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Multidecadal climate oscillations detected in a transparency record from a subtropical Florida lake

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Abstract

Synchronous interannual variability in water transparency observed in neighboring lakes has been linked to regional precipitation and resultant runoff of dissolved organic material, but many climate forcings oscillate over time scales longer than most limnological records can detect. A strong relationship ($R^2 = 0.86$) between transparency and the previous two years' rainfall and lake stage in a 25-yr record from a Florida lake enabled us to hindcast transparency from a longer 75-yr record of rainfall and lake stage. Predictions revealed a ~30-yr cycle in transparency linked to the Atlantic Multidecadal Oscillation (AMO). Transparency was greatest (4–8 m) in the cool phase of the AMO (~1962–1993) associated with below-average rainfall in south Florida and lowest (0.1–3.0 m) during two warm phases (~1932–1961, 1994–present) associated with above-average, but more variable, annual rainfall. Models that predict effects of large-scale hydrologic restoration projects on solute export from South Florida's expansive wetlands need to account for recent entry into a warm AMO phase, where teleconnections between the AMO phases and runoff are opposite of those shown for the U.S. interior.

Synchronous variability in concentrations of colored dissolved organic material (CDOM) in neighboring lakes has been attributed to changes in precipitation and resultant carbon export synchronized by regional meteorological drivers (Pace and Cole 2002). Because CDOM controls a variety of biophysical properties of lakes and is sensitive to climate and land-use change, understanding the scales of and causes for variability in CDOM is critical to predicting how aquatic ecosystems will respond to changes in climate and land use. While streamflow in many regions has been linked to cyclical oceanic-atmospheric climate drivers (Tootle et al. 2005), and changes in runoff have been shown to drive long-term trends in DOM concentrations (Hudson et al. 2003; Eimers et al. 2008), few limnological studies are of significant duration to link cyclical teleconnections to CDOM concentrations and resultant biophysical properties of lakes.

Because of their sensitivity to climate on a variety of temporal scales, lakes can serve as important sentinels of ecological responses to directional and cyclical climate change and climate disturbances (Williamson et al. 2009). Long-term studies in temperate lakes have revealed cyclical climate controls [El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation, North Atlantic Oscillation] on the timing of ice breakup, epilimnetic temperatures, and mixing depths (Strub et al. 1985; King et al. 1999; Straile et al. 2003) and commensurate biological changes (Winder and Schindler 2004). While these studies focused on changes driven by fluctuations in temperature and irradiance rather than oscillations in rainfall and water and solute delivery, they do illustrate how conclusions of directionality inferred from narrow sampling windows would differ greatly from those inferred from longer records.

Florida has nearly 8000 lakes exhibiting a wide range of water color (Canfield et al. 1984), which controls variability in water transparency and oxygen concentrations and which determines the relationship between nutrient availability and primary production (Crisman et al. 1998). While geological heterogeneity is the suspected driver of the observed range in color concentrations in Florida lakes (0–600 cobalt platinum units (PTU); Canfield et al. 1984), few long-term studies have examined temporal variability in color, although runoff of CDOM from South Florida's estuaries has been shown to be partly controlled by rainfall (Morrison et al. 2006). In peninsular Florida, precipitation is largely controlled by a combination of the ENSO generated in the Pacific, fluctuating on a 2–7-yr time scale, and the AMO, which reflects a 20–40-yr oscillation in Atlantic sea-surface temperatures (Enfield et al. 2001). While Miralles-Wilhelm et al. (2005) improved estimations of inflows to Lake Okeechobee by modeling the influence of rainfall cycles on water delivery, no studies have directly examined the influence of these teleconnections on Florida lakes.

Lake Annie is a small (0.364 km^2) and, for Florida, a relatively deep (Z_{max} = 21 m) sinkhole lake in south-central Florida lying within the protected watershed of Archbold Biological Station (ABS). As a headwater lake nested in an 80-m-deep sandy aquifer, the majority of water moving into and out of Lake Annie during drought years flows through the ground (Sacks et al. 1998). The height of the groundwater table reflects long-term precipitation trends and influences the magnitude of overland flow to

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the lake in wet years. Successive wet years raise the water table and accelerate transport of materials, particularly CDOM, from the catchment, which causes a reduction in water transparency (Gaiser et al. 2009). The "astatic" nature of water table height at Lake Annie is similar to many other Florida lakes, which have been shown to react quickly to variability in rainfall in the watershed (Brenner et al. 1990), so it is suspected that this process may be a common driver of color variability within Florida's lakes.

While patterns in the 25-yr record from Lake Annie suggest a regulatory role for cyclical climate forces, the 25-yr duration precluded a systematic analysis of drivers operating on multidecadal time scales. However, even though methodical limnological monitoring did not begin until the mid-1980s, lake level and precipitation records extend back to 1932. The purpose of this work is to use the strong relationship between water level, rainfall, and transparency to predict fluctuations in transparency over the longer 75-yr record, and then to determine the degree to which transparency may be controlled by the two cyclical drivers of Florida rainfall, the AMO and the ENSO.

Methods

Study site—Lake Annie is located at 33.7 m above mean sea level (amsl) on the Lake Wales Ridge in the southern part of Highlands County, Florida (27°12′35″N, 81°20′57″W). It is a headwater lake that is connected by an outlet to a chain of doline lakes that eventually drain into Lake Okeechobee and the Everglades watershed. The regional climate is humid and subtropical, with about 60% of rainfall occurring during summer months. While 80% of the lake's water budget is controlled by groundwater exchange during dry years (Sacks et al. 1998), two ditches, dredged on the south and east side of the lake in the early part of the twentieth century and connected to a linear ditch lying north–south along the railroad line to the east of the lake, supply intermittent surface flow into the lake during times of high rainfall (Gaiser et al. 2009). A series of shallow seasonal wetlands to the south are within the catchment, and a forested bayhead wetland on the eastern periphery can also connect to the lake during periods of high water. The majority of the catchment lies to the south on ABS and is undeveloped, although a citrus grove was planted about 300 m to the west but outside the watershed of the lake circa 1983, and a degraded cow pasture lies on muck soils to the east of the railroad line and the forested bayhead on the eastern rim of the lake. Although these sources may supplement nutrient delivery to the lake, chlorophyll *a* concentrations indicate oligotrophy (2–10 $\mu g\ L^{-1}$) throughout the 25-yr period of limnological record, and they do not contribute to variance in transparency once water color is taken into account (Gaiser et al. 2009).

Total annual precipitation was calculated from daily values recorded manually since 1931 at the ABS National Oceanic and Atmospheric Administration Cooperative weather station located 2.8 km from the lake. Mean monthly lake level was calculated from weekly measurements made by A. Blair (unpubl.) from 1932 to 1941, by the United States Geological Survey, and then by the Southwest Florida Water Management District (SWFWMD) from 1952 to present at a geo-referenced stage recorder installed at the north edge of the lake, near the outlet. Water transparency has been measured monthly since 1984 using the depth (in cm) of disappearance of a Secchi disk suspended off the shaded side of the boat above the deepest point in the lake. The record was divided into a calibration period (1984–2008) for which rainfall, lake stage, and transparency values were available and a hindcasting (prediction) period (1932–1983) where water transparency was derived from the best combination of rainfall and lake-stage values. To build this model, Secchi transparency values were first logarithmically transformed to avoid negative predictions. Because maximum lake stage normally occurs between October and December after the seasonal peak in rainfall (Gaiser et al. 2009), we developed a stepwise linear regression with maximum lake stage and total annual rainfall as dependent variables and Secchi transparency in December as the dependent variable. We also added maximum stage and total rainfall of the prior year as additional independent variables to account for the ~2-yr water-residence time of the lake (Sacks et al. 1998). The best model was then used to hindcast transparency for the prediction period (1932–1983). Observed and predicted values were then related to the climate indices using linear regression. Mean annual AMO index values were calculated from the Kaplan Sea Surface Temperature Anomaly (SST; Kaplan 2006, available from http://www.cdc.noaa.gov/Timeseries/AMO/), and Southern Oscillation Index (SOI) values were calculated from standardized sea-level pressure difference measured between Tahiti and Darwin (available at http://gcmd.nasa.gov/records/GCMD_NOAA_NWS_CPC_SOI.html).

Results

Total annual precipitation averaged 136 cm over the 75-yr record, from a minimum of 69 cm during a drought in 2000 to a maximum of 194 cm in 1953 (Fig. 1A). Maximum water levels ranged from 33.6 m amsl to 34.5 m amsl during the calibration period and from 33.6 m amsl to 34.3 m amsl during the prediction period. A period of low values (33.6–33.8 m amsl) beginning in the late 1970s was preceded by a steady decline from very high stage values (34.0–34.2 m amsl) that occurred between 1951 and 1963 when annual precipitation was highest. The stage of the lake in 1954 and 1960 was 20 cm higher and in 2005 was 50 cm higher than the period of lowest values between 1975 and1995. During the 1984–2008 period of measure, December Secchi disc transparency averaged 4.1 m, with a high of 6.1 m in 1989 preceding a gradual reduction to a low of 0.7 in 2008 (Fig. 1B). The AMO Index shows three phases: a warm phase from 1932 to 1961, a cold phase from 1962 to 1993, and another warm phase in the recent record beginning in 1994 (Fig. 1B).

The stepwise multiple linear regression found that maximum lake stage described the most variability in Secchi transparency in December of the same year (R^2 = 0.78). Adding maximum lake stage of the year before to the model explained an additional 6% of the variance in December transparency. Total annual precipitation in the

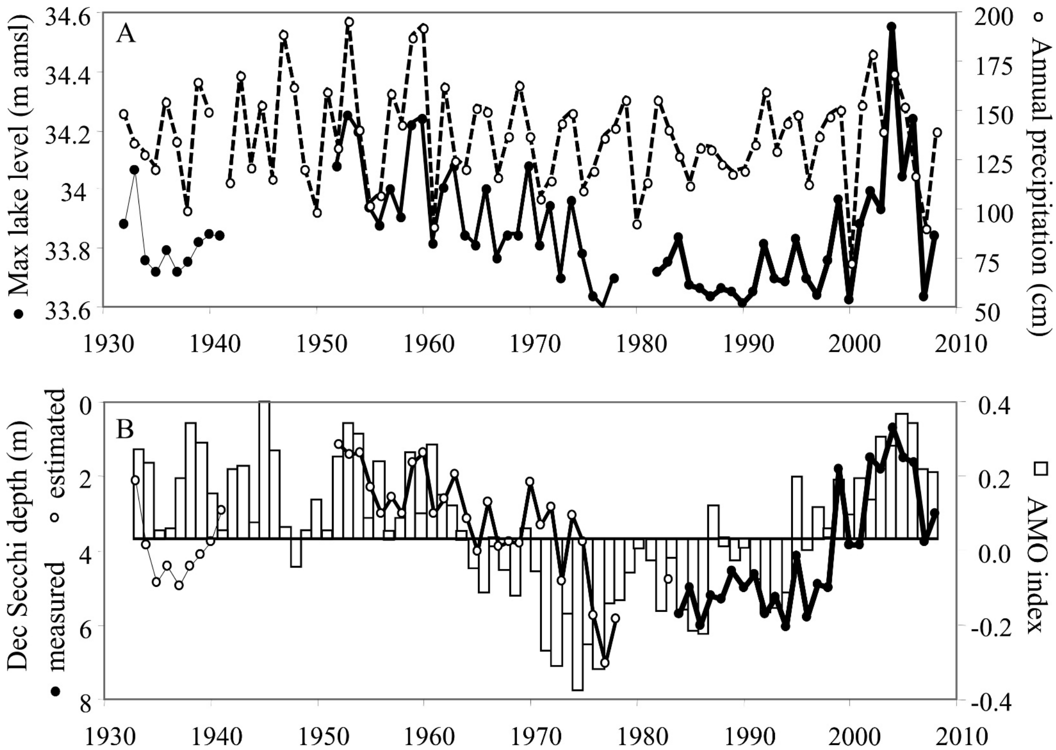

Fig. 1. Long-term records of (A) maximum annual lake level (filled circles) and total annual precipitation (open circles) and (B) December Secchi disk depth measured (filled circles) and predicted from lake level (open circles) plotted with the mean AMO index values (open bars) for the same years. Line thickness for lake level and Secchi depth correspond to the three periods of record (thin lines = 1932–1941, uncalibrated stage; medium lines = 1951–1978, calibrated stage; thick lines = 1982–present, coordinated stage and Secchi recordings).

current and prior years resulted in slight improvement of the model ($R^2 = 0.86$; Fig. 2). The final model used for calibration was log SD $= -0.9888 \times MS_0 - 0.2235 \times MS_{-1} + 0.0007 \times CP_0 + 0.0002 \times CP_{-1} + 41.4629$, where SD is the December Secchi transparency (in m), MS_0 and MS_{-1} are maximum lake stage (in m amsl) of the preceding and penultimate year, respectively, and CP_0 and CP_{-1} are the cumulative precipitation (in cm) of the preceding and penultimate year, respectively. Using this equation, we hindcasted transparency from lake-level values back to 1932 (excluding 1941–1951, when lake level was not measured). The mean predicted transparency was 3.4 m, with a high of 7.0 m occurring in 1977 (Fig. 1B) and a low of 1.3 in 1952 that remained below average until 1963.

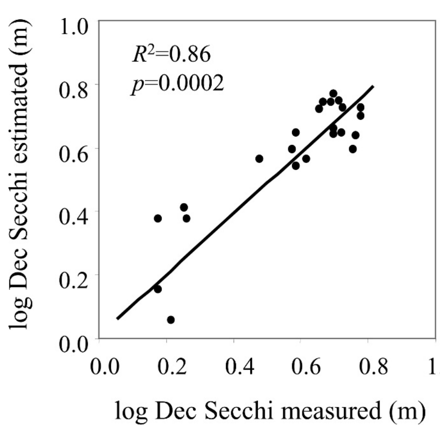

Fig. 2. The relationship between logarithmically transformed December Secchi transparency estimated from the stepwise multiple regression model of maximum lake stage and annual rainfall and measured logarithmically transformed December Secchi disk depth in Lake Annie between 1984 and 2008.

We found a significant correlation between Secchi depth and the AMO, with a stronger relationship ($r^2 = 0.57$) for the period of measure (1984–2005) than for the estimated longer record ($r^2 = 0.19$ for 1932–1983; Fig. 3). If we remove the years where it is unclear whether lake stage was properly calibrated to modern benchmarks (1932–1941), the relationship in predicted values improves ($r^2 = 0.51$ for 1952–1983). In contrast, there was no significant correlation between SOI and the 25-yr measured or 75-yr estimated Secchi depth, and SOI only explained 0.9% more variability in calculated Secchi depth when added to AMO in a multiple linear regression model. The lack of a relationship between SOI and Secchi depth held true for both warm (positive) and cold (negative) phases of the AMO ($r^2 < 0.08$ for both phases).

Discussion

Our estimations of past transparency from our 75-yr record of lake level suggest that the shift between clear and

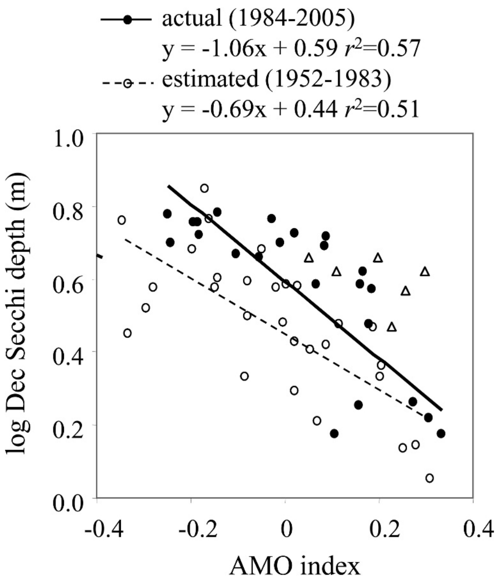

Fig. 3. Relationship between the AMO index and Secchi disk depth measured between 1984 and 2008 (filled circles) and predicted for 1952–1983 (open circles). Values for the earlier, uncalibrated period (1932–1941) are shown (open triangles) but are not included in the prediction model.

stained conditions that characterized the 25-yr limnological record was not unique (Fig. 1B). Instead, this pattern appears to follow a multidecadal cycle that roughly corresponds to the warm and cool phases of the AMO cycle. While our study was neither designed nor intended to study the teleconnections between AMO, ENSO, and Florida rainfall, climatological studies with this focus have shown that these are the major source of interdecadal climate variability in this region (Wanner et al. 2001). In examination of continental scale patterns of precipitation, Enfield et al. (2001) found that the warm phase of the AMO reduces rainfall and exacerbates El Niño winter droughts in the continental interior, while having the opposite influence in Florida where AMO warm phases are generally wetter. Curtis (2008) further linked increased storm activity and increased precipitation intensity in Florida to the warm phase of the AMO during times when the rest of the southeastern United States was in drought. Recent analyses of stage and flow rates in Florida's rivers point to the AMO as an important driver of long-term trends (Tootle et al. 2005; Kelly and Gore 2008). Although this would imply increased water-table heights and shortened water-residence times in lakes and reservoirs, we did not find any published work linking these hydrologic variables to the AMO.

The most recent cool phase of the AMO ran from about 1962 to 1993, overlapping with the first half of the Lake Annie monthly limnological records starting in 1984, and corresponding to a time when groundwater and lake levels were lower and the lake was very clear (Fig. 1B). The earlier AMO warm phase (1932–1961) is associated with a period of lower predicted water clarity (Fig. 1B), although the fixed stage of the outlet reduces the accuracy of model predictions during periods of enhanced water delivery. This coincides with reports of the lake being very darkly stained during the 1950s and 1960s, followed by a time in the 1970s when the lake was reported to be quite clear (J. Layne unpubl.). Climate at low latitudes appears to be strongly regulated by climate cycles with effects that may be exacerbated by stochastic events such as hurricanes and tropical storms (Hanson and Maul 1991). The interplay of deterministic trends with stochastic climate events is best exemplified in the wettest years of the limnological record for Lake Annie, when several tropical storm and hurricane events between 2002 and 2005 followed the extreme drought year of 2000 (all expected consequences of an AMO warm phase) that resulted in the most dramatic shift in transparency observed over the period of record. Although the AMO signal is detected in our record, it explains only about half the variance in transparency, possibly due to the fact that organic materials may be quickly flushed from the parched watershed during large storm events at the onset of a warm phase resulting in a CDOM load that does not persist through the subsequent period of continued high rainfall.

While we did not observe an independent or AMO-modulated effect of ENSO on water transparency, other studies in South Florida have associated El Niño episodes with increases annual and seasonal rainfall that increase runoff, solute delivery to coastal estuaries, and productivity in coastal estuaries (Childers et al. 2006; Morrison et al. 2006). Tootle et al. (2005) showed the importance of ENSO–AMO teleconnections in regulating stream flow across the United States, and found that La Niña events occurring during an AMO cold phase result in significantly greater stream flow than those occurring in an AMO warm phase. However, we did not detect an effect of ENSO on transparency during warm or cold AMO phases. The presence and absence of the AMO and ENSO signals, respectively, in the Lake Annie transparency data may be due to the multi-year lag in response of groundwater level to rainfall. The ENSO signal may have been shortened and dampened in groundwater levels in this watershed to a degree that would not enable detection in altered CDOM transport, while the cumulative multidecadal cycle would have been reflected in groundwater stage, solute concentrations, and dependant limnological features.

The consequences of climate-driven fluctuations in light availability to biotic structure and metabolism in subtropical and tropical lakes have only begun to be explored (Tsai et al. 2008), but this study shows that water clarity can be predicted from climate variables in lakes where local anthropogenic changes have been minimized. Evidence of cyclical controls on solute dynamics from pristine systems can then be applied in order to understand patterns in systems where anthropogenic alterations are superimposed. For example, this study coincides with an examination of AMO signals on solute export from the Florida Everglades (Briceno and Boyer in press), where water delivery is often presumed to be predominantly under human control. Multi-billion dollar hydrologic restoration plans for South Florida have only just started to encompass recent entry into an AMO warm phase that is projected to continue to bring more rainfall and storms through Florida (Enfield et al. 2001). Perhaps because the AMO modulates climate in an opposite pattern to the rest of the continental United States, the majority of the South Florida restoration planning period in the 1980s and 1990s did not take the AMO into account. The critical discrimination of cyclical from directional climate controls on long-term changes observed in lakes will require commitment to long-term data collection programs. To this end, Lake Annie was brought into the Global Lake Ecological Observatory Network (GLEON) in February 2008 and was equipped with a suite of high-resolution limnological sensors that will enable analyses of climatic responsiveness across a multitude of spatial and temporal scales.

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