



Major shifts in multidecadal moisture variability in the Mid-Atlantic region during the last 240 years

Cheng Zhao,¹ Zicheng Yu,¹ Long Li,¹ and Gray Bebout¹

Received 3 March 2010; revised 28 March 2010; accepted 31 March 2010; published 5 May 2010.

[1] The paucity of high-resolution paleoclimate records limits our ability to extend instrumental data into a longer time-frame and to better understand multidecadal climate variations in the Mid-Atlantic region. Here we present an ~2 year-resolution endogenic calcite $\delta^{18}\text{O}$ record for the last ~240 years from a freeze core at White Lake in northern New Jersey. The $\delta^{18}\text{O}$ data, consistent with the paleosalinity reconstructions from Chesapeake Bay, suggest regional-scale multidecadal moisture variations, including dry conditions at 1780–1840, wet conditions at 1840–1920, and ~20 year moisture oscillations after 1920. We attribute these moisture changes to shifts in the extent and location of the jet stream and resultant change in storm track trajectories, with eastward and seaward displacement of storm tracks corresponding to dry climate. The increase in moisture variability since 1920, shortly after the steady increase in global air temperature, suggests that change in mean climate state can induce large changes in moisture variability. **Citation:** Zhao, C., Z. Yu, L. Li, and G. Bebout (2010), Major shifts in multidecadal moisture variability in the Mid-Atlantic region during the last 240 years, *Geophys. Res. Lett.*, 37, L09702, doi:10.1029/2010GL043133.

1. Introduction

[2] Instrumental data show that multidecadal moisture oscillations are an important climatic feature in the 20th century. For example, severe droughts during the 1930s and mid 1960s have been documented in many parts of the United States. Analysis of available meteorological data indicates that large-scale atmospheric circulation [Yarnal and Leathers, 1988] and Atlantic Multidecadal Oscillation (AMO) [Enfield et al., 2001; McCabe et al., 2004] can play an important role in these multidecadal moisture variations. Anthropogenic global warming, superimposed on other natural processes, can also have significant influences on long-term climate change and climate variability. For example, a trend of increasing Great Lake-effect snowfall during the 20th century is believed to be a response to global warming [Burnett et al., 2003]. An increased variability of the North Atlantic Oscillation (NAO) since 1920 has also been reported as a response to anthropogenic warming [Goodkin et al., 2008]. However, the available instrumental data for the Mid-Atlantic region are either incomplete or inconsistent with each other, making it difficult to further test these ideas for a longer time-frame. Extending the instrumental record to

longer time periods requires high-resolution paleoclimate reconstructions, and surprisingly very few high-resolution paleoclimate records [e.g., Cronin et al., 2000] are available for the highly populated Mid-Atlantic region.

[3] In this paper, we present an ~2-year resolution calcite oxygen isotope ($\delta^{18}\text{O}$) record from a freeze-core at White Lake in northern New Jersey. The objectives of this study were (1) to derive a composite moisture history for the Mid-Atlantic region for the last ~240 years based on the $\delta^{18}\text{O}$ data obtained from White Lake and the paleosalinity reconstructions from Chesapeake Bay [Cronin et al., 2000], (2) to investigate potential effects of atmospheric circulation and ocean conditions on multidecadal-scale moisture changes, and (3) to evaluate the possible effects of global warming on moisture variations in recent decades.

2. Study Region and Site

[4] White Lake (41°00'N, 74°55'W, 138 m asl) is a hardwater lake located in northern New Jersey (Figure 1a). The lake owes its hardwater nature to the underlying limestone bedrock. White lake is primarily recharged by groundwater, with a small ephemeral inlet and an outlet. As shown in the instrumental data (1895–2006) from New Jersey Division 1 (northern New Jersey) (<http://www1.ncdc.noaa.gov/pub/data/cirs/>), the regional mean annual temperature is 10.4°C with average summer (June to August) temperature of 21.5°C and winter (December to February) temperature of –1.1°C, and the mean annual precipitation is 1177 mm with even distribution in each month.

[5] White Lake has a surface area of 0.26 km² and a catchment area of ~2 km². The average water depth of the lake is 6.7 m, with a maximum depth of 13.4 m. White Lake has a relatively high pH (~8.5) and alkalinity (192 mg/L). Summer (May to August) surface-water temperatures are 21–28°C, based on measurements made between 1997 and 1998 [New Jersey Division of Fish Game and Wildlife, 1999]. A marl bench, a band of unconsolidated carbonate-rich sediment, is visible as a light-colored band in the shallow water (<3 m) around the periphery of the lake [Li et al., 2008].

3. Methods

[6] A 33.3 cm-long freeze-core (core WL03-4) was retrieved from the deepest part of the lake in March 2003. Chronology of the core was established using ²¹⁰Pb analyses for the top 24 cm (Figure 2a), and lithological correlations for the lower part with a parallel 60-cm-long gravity core (core WL03-3) dated by ¹⁴C methods (see details in Li et al., 2008). The dating errors were less than 3 years over the last 80 years, and increased to ~20 years around 1840 AD (Figure 2a). Additional ~3-year uncertainties could be produced by the subsampling process. Based on the current age

¹Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pennsylvania, USA.

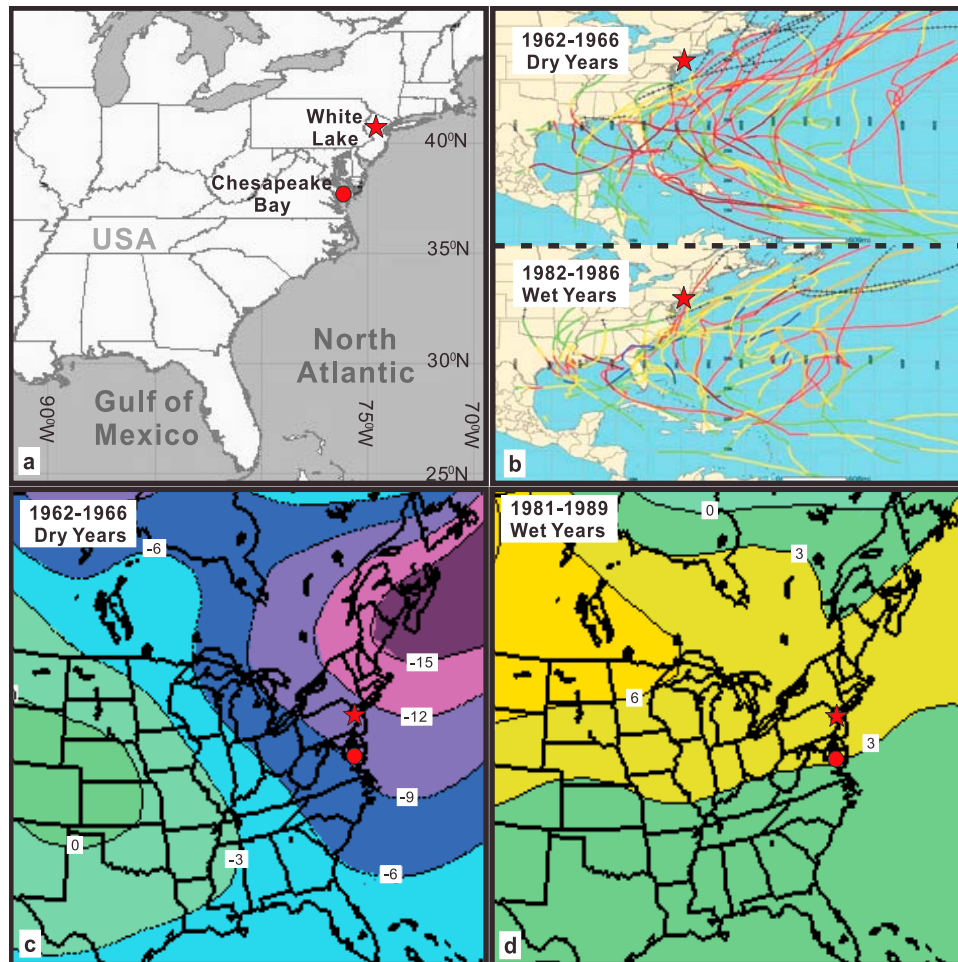


Figure 1. (a) Location map showing the study site. Red star indicates the location of White Lake, and red circle represents the location of Chesapeake Bay [Cronin *et al.*, 2000]. (b) The observed historical hurricane tracks at (top) 1962–1966 and (bottom) 1982–1986, obtained from the National Hurricane Data Center (<http://csc-s-maps-q.csc.noaa.gov/hurricanes/index.jsp>). The composite anomalies of 500 mb geopotential height reanalysis (compared to the average of 1949–1999, with the units of contour lines in meters) for the periods (c) 1962–1966 and (d) 1981–1989, obtained from the National Centers for Environmental Prediction (NCEP) (<http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>).

model, the core has a nearly constant sedimentation rate of about 1.4 mm/year.

[7] For stable isotope analyses, well-preserved endogenic calcite samples were taken at 3-mm intervals and air dried at room temperature. Biogenic shells and plant fragments were handpicked under a stereo microscope and discarded. Each of the 111 calcite samples was reacted overnight with 100% phosphoric acid in glass vessels held at a constant temperature of 25°C in a water bath. The resulting CO₂ gas was cryogenically purified and analyzed for oxygen and carbon isotopes, in dual-inlet mode, using a Finnigan MAT 252 isotope ratio mass spectrometer at Lehigh University. The results are presented in the conventional delta (δ) notation, defined as $[(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}] \times 1000$ (where R is the absolute ratio of ¹⁸O/¹⁶O, and Vienna-PDB [Peedee belemnite] is used as the standard). Multiple analyses of lab standards show an analytical reproducibility of better than $\pm 0.3\text{‰}$ (2σ) for $\delta^{18}\text{O}$.

[8] We performed a 20–100 year band-pass filter on instrumental Palmer Hydrological Drought Index (PHDI)

time series to highlight the multidecadal-scale moisture variations. For both the $\delta^{18}\text{O}$ data from White Lake and the published paleosalinity data from Chesapeake Bay [Cronin *et al.*, 2000], we resampled them at 2-year resolution and standardized by removing its mean value and dividing by its standard deviation. We derived the composite moisture record for the Mid-Atlantic region by averaging the standardized records from both White Lake and Chesapeake Bay and then standardizing the average time series.

4. Results

[9] The age model (Figure 2a) shows that the freeze core WL03-4 covers the last ~240 years, corresponding to the period since ~1770 [Li *et al.*, 2008]. The $\delta^{18}\text{O}$ values range from -8.9‰ to -5.7‰ . After the lowest value in the 1770s, the $\delta^{18}\text{O}$ data show high values of about -6.5‰ with 0.5‰ fluctuations for the period of ~1780 to 1840 (Figure 2b), and a decrease to about $< -7\text{‰}$ for the period of 1840 to 1920. The $\delta^{18}\text{O}$ values show an abrupt positive shift from -7.5‰

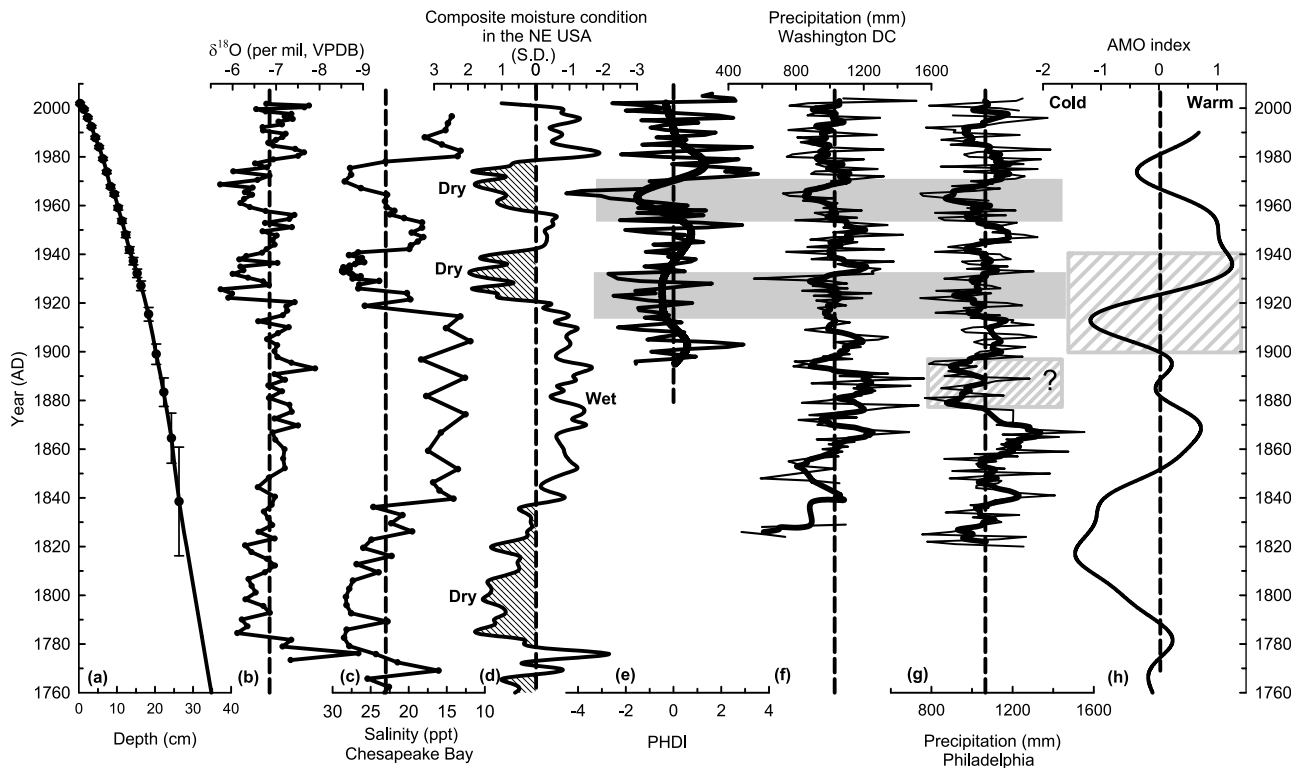


Figure 2. Regional moisture correlation in the Mid-Atlantic region. (a) Age model for core WL03-4 [Li *et al.*, 2008]. (b) $\delta^{18}\text{O}$ values from White Lake, northern New Jersey. (c) Paleosalinity data from Chesapeake Bay [Cronin *et al.*, 2000]. (d) The composite moisture record in the Mid-Atlantic region. (e) Instrumental PHDI index from New Jersey Climate Division 1 (northern New Jersey) with a smoothed time series using a 20–100 year band-pass filter (thick line). (f) Instrumental precipitation data from Washington DC (<http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php>) and (g) Philadelphia with 5-year moving average curve (bold). (h) Reconstructed AMO index for the last ~250 years [Gray *et al.*, 2004]. Note that the scales of x-axis in Figures 2b, 2c, and 2d are reversed. The dashed vertical line in each panel indicates the average value. The periods of abnormal precipitation data in Philadelphia and the reversed AMO-climate association are indicated by hatched pattern. Dry intervals recorded by instrumental data were indicated by the gray bars in Figures 2e, 2f, and 2g.

to -5.7‰ at 1920, and then pronounced ~ 20 -year large-amplitude oscillations between -5.7‰ and -7.8‰ . There is no obvious long-term overall trend for the last 240 years.

5. Discussion

5.1. Proxy Records of Multidecadal Moisture Variations

[10] Equilibrium $\delta^{18}\text{O}$ values of endogenic calcite can reflect the lake water isotope composition and water temperatures. The water in White Lake is derived from shallow groundwater and precipitation, with the groundwater being recharged by precipitation. Evaporation would be expected to increase the $\delta^{18}\text{O}$ values of the lake water. Calcite precipitation in marl lakes predominately occurs in summers, oftentimes induced by the photosynthesis of aquatic plants during growing seasons. The most recently precipitated calcite appears to have formed in isotopic equilibrium with the lake water because the measured $\delta^{18}\text{O}$ value of the calcite at the top of the core (-6.8‰) is close to the predicted equilibrated $\delta^{18}\text{O}$ value (-6.2‰ as calculated using the equations of Kim and O'Neil [1997] and Leng and Marshall [2004], with the measured $\delta^{18}\text{O}_{\text{lake water}} = -3.8\text{‰}$ and $T_{\text{lake water}} = 25.1^\circ\text{C}$ in summer 2002). The isotopic composition of precipitation is controlled by the moisture

source and by air temperature. Instrumental air temperature data in this region show no significant correlation with the calcite $\delta^{18}\text{O}$ values for the last ~ 100 years, and temperature changes at the lake water surface likely follow the air temperature changes. Changes in the moisture source of precipitation could also influence the $\delta^{18}\text{O}$ values of lake water. For example, Burnett *et al.* [2004] investigated the moisture sources of winter precipitation in New York state and concluded that the lake-effect precipitation had a much lower $\delta^{18}\text{O}$ values (-17.9‰) than the moisture originating in the Gulf of Mexico and in the nearby Atlantic Ocean (-8.2‰). However, the averaged $\delta^{18}\text{O}$ values of annual precipitation in northern New Jersey is about -8‰ [Bowen and Wilkinson, 2002], suggesting a small contribution of moisture from lake-effect precipitation. Thus the major moisture source in northern New Jersey is more likely the Gulf of Mexico and tropical Atlantic Ocean [Lawrence *et al.*, 1982].

[11] We suggest that the changes in $\delta^{18}\text{O}$ values of White Lake could be correlated with changes in wet/dry climate condition. The $\delta^{18}\text{O}$ values from White Lake have an inverse relationship with the instrumental PHDI data in northern New Jersey and the precipitation data in Washington DC and in Philadelphia at the multidecadal scale over the last ~ 100 years, with higher $\delta^{18}\text{O}$ values corresponding to lower PHDI, lower precipitation, and drier climate (Figures 2b and

2e–2g). Also, the $\delta^{18}\text{O}$ variations at White Lake are consistent with the paleosalinity reconstructed from Chesapeake Bay over the last ~240 years [Cronin *et al.*, 2000], with higher $\delta^{18}\text{O}$ values at White Lake corresponding to higher salinities at Chesapeake Bay (Figures 2b and 2c). Paleosalinity was reconstructed using a quantitative relationship between the salinity and relative abundance of the benthic foraminifer *Elphidium* [Cronin *et al.*, 2000]. Changes in paleosalinity at Chesapeake Bay reflect changes in precipitation in the watershed and fresh-water discharge to the Bay [Cronin *et al.*, 2000]. Under dry conditions, the lower lake level and longer lake water residence time would effectively strengthen the evaporative effect and then increase the $\delta^{18}\text{O}$ value of lake water. The small mismatches between these curves, for some periods, are likely caused by the dating uncertainties in both records. The abnormal low precipitation interval recorded for Philadelphia between 1880 and 1900 could reflect a more localized climate (Figure 2g).

[12] The composite moisture record from the calcite $\delta^{18}\text{O}$ values at White Lake and the salinity data from Chesapeake Bay highlights the general temporal patterns of moisture changes for the last ~240 years in the Mid-Atlantic region (Figure 2d). After a short wet interval in the 1770s, a dry condition extended from 1780 to the end of the Little Ice Age (LIA) at ~1840. By the end of the LIA, the regional moisture shifted to an 80-year-long wet interval between 1840 and 1920. This shift is more abrupt at Chesapeake Bay than at White Lake (Figures 2b and 2c), probably reflecting (1) the sudden disappearance of saline foraminifer *Elphidium*, the dominant species as salinity proxy used at Chesapeake Bay, caused by freshwater incursions under a wet climate, and (2) the amplification of freshening event at Chesapeake Bay due to its large watershed to open water ratio (~14:1), compared to White Lake (= 7:1). Since 1920, the moisture conditions became more variable with ~20-year oscillations including dry periods at ~1920–1940 and ~1960–1980 as well as wet intervene periods at ~1940–1960 and ~1980–2003 (Figure 2d).

5.2. Causes and Mechanisms of Multidecadal Moisture Variations

[13] The observed multidecadal-scale moisture oscillations in the Mid-Atlantic region could be controlled by changes in the extent and mean position of the jet stream. During the dry period in the 1960s, a much deeper trough was centered in the northwestern Atlantic Ocean but exerted some influence further south into the southeastern United States, as shown in the anomalies of 500 mb geopotential heights (Figure 1c). Consequently, warm moisture from the Gulf of Mexico was diverted to Atlantic Ocean offshore along the east branch of the trough, causing a dry condition in the Mid-Atlantic region [Yarnal and Leathers, 1988; Rodionov, 1994]. Opposite situations occurred in the wet 1980s. The deepened trough disappeared all over the eastern United States and the geopotential heights were higher than normal (Figure 1d). This pattern not only occurred in winter months, but also in all other seasons, although with weaker intensities [Yarnal and Leathers, 1988]. We suggest that similar changes in the extent and position of the trough controlled moisture conditions during the earlier wet and dry periods.

[14] The extent and position of the jet stream influence the wet/dry condition through regulation of storm trajectories and thus affect the precipitation in the Mid-Atlantic region

[Yarnal and Leathers, 1988; Rodionov, 1994]. Meteorological observations suggested that a major part of precipitation in the Mid-Atlantic region was brought by the extratropical storms [Lawrence *et al.*, 1982; Burnett *et al.*, 2004]. Tropical storms might also have some contributions. During the dry years, various storms originating in the Gulf of Mexico and tropical Atlantic Ocean could be deflected by the trough and displaced southeastward and restricted to the coastal Atlantic Ocean. Consequently, less moisture would reach inland area in the Mid-Atlantic region, leading to less precipitation and thus a drier climate. During the wet periods, storm tracks were displaced further north and west and reached the Mid-Atlantic region, leading to greater precipitation and thus wetter conditions. The relationship between lake levels and storm tracks has been observed in the Great Lakes, with a reduced frequency of Colorado Cyclones corresponding to low lake levels in the 1960s [Rodionov, 1994]. Here, we use the observed trajectories of historical hurricanes originated from Atlantic basin as an example to show this relation (Figure 1b). Comparing the wet periods between 1982 and 1986, all hurricanes that occurred during the dry period between 1962 and 1966 were displaced southeastward and restricted to the coastal Atlantic Ocean (Figure 1b). Similar situations developed during an earlier dry period in the 1920s and wet periods in the late 19th century and in the 1950s (not shown). Meteorological investigations show that the eastward and seaward displacement of storms would be associated with low $\delta^{18}\text{O}$ values for precipitation because the frontal surface, where most of the precipitation forms, is always found at high altitude [Lawrence *et al.*, 1982]. This fact further suggests that the observed high $\delta^{18}\text{O}$ values during seaward storm tracks and dry intervals were caused by an evaporation effect at the lake surface.

[15] It is interesting to point out that the shift from a dry to wet climate at the end of the LIA corresponded to a transition of AMO [Gray *et al.*, 2004] from a cold (negative) to warm (positive) phase around 1840–1850 (Figures 2d and 2h). As reported in analyses of instrumental data [Enfield *et al.*, 2001; McCabe *et al.*, 2004], the moisture condition in this region could be associated with the Atlantic sea surface temperatures at the multidecadal scale. This relationship has been observed at the millennial scale for the last ~7000 years from lake-level records derived from long cores at White Lake [Li *et al.*, 2007] and geochemical data for speleothems in western Virginia [Springer *et al.*, 2008]. The moisture reconstructions in our study at least partly support the positive association of AMO and wet climate pattern in most intervals in the Mid-Atlantic region over the last ~240 years. For example, the negative AMO at 1790–1850 and 1960–1980 corresponded to dry climates in the Mid-Atlantic region, but the positive AMO at 1850–1900 and 1940–1960 corresponded to wet climates (Figures 2d and 2h). However, this relationship was reversed between 1900 and 1940, showing a negative AMO-wet climate association. This observation could reflect the integration of multiple climate signals contained in tree-ring inferred AMO records (such as temperature and precipitation) [Gray *et al.*, 2004], the potential influences of Pacific air [Enfield *et al.*, 2001], and the site difference between the Mid-Atlantic region and a more broader area of the AMO record (including eastern North America, western Europe, Scandinavia and the Middle East) [Gray *et al.*, 2004].

[16] The increased multidecadal-scale moisture variability after 1920 in the Mid-Atlantic region could be attributed to the increases in global air temperature. Many climatic features have been suggested as effects of global warming in the Northern Hemisphere. For example, global warming was proposed to be the cause of the increasing Great Lake-effect snowfall during the 20th century [Burnett *et al.*, 2003], an increase in NAO multidecadal variability since 1920 [Goodkin *et al.*, 2008], an accelerating snow accumulation at Mount Logan in northwestern North America after the mid-19th century [Moore *et al.*, 2002], an increase in the frequency and strength of Indian Ocean Dipole events in the 20th century [Abram *et al.*, 2008], and the observed increases in precipitation at northern mid-latitudes in the 20th century [Zhang *et al.*, 2007]. An increase in the NAO variability [Goodkin *et al.*, 2008] and associated stronger ocean-atmosphere circulation could induce greater moisture variability in the Mid-Atlantic region. Thus, the increased moisture variability after 1920 likely represents a regional climate response to anthropogenic global warming.

[17] **Acknowledgments.** We thank Y. X. Li, T. Guida, A. Gonyo, and R. E. Moeller for field and lab assistance, and two anonymous journal reviewers for helpful comments that improved the manuscript. This project was supported by the Petroleum Research Fund (American Chemical Society) to Z.Y. and the Lehigh University Faculty Research Fund.

References

- Abram, N. J., M. G. Gagan, J. E. Cole, W. S. Hantoro, and M. Mudelsee (2008), Recent intensification of tropical climate variability in the Indian Ocean, *Nat. Geosci.*, *1*, 849–853, doi:10.1038/ngeo357.
- Bowen, G. J., and B. Wilkinson (2002), Spatial distribution of $\delta^{18}\text{O}$ in meteoric precipitation, *Geology*, *30*, 315–318, doi:10.1130/0091-7613(2002)030<0315:SDOIM>2.0.CO;2.
- Burnett, A. W., M. E. Kirby, H. T. Mullins, and W. P. Patterson (2003), Increasing Great Lake-effect snowfall during the twentieth century: A regional response to global warming?, *J. Clim.*, *16*, 3535–3542, doi:10.1175/1520-0442(2003)016<3535:IGLSDT>2.0.CO;2.
- Burnett, A. W., H. T. Mullins, and W. P. Patterson (2004), Relationship between atmospheric circulation and winter precipitation $\delta^{18}\text{O}$ in central New York State, *Geophys. Res. Lett.*, *31*, L22209, doi:10.1029/2004GL021089.
- Cronin, T., D. Willard, A. Karlsen, S. Ishman, S. Verardo, J. McGeehin, R. Kerhin, C. Holmes, S. Colman, and A. Zimmerman (2000), Climatic variability in the eastern United States over the past millennium from Chesapeake Bay sediments, *Geology*, *28*, 3–6, doi:10.1130/0091-7613(2000)28<3:CVITEU>2.0.CO;2.
- Enfield, D. B., A. M. Nestas-Nunez, and P. J. Trimble (2001), The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080, doi:10.1029/2000GL012745.
- Goodkin, N. F., K. A. Huguen, S. C. Doney, and W. B. Curry (2008), Increased multidecadal variability of the North Atlantic Oscillation since 1781, *Nat. Geosci.*, *1*, 844–848, doi:10.1038/ngeo352.
- Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson (2004), A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D., *Geophys. Res. Lett.*, *31*, L22205, doi:10.1029/2004GL019932.
- Kim, S. T., and J. R. O'Neil (1997), Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates, *Geochim. Cosmochim. Acta*, *61*, 3461–3475, doi:10.1016/S0016-7037(97)00169-5.
- Lawrence, J. R., S. D. Gedzelman, J. W. C. White, D. Smiley, and P. Lazov (1982), Storm trajectories in eastern US D/H isotopic composition of precipitation, *Nature*, *296*, 638–640, doi:10.1038/296638a0.
- Leng, M. J., and J. D. Marshall (2004), Palaeoclimate interpretation of stable isotope data from lake sediment archives, *Quat. Sci. Rev.*, *23*, 811–831, doi:10.1016/j.quascirev.2003.06.012.
- Li, L., Z. C. Yu, R. E. Moeller, and G. E. Bebout (2008), Complex trajectories of aquatic and terrestrial ecosystem shifts caused by multiple human-induced environmental stresses, *Geochim. Cosmochim. Acta*, *72*, 4338–4351, doi:10.1016/j.gca.2008.06.026.
- Li, Y. X., Z. C. Yu, and K. P. Kodama (2007), Sensitive moisture response to Holocene millennial-scale climate variations in the Mid-Atlantic region, USA, *Holocene*, *17*, 3–8, doi:10.1177/0959683606069386.
- McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U. S. A.*, *101*, 4136–4141, doi:10.1073/pnas.0306738101.
- Moore, G. W. K., G. Holdsworth, and K. Alverson (2002), Climate change in the North Pacific region over the past three centuries, *Nature*, *420*, 401–403, doi:10.1038/nature01229.
- New Jersey Division of Fish Game and Wildlife (1999), Fisheries management plan, White Lake, N. J. Div. of Fish, Game and Wildlife, Trenton, N. J.
- Rodionov, S. N. (1994), Association between winter precipitation and water level fluctuations in the Great Lakes and atmospheric circulation patterns, *J. Clim.*, *7*, 1693–1707, doi:10.1175/1520-0442(1994)007<1693:ABWPAW>2.0.CO;2.
- Springer, G. S., H. D. Rowe, B. Hardt, R. L. Edwards, and H. Cheng (2008), Solar forcing of Holocene droughts in a stalagmite record from West Virginia in east-central North America, *Geophys. Res. Lett.*, *35*, L17703, doi:10.1029/2008GL034971.
- Yarnal, B., and D. J. Leathers (1988), Relationships between interdecadal and interannual climatic variations and their effect on Pennsylvania climate, *Ann. Assoc. Am. Geogr.*, *78*, 624–641, doi:10.1111/j.1467-8306.1988.tb00235.x.
- Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, and T. Nozawa (2007), Detection of human influence on twentieth-century precipitation trends, *Nature*, *448*, 461–465, doi:10.1038/nature06025.

G. Bebout, L. Li, Z. Yu, and C. Zhao, Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA 18015, USA. (chz8@lehigh.edu)