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

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[1] 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

[2] 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.

[3] 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 km^2 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 $\sim$ 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

[4] 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 DBLN6 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)].

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

$$J = \Delta C * K,$$

where ΔC 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

[6] 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-

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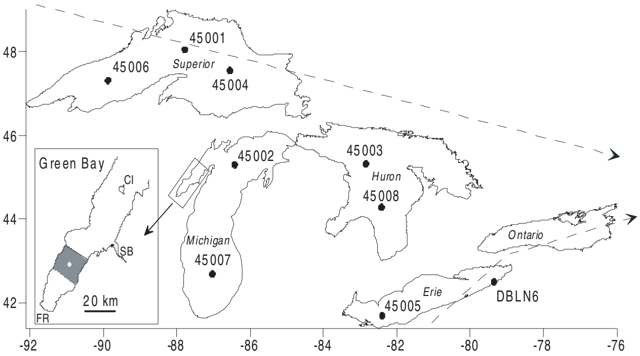

Figure 1. Storm tracks, shown in stylized form (dashed lines), lie north and south of the Laurentian Great Lakes basin. Evidence of a summer wind shift over the Laurentian Great Lakes was found in a 20-year record of hourly wind vectors recorded at nine NDBC meteorological stations (filled circles). Biophysical effects of a shift in the wind field were observed in southern Green Bay (inset, gray shaded region). Water column profiles were measured at station GB17 (inset, open circle). Other geographical features are identified in the text.

tember of 1980–1999 were calculated from hourly wind speeds and directions and are shown in Figure 2 (dotted line). Not surprisingly, large variations in average wind direction were observed during each of the four months with the largest directional spread occurring in June (85°–249°) and the smallest 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. Winds during any given month, however, backed (counterclockwise) from the southwest to the south over the course of 20 years. During June, winds backed 44° between the 1982 and 1997 centered averages. A similar shift of 28° occurred during July and a shift of 61° occurred during August. In the September winds, however, no significant change in direction was observed (i.e. an endpoint shift of only 5°).

[7] This shift in wind direction appeared to begin at the end of the 1980s. Decade averaged wind vectors (Figure 2, solid arrows) showed directional changes of similar magnitude to the 5-year endpoint averages of 1982 and 1997. Compared to the average wind direction of the 1980s, the average wind direction in the 1990s backed 42° during June, 26° during July, 38° during August and only 16° during September. We tested the null hypothesis—that the change in wind direction could have occurred by chance—using the distribution free Wilcoxon rank-sum test and found that the wind shifts were statistically significant for June ($\alpha \leq 0.01$), July ($\alpha \leq 0.01$) and August ($\alpha \leq 0.03$). In September, however, the null hypothesis was not rejected ($\alpha > 0.2$).

[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 southwest 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 ($r^2 = 0.77$) 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 1988 (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

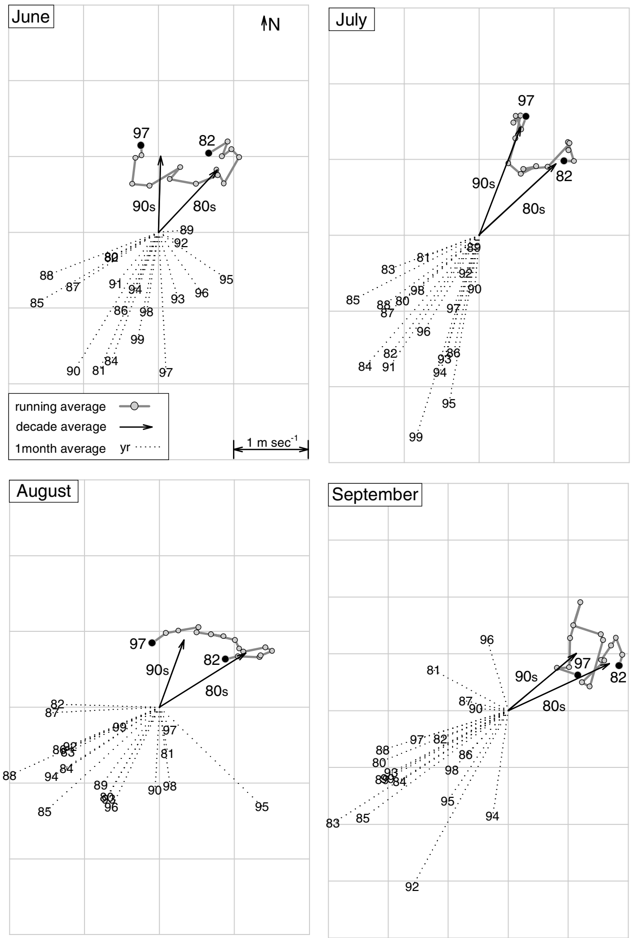

Figure 2. Month averaged wind vectors from northern Lake Michigan (NDBC buoy no. 45002) for June, July, August and September of 1980–1999. Vectors for each year (yr—dotted line) are plotted with heads at the origin. Gray circles (connected inline) represent vector heads of a centered 5-year running average of monthly wind vectors with tails at the origin (not shown). The end point vector heads of 19(82) and 19(97) are shown as black circles. Decade averaged vectors (80s and 90s) for each month are shown as arrows with tails at the origin. Wind vectors were recorded for 92.6% of the specified (58560 hour) time period. Buoy no. 45002 was not operational during the months of June 1983, August 1991 and September 1991.

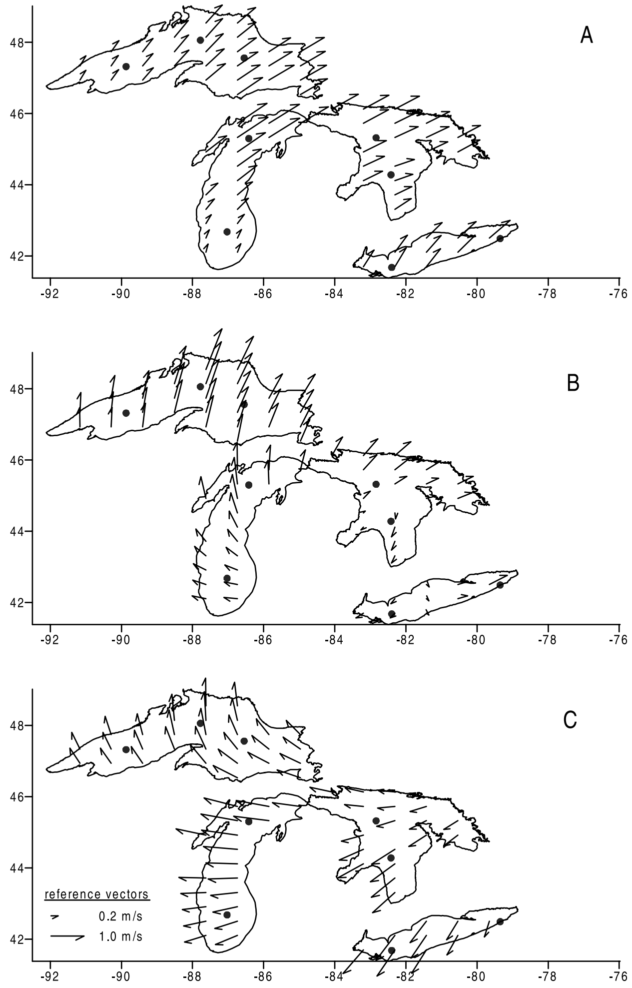

Figure 3. Average August wind field over the Great Lakes basin in (a) 1981–1985 and (b) 1995–1999. (c) Change in the wind field between 1981–1985 and 1995–1999. Wind vectors were recorded for 95.5% of the specified (66960 hour) time period. No wind data was available in: *i*) August of 1981 at stations DBLN6 and 45008 and *ii*) August of 1982 at station DBLN6. Grid node values in a 150 × 150 node matrix were calculated using an exact inverse distance method. Terrestrial grid nodes (outside of the Great Lakes shoreline boundary) were blanked. The NDBC does not maintain a meteorological buoy on Lake Ontario. We therefore excluded the lake from our analysis of wind fields.

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.

[11] 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

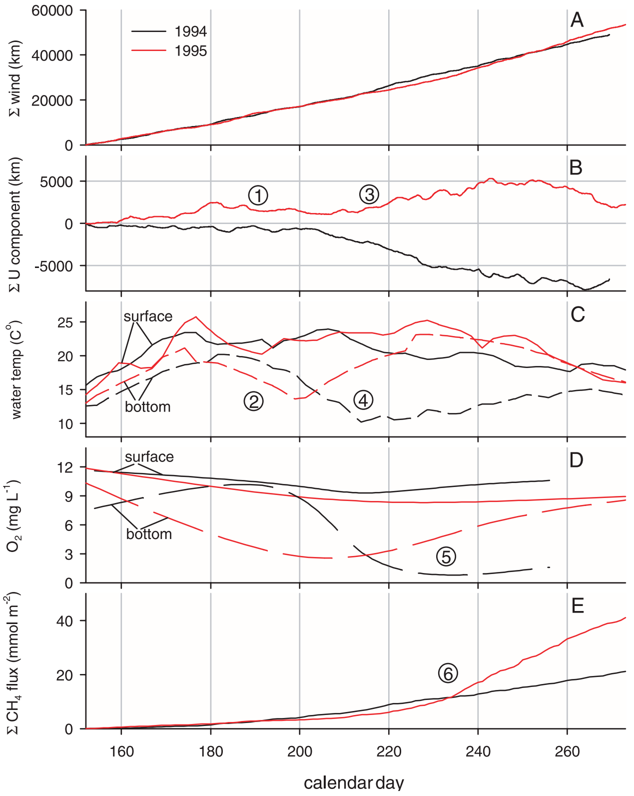

Figure 4. Biophysical effects of wind direction over the southern Green Bay study site (shaded area, Figure 1—inset) from 01 June to 30 September of 1994 and 1995. Labeled events (1–6) are discussed in the text. (a) Wind speed measured at NDBC buoy no. 45002 (shown as total distance traveled). (b) Progressive U component of wind vector where positive value indicates easterly flow. (c) Surface and bottom water temperature based on AVHRR satellite imagery and CTD casts at station GB17 (open circle, Figure 1—inset). (d) Surface and bottom water oxygen concentrations obtained from CTD/O_2 electrode casts at station GB17. (e) Accumulative methane flux to the atmosphere.

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 Bisanz*, 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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