Biophysical effects of a decadal shift in summer wind direction over the Laurentian Great Lakes

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Analysis of summer surface wind fields over the Laurentian Great Lakes from 1980 to 1999 show a statistically significant shift in wind direction beginning around 1990. Directional changes in the average wind field over the Great Lakes basin are consistent with a southward migration of the dominant summer storm track. In Green Bay (NW Lake Michigan), we show that the new wind field has most likely resulted in a decrease in water mass exchange with Lake Michigan leading to a decrease in bottom water hypoxia, warmer bottom water temperatures and an increase in benthic microbial metabolism. INDEX TERMS: 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 1845 Hydrology: Limnology; 4215 Oceanography: General: Climate and interannual variability (3309); 4804 Oceanography: Biological and Chemical: Benthic processes/benthos

1. Introduction

Wind direction over the Laurentian Great Lakes is predominantly controlled by midtropospheric flow and the periodic passage of mobile cyclonic low-pressure systems and their associated fronts [Eichenlaub, 1979]. Lows traveling through the Great Lakes region frequently follow one of two major storm tracks that run just north and south of the lakes before converging over the St. Lawrence River basin (Figure 1). The distribution of lows between the two storm tracks has been shown to change with the seasons and from year to year depending on the latitude and zonal index of the Polar jet [Hayden, 1999]. During the summer, the majority of lows have historically followed a northern track roughly tracing the border between the United States and Canada [Isard et al., 2000]. To determine to what extent this pattern has varied from summer to summer and what effect storm track variation has had on surface wind fields, we here examine hourly, buoy-recorded, summertime wind vectors spanning a 20-year period beginning in 1980 and show that a major shift in wind direction occurred at—and has persisted since—the end of the 1980s.

We demonstrate the potential biophysical effects of a wind shift on coastal and estuarine-like regions of the Great Lakes by showing how temperature, oxygen concentration and methane production in a 298 km² area of southern Green Bay (gray shaded region, Figure 1—inset) responded to two different wind fields that occurred over two consecutive summers. Because wind-driven circulation reduces the water residence time of lower Green Bay from ~ 3.5 years (based on simple riverine inputs) to less than one year [Miller and Saylor, 1993], the effects of a wind shift over Green Bay are particularly relevant to understanding pollution loading to Lake Michigan since Green Bay provides the largest single source of nutrients and PCBs to the lake. Over 20% of the estimated total phosphorus loading and over 53% of the PCB loading to the lake is discharged from the Fox River (FR, Figure 1—inset) [Robertson, 1996] and any wind induced change to circulation in the bay could be important to ultimate transport into Lake Michigan. We limited our investigation to the summer months of June through September because of the increased effect a wind shift would have on the biophysical parameters of a thermally stratified freshwater system.

2. Experimental

Hourly wind speeds and directions from nine Great Lakes meteorological stations (Figure 1, filled circles) were obtained from the World Wide Web database of the National Data Buoy Center (NDBC). Onshore stations, with the exception of DBNL6 in eastern Lake Erie, were excluded from the study to avoid the possible effects of changing shoreline obstructions on local wind direction over the course of 20 years. Green Bay surface temperatures were obtained from AVHRR satellite imagery from the NOAA Great Lakes CoastWatch Program [Schwab et al., 1992]. Water column data from Green Bay including temperature, oxygen and methane concentrations were collected on a series of 12 cruises during 1994 and 1995 [Cruise dates (and equivalent calendar days) relative to this paper are: 1994) 03 June (154), 13 July (194), 02 August (214), 23 August (235), 13 September (256) and 25 October (298); 1995) 23 May (143), 19 July (200), 29 August (241) and 10 October (283)].

The flux (J) of methane across the air-water interface of southern Green Bay was calculated using Fick’s first law of diffusion,

\[ J = \Delta C \cdot K, \]

where \( \Delta C \) is the concentration gradient of CH\(_4\) across the air-water interface and K is a transfer coefficient empirically correlated with wind speed. Daily estimates of methane flux in each zone were calculated using measured (and linearly interpolated inter-cruise) surface water concentrations, measured and interpolated partial pressures of atmospheric methane, hourly shear-corrected wind velocities from buoy no. 45002, and the wind speed/transfer coefficient relationships determined by Broecker et al. [1978]. Approximately 20 ± 5 measurements of methane were made during each cruise through the (shaded) region of interest in Figure 1. Spatially weighted average concentrations of methane were calculated using an exact inverse distance method. Weighted averages calculated using a simple linear Kriging method agreed to within 10%. Surface water temperatures required to calculate methane-specific transfer coefficients were derived from AVHRR satellite imagery. A complete description of the methods can be found in Waples [1998].

3. Results and Discussion

Because of our interest in the effects of atmospheric forcing on water circulation in Green Bay, we first examined the temporal (summertime) variation in wind direction at buoy no. 45002 in northern Lake Michigan (i.e. the closest buoy to Green Bay). Monthly-averaged wind vectors for June, July, August and Sep-
of the late 1990s revealed backed 42° over the entire Great Lakes area (Figure 3a), winds were observed during each of the four months with the largest directional spread occurring in July (185°–249°). Wind directions plotted as centered 5-year running averages (Figure 2, gray line) showed that winds gradually veered (clockwise) as the summer progressed from June through September. 

Wind direction was observed (i.e., an endpoint shift of only 5°) during June of 1980, 1985, 1987 and 1989. In September, however, the null hypothesis was not rejected (α > 0.2).

[8] Interpolated wind fields over the Great Lakes region were calculated with averaged wind vectors from August of 1981–1985 and August of 1995–1999 at all nine meteorological stations (see Figure 1). While summer winds during the early 1980s tended from the south over the entire Great Lakes area (Figure 3a), winds backed to varying degrees at all buoyed stations by the late 1990s (Figure 3b) with the largest change in net wind direction occurring over the southern half of the Great Lakes. Subtracting the wind field of the late 1990s from the wind field of the early 1980s revealed synoptic-scale coherence in the wind shift (Figure 3c). The U (East-West) component of the averaged surface wind vectors decreased in the late 1990s by an average of 0.4 m sec⁻¹ with the largest decrease of 1.1 m sec⁻¹ occurring in northern Lake Michigan (buoy no. 45002) and the smallest decrease of less than 0.1 m sec⁻¹ occurring in eastern Lake Erie (station no. DBLN6). Changes in the V (North-South) component of the averaged surface wind vectors correlated strongly with latitude (r² = 0.77) and ranged from an increase of 0.8 m sec⁻¹ in northern Lake Superior (buoy no. 45001) to a decrease of 0.7 m sec⁻¹ in southern Lake Erie (buoy no. 45005).

[9] The most likely explanation for this shift in wind direction is a southward displacement of the dominant summer storm track. Preliminary analysis of 4x daily sea level pressure data from the NCEP-NCAR Reanalysis project supports this hypothesis. When averaged surface winds over northern Lake Michigan (at buoy no. 45002) tended from the WSW during June of 1980, 1985, 1987 and 1998 (see Figure 2), the dominant storm track was located just north of the Great Lakes basin at ~52°N latitude. During June of 1992, 1993, 1995 and 1996, however, when averaged winds over northern Lake Michigan tended from the SE, the dominant storm track ran approximately 11 degrees further south at ~42°N latitude.

[10] Wind-driven changes in estuarine circulation and coastal hydrodynamics have been shown to affect water column profiles of temperature, salinity and dissolved oxygen [Goodrich et al., 1987; Welsch and Eller, 1991] as well as fish and invertebrate populations [Kilgour et al., 2000; Officer et al., 1984]. Specific physical
effects of a summer wind shift on each of the Great Lakes, however, will depend primarily on basin morphometry and geographical orientation to the new wind field. Moreover, the secondary and tertiary effects of a shift in wind direction may not be intuitive. Our observations in Green Bay are a case in point.

Wind speeds over northern Lake Michigan—and presumably Green Bay—were quite similar during the summers of 1994 and 1995 (Figure 4a). During July of both years, averaged SSW winds of 196° (1994) and 190° (1995) blew parallel to the major axis of Green Bay [Figure 4b, (1)]. As wind-driven transport of warm surface water out of the bay initiated a return flow of cold Lake Michigan water below the thermocline—a phenomenon observed in at least 3 out of 4 summers between 1985–1988 by other investigators as far south as the mouth of the Fox River [Kennedy, 1991]—bottom water temperatures in the southern bay fell [Figure 4c, (2)]. This phenomenon continued during August of 1994 as averaged winds blew from the SW (238°). In August of 1995, however, averaged SE winds of 134° [Figure 4b, (3)] blew perpendicular to the major axis of the bay [frequency analysis of hourly wind vectors revealed that winds from the SW and NW quadrants dropped from 72.8 % of the total (n = 742) during August of 1994 to only 31.2 % of the total (n = 740) during August of 1995] and water mass exchange with Lake Michigan effectively came to a halt. While bottom water temperature in the southern part of the bay consequently decreased as the summer progressed in 1994 (from 18.1°C on 13 July to 11.4°C on 23 August), they increased in 1995 (from 13.7°C on 19 July to 22.3°C on 29 August) [Figure 4c, (4)]. These differences in thermal stratification affected the rate of oxygen transport to bottom waters. Increased stratification inhibited vertical mixing in 1994 and bottom waters of southern Green Bay turned hypoxic as oxygen concentrations decreased from 9.9 mg L⁻¹ (or 107% saturation) on 13 July to 0.8 mg L⁻¹ (or 7 % saturation) on 23 August. In 1995, the opposite occurred as nearly isothermal conditions allowed vertical mixing to occur and bottom water oxygen concentrations increased from 2.7 mg L⁻¹ (or 27 % saturation) on 19 July to 6.0 mg L⁻¹ (or 71 % saturation) on 29 August [Figure 4d, (5)]. Differences in bottom water temperature in southern Green Bay appeared to affect methane production in underlying anaerobic sediment as well. Microbial metabolism is a temperature dependent process with methane production rates typically showing a 2.5 to 3.5-fold increase for each 10°C rise in temperature at ambient temperatures ranging from 5 to 30°C [Klump and Martens, 1989]. This is
consistent with measured Arrhenius constants of ~23 kcal mol\(^{-1}\) for Green Bay sedimentary carbon metabolism (J. V. Klump, unpublished data). The average flux of methane to the atmosphere in July of 1995 (0.09 mmol m\(^{-2}\) day\(^{-1}\)) lagged the previous year’s estimate during the same time period (0.15 mmol m\(^{-2}\) day\(^{-1}\) in July 1994) just as bottom water temperatures in July of 1995 were ~4°C lower than the previous year’s level. When bottom water temperatures in August of 1995 rose ~12°C above the previous year’s level, methane flux to the atmosphere doubled from an average of 0.24 mmol m\(^{-2}\) day\(^{-1}\) in August of 1994 to 0.49 mmol m\(^{-2}\) day\(^{-1}\) in August of 1995 [Figure 4e, (6)]. We attribute the increase in methane flux to an increase in methane production rather than an (short-term) increase in ventilation of the water column methane inventory. Methane flux during August of both years exceeded the total standing stock of methane in the water column by a factor of ~20. [Incubation experiments with water samples collected from Sturgeon Bay (SB, Figure 1—inset) show methane oxidation to be a negligible sink for methane compared to ventilation to the atmosphere].

[12] Because summertime cross-axial wind regimes over Green Bay have become more frequent in the 1990s, based on our observations in 1994 and 1995, we predict that, compared to the 1980s, water mass exchange with Lake Michigan has decreased, leading to weaker thermal stratification and increased vertical mixing. Increased vertical mixing would increase summertime bottom water oxygen concentrations as well as temperature, leading to increased microbial metabolism and a potentially significant reduction in the flux of carbon, nutrients and other chemicals to Lake Michigan.

[13] Consideration of the local wind field history is crucial to understanding coastal and estuarine ecosystems and may help to explain fluctuations in chemical inventories and biological populations that might otherwise be attributed to anthropogenic stress or coastal management and remediation efforts [Peterson et al., 1995; Jickells, 1998]. Furthermore, recent assessments of the possible impact of climate change on the Laurentian Great Lakes [Mortsch and Quinn, 1996; Magnuson et al., 1997; Sousounis and Bissan, 2000] have not considered the likelihood of a shifting wind field and its concomitant effects. We believe that this needs to be addressed.

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