resolution comparable to instrumental climate data. The oxygen isotopic composition (δ^{18}O) of coral skeletal aragonite is a function of both SST and seawater δ^{18}O ($\delta^{18}O_{seawater}$; Quinn et al., 1998), the latter being dependent mainly on the evaporation-precipitation balance (Delaygue et al., 2000). However, compared to the extensive research employing coral paleoclimate reconstructions from the Indo-Pacific Ocean (Cobb et al., 2003), only a few studies have analyzed coral proxy records from the tropical Atlantic (e.g., Goodkin et al., 2005; Moses et al., 2006). None of these proxy records provided a clear link to the most important climatic indices in the North Atlantic: the AMO and hurricane activity. A recent study (Hetzinger et al., 2006) has demonstrated for the first time that fast-growing, massive Caribbean brain corals of the species *Diploria strigosa* can provide accurate, monthly-resolved records of climate variability in the tropical North Atlantic, the region where Atlantic tropical cyclones develop (the so-called "main development region" or MDR; 10°–20°N; Goldenberg et al., 2001).

Here we present a new monthly-resolved coral proxy record (δ^{18}O) from the southeastern Caribbean. We compare a strong multidecadal signal found in the coral record with the dominant mode of low-frequency climate variability in the Atlantic Ocean, the AMO. The utilization of coral δ^{18}O as a proxy for past hurricane activity is assessed by comparing the proxy-based record to an index of Atlantic hurricane activity.

---

*Current address: Department of Chemical & Physical Sciences, University of Toronto, Mississauga, Ontario, Canada; E-mail: shetzinger@ifm-geomar.de.

Geology, January 2008; v. 36; no. 1; p. 11–14; doi: 10.1130/G24321A.1; 3 figures; Data Repository item 2008007.

DATA AND METHODS

The Archipelago Los Roques is located ~140 km off the northern coast of Venezuela at the southern boundary of the Caribbean Current and reflects open-ocean conditions (Fig. DR1 in the GSA Data Repository[1]). In December 2004, we drilled a 1.15 m coral core from a hemispherical *Diploria strigosa* colony growing in a water depth of 2 m in the fringing reef near Cayo Sal (11.77°N, 66.75°W), at the southernmost rim of the archipelago. Microsamples for oxygen isotope analysis were retrieved in 1 mm increments yielding approximately monthly resolution (uncertainty of the age model is ~1–2 months in any given year). Coral $\delta^{18}O$ was analyzed using a Thermo Finnigan Gasbench II Deltaplus at IFM-GEOMAR (for detailed methods see GSA Data Repository). The monthly $\delta^{18}O$ record extends from 1918 to 2004 (Figs. 1A and DR2).

RESULTS AND DISCUSSION

Figure 1A confirms that year-to-year variations in coral $\delta^{18}O$ are significantly correlated with SST at the study site. Both coral $\delta^{18}O$ and SST show pronounced multidecadal variations with a period of ~60 yr (Fig. 1B). However, the magnitude of the multidecadal variations in coral $\delta^{18}O$ is larger than expected based on SST alone. The standard deviation of the smoothed SST index shown in Figure 1B is 0.12 °C (based on SST from the HadISSTv.1.1 database; Rayner et al., 2003), while the standard deviation of coral $\delta^{18}O$ is 0.06‰, which would correspond to 0.3 °C, assuming well-established relationships. Hence, ~50% of the amplitude is due to variations in $\delta^{18}O_{seawater}$. The $\delta^{18}O_{seawater}$ contribution is estimated by calculating the $\delta^{18}O_{residual}$ (i.e., by subtracting the SST component from measured coral $\delta^{18}O$; for details see GSA Data Repository). Figure 1C compares the $\delta^{18}O_{residual}$ with a regional precipitation index computed from weather stations in the southeastern Caribbean, which includes the study site. The $\delta^{18}O_{residual}$ and precipitation are highly correlated at low frequencies, implying that multidecadal $\delta^{18}O_{seawater}$ variations are primarily atmosphere-driven. Both indices show pronounced multidecadal fluctuations with a period of ~60 yr. We note that warmer SSTs at Los Roques broadly coincide with higher precipitation in the southeastern Caribbean at multidecadal time scales, effectively amplifying the climate signal in the coral $\delta^{18}O$ record (compare Figs. 1B and 1C).

Previous studies have shown that low-frequency SST variability in the tropical North Atlantic influences the intensity of hurricanes (e.g., Webster et al., 2005). Los Roques coral $\delta^{18}O$ correlates very well with large-scale SST variations in the tropical North Atlantic (Fig. 2A), especially SST in the south-central part of the MDR of Atlantic hurricanes, making this site a very sensitive location for the detection of past changes in hurricane activity. Vertical wind shear is another important factor controlling hurricane activity (Goldenberg et al., 2001). The coral $\delta^{18}O$ correlates well with multidecadal fluctuations in vertical wind shear over the MDR (Fig. 2B). The two are apparently related because the latter are associated with meridional displacements of the intertropical convergence zone (Knight et al., 2006). The coral, due to its position, is able to track shifts in the intertropical convergence zone through the variations in precipitation, which it records (Fig. 1C). Recording both SST and vertical wind shear over the MDR, the coral $\delta^{18}O$ variability should therefore be an excellent proxy archive to infer past changes in hurricane activity.

We directly compare the coral $\delta^{18}O$ record to the index of accumulated cyclone energy (ACE), a measure of hurricane activity that takes into account the number, strength, and duration of all tropical storms in a season (Bell et al., 2000) and shows pronounced multidecadal variability. An ordinary least squares regression analysis indicates the existence of a strong and statistically significant relationship between seasonal mean August-September-October averaged coral $\delta^{18}O$, which represents the climatological peak of the Atlantic hurricane season, and the ACE index (Fig. 3A; r = –0.66; 1920–2002). A comparison with the so-called "power dissipation index" (Emanuel, 2005), another commonly used hurricane index, revealed similar results (the ACE index and the power dissipation index correlate at 0.97; Klotzbach, 2006). Note that proxy records with at least seasonal resolution are a prerequisite for the reconstruction of hurricane activity in the tropical North Atlantic, as the hurricane season is restricted to the summer months. The coral proxy record is a particularly good indicator of decadal to multidecadal swings in the ACE index (Fig. 3A), and its relationship to the ACE index is equal to or better than the relationship between SST and ACE. The correlations for unsmoothed August-September-October values are r = –0.44 (1918-2004) for HadISST averaged over the region most favorable for hurricane development (Emanuel, 2005) (6°–18°N, 20°–60°W) and ACE, and r = –0.54 for 5 yr means (1920-2002), respectively. The correlation between coral $\delta^{18}O$ and the ACE index is higher (r = –0.52 for unsmoothed values, 1918–2004; and r = –0.66 for 5 yr means, 1920–2002).

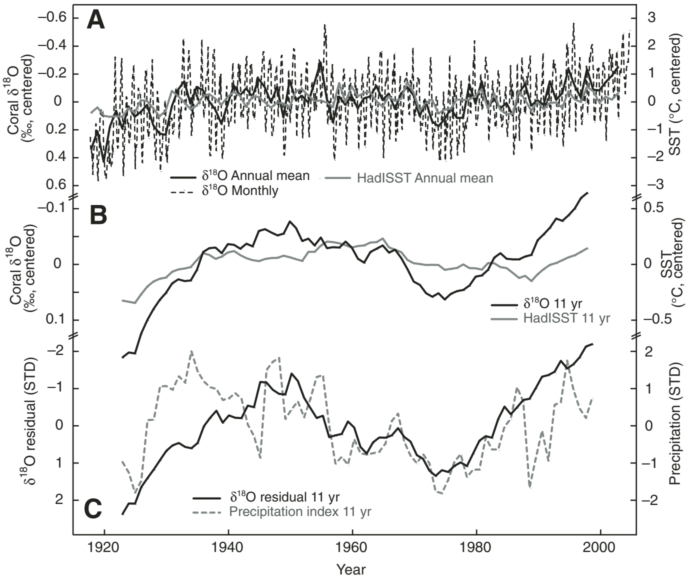

Figure 1. Coral $\delta^{18}O$ chronology and climate parameters. A: Monthly and annual mean oxygen isotopes ($\delta^{18}O$) from the Los Roques coral core compared to annually resolved gridded SST (HadISSTv.1.1) at the study site (12°N, 66°W). Coral $\delta^{18}O$ and local SST data are negatively correlated (r = –0.58 for annual means). The correlation is significant at the 1% level, assuming 83 degrees of freedom. B: Comparison between coral $\delta^{18}O$ and SST data averaged using an 11 yr running filter. The correlation is high (r = –0.69; 1923–1998). Data in A and B were centered by subtracting the mean and scaled so that –0.2‰ $\delta^{18}O$ corresponds to 1 °C. C: Coral $\delta^{18}O_{residual}$ compared to a southeastern Caribbean precipitation index computed from 60 stations for the region 70°–60°W, 10°–13°N. Monthly weather station precipitation data were extracted from the Global Historical Climate Network (NOAA NCDC GHCNv.2, obtained at http://iridl.ldeo.columbia.edu/). Both time series were averaged using an 11 yr running filter. The correlation is high (r = –0.46; 1923–1998; and r = –0.67 for detrended values). Note: Correlations in B and C are not significant at the 5% level due to the reduced degrees of freedom; even so, it is clear that the multidecadal fluctuations in the $\delta^{18}O_{residual}$ (C) follow the precipitation index. Data shown in C were normalized to unit variance for comparison. STD—standard deviation. Analytical uncertainty of $\delta^{18}O$ measurements is less than 0.06‰ (1σ).

---

[1] GSA Data Repository item 2008007, Figure DR1 (oceanographic setting of the study site), Figure DR2 (X-radiographs with sampling transects), and description of methods and laboratory techniques, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

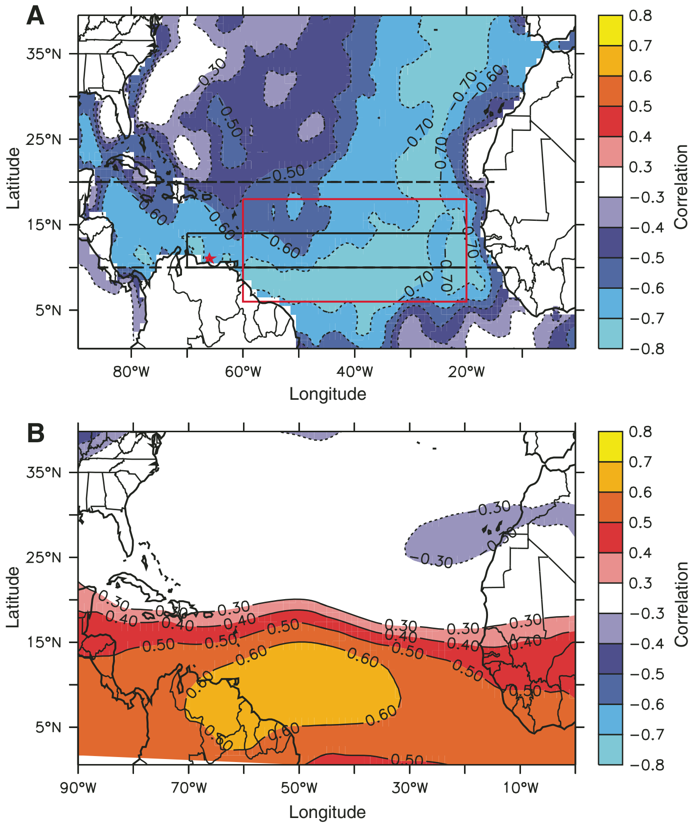

Figure 2. A: Spatial distribution of correlations between annual mean coral δ^{18}O and SST (Smith and Reynolds, 2004). Data presented in A and B cover the period 1918–2003, and were detrended and annual means smoothed with a 5 yr running mean. Dashed lines indicate northern and southern boundaries (10°–20°N) of the main development region (MDR) of Atlantic hurricanes. Correlation of coral δ^{18}O and SST is high and significant at the 1% level in the south-central portion of the MDR used by Goldenberg et al. (2001) (r = –0.74; black box; 10°–14°N, 20°–70°W), as well as in the box used by Emanuel (2005) (r = –0.75; red box; 6°–18°N, 20°–60°W). Asterisk marks location of Los Roques study site. B: As in A except for vertical wind shear as simulated by an ensemble simulation with an atmospheric model general circulation (Latif et al., 2007). Correlation of coral δ^{18}O and vertical wind shear is high in the south-central portion of the MDR (r = 0.62). Simulated values of vertical wind shear are used, as there are no observed estimates prior to 1948. Model and atmospheric reanalyses agree over the observed period (Latif et al., 2007).

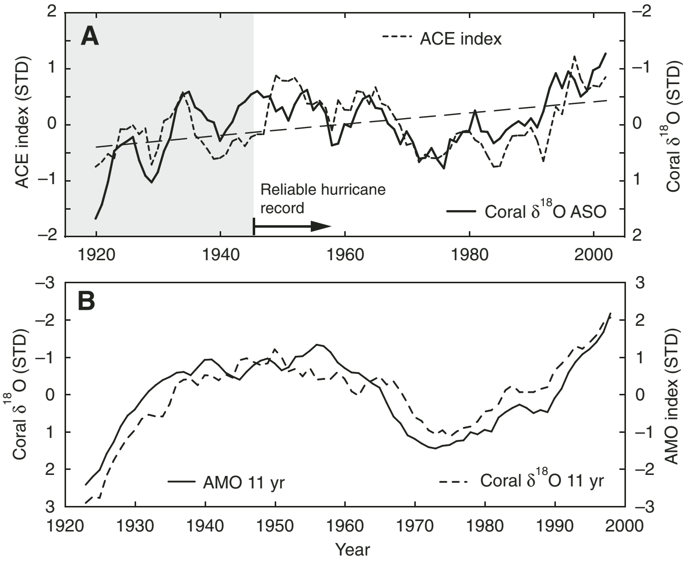

Figure 3. A: Comparison between coral δ^{18}O and the index of accumulated cyclone energy (ACE) for the North Atlantic. Data shown are for the peak months of the Atlantic hurricane season, August-September-October (ASO), and were averaged using a 5 yr running filter. The correlation is high (r = –0.66) and significant at the 1% level, assuming 14 degrees of freedom (1920–2002); r = –0.52 for unsmoothed ASO data (not shown), 1918–2004. The correlation is also stable for detrended values (r = –0.50 for unsmoothed ASO data; and r = –0.67 for 5 yr means, same time intervals as above). Dashed line represents the upward trend seen in coral δ^{18}O over the 1920–2002 time period. The trend is statistically significant at the 0.1% level, assuming nine degrees of freedom. B: Comparison between coral δ^{18}O and the AMO index (North Atlantic SST averaged between 0 and 70°N; Enfield et al., 2001). Seasonal mean values were removed from the monthly data before averaging to annual resolution. Then an 11 yr running filter was applied. The correlation is high (r = –0.86) and statistically significant at the 5% level, even with only four effective degrees of freedom. AMO—Atlantic Multidecadal Oscillation; ASO—August-September-October; STD—standard deviation.

These comparisons corroborate the ability of the coral to record SST variability in the Atlantic hurricane MDR. The covarying precipitation enhances the climatic signal in the proxy record, but it is also an indicator for vertical wind shear over the MDR. Given that tropical cyclone activity is linked to both tropical Atlantic SST (e.g., Emanuel, 2005; Mann and Emanuel, 2006) and vertical wind shear (Goldenberg et al., 2001), our findings demonstrate that the coral-derived proxy data can be used to infer changes in the hurricane activity on time scales that extend well beyond the reliable record.

In addition, Figure 3A shows a clear and statistically significant negative trend in the coral δ^{18}O record that is superimposed on the decadal to multidecadal cycles. The observed trend in the coral δ^{18}O indicates a significant warming and/or freshening of surface waters in the genesis region of tropical cyclones. However, because of the multidecadal variability, longer coral records are needed to reliably estimate a linear trend.

Making the coral proxy of equal importance is the close relationship between the decadal to multidecadal cycles in the coral δ^{18}O and the AMO (Fig. 3B). The AMO is the major mode of low-frequency climate variability in the North Atlantic Ocean (Enfield et al., 2001). Its global impacts on climate and ecology are only recently becoming appreciated (Enfield and Cid-Serrano, 2006; Goldenberg et al., 2001; Knight et al., 2006). The mechanisms underlying this multidecadal variability remain controversial, primarily because of the limited instrumental record (Latif et al., 2006). Despite the fundamental importance of the AMO for Northern Hemisphere climate variability, most available reconstructions of the AMO are solely based on continental proxies with annual or lower resolution (Delworth and Mann, 2000; Gray et al., 2004). So far, coral proxies have failed to show a clear AMO signature and cannot be used for the reconstruction of this important climate mode. In Figure 3B, we compare our Los Roques coral δ^{18}O record with the AMO index of Enfield et al. (2001), which provides an index of multidecadal SST anomalies in the Atlantic basin north of the equator. The correlation between the smoothed Los Roques coral δ^{18}O and the similarly smoothed AMO index is high (r = –0.86; Fig. 3B) and statistically significant. Owing to the predominance of the AMO signal in the southeastern Caribbean, both in SST and in rainfall (see also Sutton and Hodson, 2005, their Figs. 2E and 2G), our coral δ^{18}O index provides an excellent record of multidecadal variability in the North Atlantic Ocean. We suggest the Archipelago Los Roques as an ideal site for coral-based AMO reconstructions in the future.

As *Diploria strigosa* coral colonies are abundant throughout the entire Caribbean and western Atlantic region and can live up to several hundred years, we are confident that corals of this genus will become an important new marine archive that can be used in future studies to reconstruct AMO variability beyond the instrumental record. Long-term, high-resolution reconstructions of AMO variability are of fundamental importance, since observation- and model-based studies (Delworth and Mann, 2000; Folland et al., 1986; Knight et al., 2005; Latif et al., 2004) imply that changes in the strength of the North Atlantic thermohaline circulation drive the associated multidecadal variability in SST. Thus, long proxy records of AMO variability may be used to infer past changes of the thermohaline circulation and forecast future behavior of the thermohaline circulation (Knight et al., 2005) and to partially clarify the issue of whether the multidecadal SST oscillations observed in the twentieth century are due to anthropogenic forcing. Fossil *Diploria strigosa* corals could provide important insights on changes of the thermohaline circulation in times of different climatic boundary conditions such as glacial/interglacial times.

ACKNOWLEDGMENTS

We thank J. Estevez for logistical support during fieldwork, L. Haxhiaj for lab assistance, and S.Y. Cahyarini for helpful discussions. This research was funded by the Deutsche Forschungsgemeinschaft (Sonderforschungsbereich 460-B1 and Du129/33 [Leibniz award]). N.K. and M.L. were supported by the DYNAMITE (GOCE 00393) project. The Atmospheric General Circulation Model simulations were performed at the Hoechstleistungsrechenzentrum Nord.

REFERENCES CITED

Bell, G.D., Halpert, M.S., Schnell, R.C., Higgins, R.W., Lawrimore, J., Kousky, V.E., Tinker, R., Thiaw, W., Chelliah, M., and Artusa, A., 2000, Climate assessment for 1999: Bulletin of the American Meteorological Society, v. 81, p. 1328, doi: 10.1175/1520-0477(2000)081<1328:CAF>2.3.CO;2.

Cobb, K.M., Charles, C.D., Cheng, H., and Edwards, R.L., 2003, El Niño/Southern Oscillation and tropical Pacific climate during the last millennium: Nature, v. 424, p. 271–276, doi: 10.1038/nature01779.

Delaygue, G., Jouzel, J., and Dutay, J.-C., 2000, Oxygen 18–salinity relationship simulated by an oceanic general circulation model: Earth and Planetary Science Letters, v. 178, p. 113–123, doi: 10.1016/S0012-821X(00)00073-X.

Delworth, T.L., and Mann, M.E., 2000, Observed and simulated multidecadal variability in the Northern Hemisphere: Climate Dynamics, v. 16, p. 661–676, doi: 10.1007/s003820000075.

DeMaria, M., and Kaplan, J., 1994, Sea surface temperature and the maximum intensity of Atlantic tropical cyclones: Journal of Climate, v. 7, p. 1324–1334, doi: 10.1175/1520-0442(1994)007<1324:SSTATM>2.0.CO;2.

Emanuel, K., 2005, Increasing destructiveness of tropical cyclones over the past 30 years: Nature, v. 436, p. 686–688, doi: 10.1038/nature03906.

Enfield, D.B., and Cid-Serrano, L., 2006, Projecting the risk of future climate shifts: International Journal of Climatology, v. 26, p. 885–895, doi: 10.1002/joc.1293.

Enfield, D.B., Mestas-Nunez, A.M., and Trimble, P.J., 2001, The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S.: Geophysical Research Letters, v. 28, p. 2077–2080, doi: 10.1029/2000GL012745.

Folland, C.K., Palmer, T.N., and Parker, D.E., 1986, Sahel rainfall and worldwide sea temperatures, 1901–85: Nature, v. 320, p. 602–607, doi: 10.1038/320602a0.

Goldenberg, S.B., Landsea, C.W., Mestas-Nunez, A.M., and Gray, W.M., 2001, The recent increase in Atlantic hurricane activity: Causes and implications: Science, v. 293, p. 474–479, doi: 10.1126/science.1060040.

Goodkin, N.F., Hughen, K.A., Cohen, A.L., and Smith, S.R., 2005, Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca: Paleoceanography, v. 20, doi: 10.1029/2005PA001140.

Gray, S.T., Graumlich, L.J., Betancourt, J.L., and Pederson, G.T., 2004, A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D.: Geophysical Research Letters, v. 31, doi: 10.1029/2004GL019932.

Gray, W.M., 1968, Global view of the origins of tropical disturbances and storms: Monthly Weather Review, v. 96, p. 669–700, doi: 10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2.

Gray, W.M., 1990, Strong association between West African rainfall and U.S. landfall of intense hurricanes: Science, v. 249, p. 1251–1256, doi: 10.1126/science.249.4974.1251.

Hetzinger, S., Pfeiffer, M., Dullo, W.-C., Ruprecht, E., and Garbe-Schönberg, D., 2006, Sr/Ca and δ^{18}O in a fast-growing *Diploria strigosa* coral: Evaluation of a new climate archive for the tropical Atlantic: Geochemistry, Geophysics, Geosystems, v. 7, no. 10, Q10002, doi:10.1029/2006GC001347.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., 2001, Climatic change: The scientific basis: Cambridge, UK, Cambridge University Press, 944 p.

Hoyos, C.D., Agudelo, P.A., Webster, P.J., and Curry, J.A., 2006, Deconvolution of the factors contributing to the increase in global hurricane intensity: Science, v. 312, p. 94–97, doi: 10.1126/science.1123560.

Kerr, R.A., 2000, A North Atlantic climate pacemaker for the centuries: Science, v. 288, p. 1984–1985, doi: 10.1126/science.288.5473.1984.

Klotzbach, P.J., 2006, Trends in global tropical cyclone activity over the past twenty years (1986–2005): Geophysical Research Letters, v. 33, doi: 10.1029/2006GL025881.

Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M., and Mann, M.E., 2005, A signature of persistent natural thermohaline circulation cycles in observed climate: Geophysical Research Letters, v. 32, doi: 10.1029/2005GL024233.

Knight, J.R., Folland, C.K., and Scaife, A.A., 2006, Climate impacts of the Atlantic Multidecadal Oscillation: Geophysical Research Letters, v. 33, doi: 10.1029/2006GL026242.

Knutson, T.R., and Tuleya, R.E., 2004, Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization: Journal of Climate, v. 17, p. 3477–3495, doi: 10.1175/1520-0442(2004)017<3477:IOCWOS>2.0.CO;2.

Landsea, C.W., Harper, B.A., Hoarau, K., and Knaff, J.A., 2006, Can we detect trends in extreme tropical cyclones?: Science, v. 313, p. 452–454, doi: 10.1126/science.1128448.

Latif, M., Roeckner, E., Botzet, M., Esch, M., Haak, H., Hagemann, S., Jungclaus, J., Legutke, S., Marsland, S., and Mikolajewicz, U., 2004, Reconstructing, monitoring, and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature: Journal of Climate, v. 17, p. 1605–1614, doi: 10.1175/1520-0442(2004)017<1605:RMAPMC>2.0.CO;2.

Latif, M., Collins, M., Pohlmann, H., and Keenlyside, N.S., 2006, A review of predictability studies of Atlantic sector climate on decadal time scales: Journal of Climate, v. 19, p. 5971–5987, doi: 10.1175/JCLI3945.1.

Latif, M., Keenlyside, N.S., and Bader, J., 2007, Tropical sea surface temperature, vertical wind shear, and hurricane development: Geophysical Research Letters, v. 34, doi: 10.1029/2006GL027969.

Mann, M.E., and Emanuel, K., 2006, Atlantic hurricane trends linked to climate change: Eos (Transactions, American Geophysical Union), v. 87, p. 233–244.

Moses, C.S., Swart, P.K., and Rosenheim, B.E., 2006, Evidence of multidecadal salinity variability in the eastern tropical North Atlantic: Paleoceanography, v. 21, PA3010, doi: 10.1029/2005PA001257.

Pielke, R.A., Jr., 2005a, Are there trends in hurricane destruction?: Nature, v. 438, p. 211–228, doi: 10.1038/nature4426.

Pielke, R.A., Jr., 2005b, Hurricanes and global warming: Bulletin of the American Meteorological Society, v. 86, p. 1571–1575, doi: 10.1175/BAMS-86-11-1571.

Quinn, T.M., Crowley, T.J., Taylor, F.W., Henin, C., Joannot, P., and Join, Y., 1998, A multicentury stable isotope record from a New Caledonia coral: Interannual and decadal sea surface temperature variability in the southwest Pacific since 1657 A.D.: Paleoceanography, v. 13, p. 412–426, doi: 10.1029/98PA00401.

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C., and Kaplan, A., 2003, Global analyses of SST, sea ice, and night marine air temperature since the late nineteenth century: Journal of Geophysical Research, v. 108, doi: 10.1029/2002JD002670.

Smith, T.M., and Reynolds, R.W., 2004, Improved extended reconstruction of SST (1854–1997): Journal of Climate, v. 17, p. 2466–2477, doi: 10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2.

Sutton, R.T., and Hodson, D.L.R., 2005, Atlantic Ocean forcing of North American and European summer climate: Science, v. 309, p. 115–118, doi: 10.1126/science.1109496.

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R., 2005, Changes in the tropical cyclone number, duration, and intensity in a warming environment: Science, v. 309, p. 1844–1846, doi: 10.1126/science.1116448.

Manuscript received 13 April 2007
Revised manuscript received 22 August 2007
Manuscript accepted 24 August 2007

Printed in USA