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Record-Breaking Lake Erie Hypoxia during 2012 Drought

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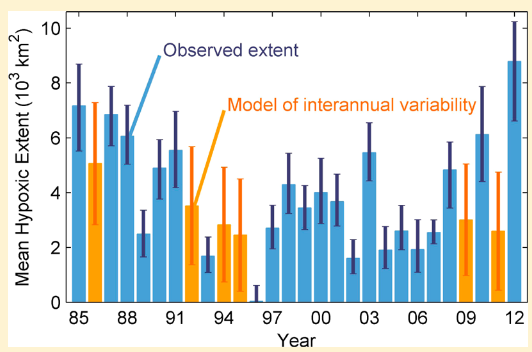
S *Supporting Information*

ABSTRACT: Hypoxia has been observed in the central basin of Lake Erie for decades. To understand the impact of various controlling factors, we analyze a record of hypoxic extents for Lake Erie for 1985–2012 and develop a parsimonious model of their interannual variability. We find that the 2012 North American drought and accompanying low tributary discharge was associated with a record-breaking hypoxic event in Lake Erie, whereas a record-setting harmful algal bloom in 2011 was likely associated with only mild hypoxia. River discharge and the timing of nutrient input therefore impact western basin bloom growth and central basin oxygen demand in distinct ways that merit further investigation. Overall, April to June tributary discharge, May to July soluble reactive phosphorus loading, July wind stress, and June northwesterly wind duration explain 82% of the interannual variability of hypoxia, and discharge alone explains 39%, indicating that meteorological factors need to be considered in the development of nutrient management strategies, especially as both extreme precipitation events and droughts become more frequent under a changing climate.



INTRODUCTION

Coastal and freshwater eutrophication exacerbated by human activity is a global problem,[1,2] with the presence of hypoxic zones and harmful algal blooms (HABs) being two consequences of primary concern.[3,4] Lake Erie, one of the Laurentian Great Lakes that together make up one of the two largest surface freshwater systems on Earth, has experienced a re-eutrophication that has been widely reported through its impacts on the size of the hypoxic zone in its central basin,[5,6] and on the resurgence of HABs in its western basin and beyond.[7,8] Although the effects are well documented, quantitative metrics for evaluating the interannual variability of HAB[8,9] and hypoxic[5,10] extent and/or intensity have only recently become available. With the current generation of 3D mechanistic models[11] not yet capable of modeling hypoxia on decadal time scales, statistical models[5] and reduced dimension mechanistic models[10] have been shown to be useful in predicting hypoxic extent.

Anthropogenic activity has the potential to impact hypoxia and HABs through both regional and global interactions. One salient example is the record-setting HAB that occurred in Lake Erie in 2011 and that was attributed to a confluence between trends in regional agricultural practices and various climatological factors, chief among them extreme springtime precipitation events, and where the climatological factors were shown to be consistent with those expected to be more frequent under anthropogenically driven climate change.[7] A second example is the widespread drought in North America that peaked in 2012 (Figure S1, Supporting Information (SI)), and that was associated with a relatively small algal bloom.[12] This drought is another example of the types of extreme climate events that are expected to occur more frequently under climate change.[13]

Here we quantify the hypoxic conditions for these two unusual years within the context of a 28-year period of record, and identify the meteorological and management (i.e., nutrient loading) factors that explain the interannual variability in the extent of the summertime hypoxic zone in the central basin of Lake Erie.

DATA DESCRIPTION AND METHODOLOGY

Cruise-Specific Hypoxic Extent Quantification. Zhou et al.[5] recently presented the first approach capable of probabilistically quantifying the spatial extent of Lake Erie hypoxia, as well as its associated uncertainty, based on limited in situ observations of bottom water dissolved oxygen (BWDO) (Figure 1) and available ancillary information (e.g., location, bathymetry, lake surface temperature, and chlorophyll concentration). The resulting hypoxic extent record and BWDO concentration covered 1987 to 2007, the period over which fully consistent remote

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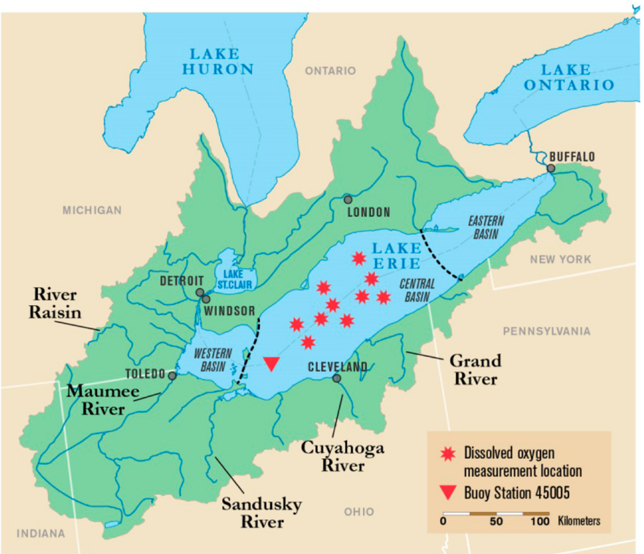

Figure 1. Map of Lake Erie watershed, major tributaries, and measurements used in the analysis. The locations of the regular dissolved oxygen measurement locations are shown in red stars, and the location of the buoy used for wind and lake surface temperature measurements is shown as a red triangle.

sensing temperature and chlorophyll concentration data are available.

The final geostatistical model in Zhou et al.[5] only relied on time-invariant ancillary information in the form of longitude and bathymetry, in addition to BWDO, making it possible to extend the period of record to 1985 to 2012 (Table S1, SI), the period over which regular BWDO sampling has been conducted in Lake Erie.

The focus of this work is on August and September, when the hypoxic extent typically reaches its maximum. We restrict our analysis to the central basin of Lake Erie, the basin most susceptible to hypoxia due to its morphology, strong stratification and nutrient loading. The spatial resolution of the estimated BWDO distribution is 2.5 × 2.5 km^2. Hypoxic extents are quantified for individual cruises (Table S1, SI) for 1985 to 2012 using universal kriging and conditional realizations as described in Zhou et al.[5] Detailed descriptions and equations for universal kriging and conditional realizations are available in Zhou et al.,[5] and key steps are summarized in the SI.

BWDO measurements used in the analysis were collected by the U.S. EPA Great Lake National Program Office,[14] Environment Canada (EC),[15] and the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL).[16] BWDO was measured at 1–2 m above the lake bottom at each sampling location. Bathymetry data are from the NOAA National Geophysical Data Center.[17] Additional details about the data used are available in the SI.

Note that for the 1985–2012 period examined here, BWDO data are not available during the early hypoxic season (August 2–22, see next section) of 1992, 1994, 1995, and 2009 and for the late hypoxic season (August 23 to September 26) of 1986 and 2011 (Table S1, SI). Limited BWDO profiles were collected in 2011 by the Water Quality Monitoring and Surveillance Division of EC (http://www.ec.gc.ca) on September 7 along the northeast shore of the central basin, and on September 12–14 near the western edge of the central basin.

Deriving Seasonally Averaged Hypoxia, Including Early Season/Late-Season Designation. On the basis of the timing of available BWDO measurements, the resulting hypoxic extent estimates are divided into four periods: August 2–12, August 13–22, August 23 to September 5, and September 6–26.[5] Most years do not have observations during all four periods, and therefore we define the average hypoxic extent within the range of August 2–22 as the "early season" and the average hypoxic extent between August 23 to September 26 as the "late season". These date ranges were defined with the goal of (i) minimizing any bias that would have occurred from simply averaging across multiple cruises over a full season in cases where multiple cruises are actually sampling a similar time period, (ii) binning dates based on time of typical data availability, and (iii) creating two periods of comparable length. The hypoxic extent conditional realizations from individual cruises are first averaged within the early and late season, and the resulting estimates are then averaged between the early and late season to create an estimate of the seasonally averaged hypoxic extent and its uncertainty. Seasonally averaged hypoxic extent estimates are therefore obtained for all years for which at least one cruise is available during both the early and late season, namely all years except 1986, 1992, 1994, 1995, 2009, and 2011 (Figure S2, SI), or 22 years within the 28-year analysis period.

Model of Interannual Variability. The new 1985 to 2012 record of hypoxic extents is used to identify the factors explaining their interannual variability, using those years for which both early season (August 2–22) and late-season (August 23 to September 26) hypoxic extent estimates are available (Figure S2, SI). We develop a parsimonious linear model of interannual variability based on variables and associated mechanisms that are hypothesized to impact hypoxia, as described in SI. Overall, eight factors that describe both management (i.e., external nutrient loading) and meteorological conditions are considered (Table 1, Table S2, SI). Phosphorus has previously been shown

Table 1. Summary of Variables Considered for the Model of the Interannual Variability in Summertime Hypoxia in Lake Erie[a]

	variable group[b]	basins	months considered	# variables	selected variable[c]
1	current year TP and *SRP* loading and concentration	western, central, both	January to July	104	$SRP_{\text{May-Jul}}$
2	previous year TP and *SRP* loading	both	January to December	4	
3	river discharge	western, central, both	January to July	132	$\ln(D_{\text{Apr-Jun}})$
4	wind speed	central	May to September	23	WS^2_{Jul}
5	wind duration by direction	central	May to September	260	$WD_{\text{NW,Jun}}$
6	lake surface temperature	central	April to September	21	
7	precipitation	lake average	March to September	28	
8	ice cover	full lake	March to April	3	

[a]Details are available in SI and Table S2. [b]Linear relationships considered for all variables; linear and natural logarithm relationship considered for discharge; linear and quadratic relationship considered for wind speed. [c]Variables are as defined in eq 3.

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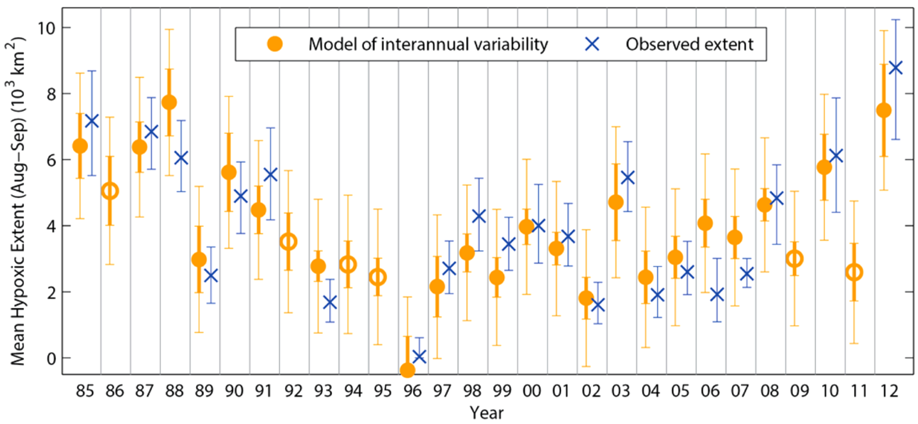

Figure 2. Annual seasonally averaged hypoxic extent from 1985 to 2012. Observed hypoxic extent is in blue, with bars indicating the 95% confidence intervals. Model of interannual variability (eq 3), is in orange, with closed symbols representing years used for model selection and calibration (i.e., years with observed hypoxic extents), open symbols representing predictions for unsampled years, thick bars representing 95% model confidence intervals, and thin bars representing 95% model prediction intervals for individual years.

to be the limiting nutrient in lakes, including Lake Erie.[6,15,18] River discharge into the lake can affect lake conditions in variety of ways, including changes in circulation and stratification. Meteorological factors including wind speed, wind direction, air temperature, and precipitation will affect stratification and circulation in the lake.[10,19] Finally, ice cover has been shown to promote winter diatom blooms that have been hypothesized to fuel the following summer's hypoxia.[20] Details about these data sets are provided in the SI. In order to give the model flexibility in the timing and functional form of the relationship between these factors and hypoxic extent, each factor is represented by multiple candidate variables, yielding 575 variables in all (Table S2, SI).

The Bayesian Information Criterion (BIC) is used to select the subset of candidate explanatory variables that best represents the interannual variability in the seasonally averaged hypoxic extent for 1985 to 2012. BIC considers both the goodness of fit and the number of variables in a candidate model,[5,21,22] and is defined as follows:

$$\mathrm{BIC} = -2\cdot\ln((\mathbf{y} - \hat{\mathbf{y}})^T(\mathbf{y} - \hat{\mathbf{y}})/n) + k\cdot\ln(n) \tag{1}$$

where $\mathbf{y}$ ($n \times 1$, 10^3 km^2) represents the seasonally averaged hypoxic extent for each of the $n = 22$ available years, $\hat{\mathbf{y}}$ ($n \times 1$) is the estimated hypoxic extent based on a multiple linear regression model involving a given subset of candidate variables, k is the number of variables in the linear model (i.e., the number of auxiliary variables plus an intercept), and T denotes a matrix transpose.

Given the large total number of candidate auxiliary variables, and the fact that many of them are strongly collinear and representative of similar types of driving processes, we restrict the final selected model to include at most one variable from each of the eight categories of variables, as was also done in, for example, Mueller et al.[22] Therefore, k varies from 2 to 9, including the intercept. BIC is tabulated for all candidate models for each size k, and the model with the lowest BIC is identified as the best model of that given size. This is also the model with the highest R^2 for a given model size (Figure S3, SI). Nominally, the model with the lowest BIC, across all model sizes, is typically considered the "best" model overall. However, given the relatively small sample size ($n = 22$) considered here, we used a BIC difference of 2, which corresponds to "positive" evidence in favor of the model,[23] as the threshold for choosing a larger model with a lower BIC over a smaller model with a higher BIC.

Once the variables included in the best model are identified, the relationship between the selected variables and the interannual variability in the seasonally averaged hypoxic extent (i.e., $\mathbf{y}$) is represented using multiple linear regression:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \tag{2}$$

where $\mathbf{X}$ is an $n \times k$ matrix of the selected variables and a column of ones representing the intercept term, β is a $k \times 1$ vector of drift coefficients for the selected variables and the intercept, and ε is an $n \times 1$ vector of regression residuals. Estimates of the drift coefficients, their uncertainties, and the impact of these uncertainties and their covariances on hypoxic extent predictions are obtained using standard tools as described in the SI. To evaluate the linearity assumption, we examine scatterplots of the bivariate relationship between hypoxic extent and each variable; and between the hypoxic extent residuals from the final multiple linear regression with one variable removed and this individual variable.

RESULTS AND DISCUSSION

Historical Hypoxic Extents. The expanded record (Figure 2, Figure S2, SI) reveals that 2012 experienced the single largest ($p = 0.10$) seasonally averaged hypoxic extent in the 28 year record (8.79 ± 0.91 [10^3 km^2]). Interestingly, the second largest hypoxic season occurred in 1985 (7.17 ± 0.79 [10^3 km^2]), the first year in the record. 2012 also experienced the single largest observed individual hypoxic extent (August 30–31, 10.81 ± 2.03 [10^3 km^2], Figure S4, SI), slightly larger than the previous record in 1987 (September 15–17, 10.15 ± 1.14 [10^3 km^2]), although the difference is not statistically significant ($p = 0.39$). These estimated BWDO concentrations are also statistically consistent with independent near-shore measurements.[24]

Perhaps ironically, except for an early August cruise (August 10, 2011) that showed no early season hypoxia, BWDO data from the Environmental Protection Agency for the 2011 season are not available due to equipment failure,[25] leaving unresolved for the time being the question of the hypoxic extent for the season coinciding with the record-setting HAB.[7] Limited mid-September observations from Environment Canada[26] adjacent to the northeast shore of the central basin and the western edge of the central basin recorded no hypoxic measurements, but these times and locations are not expected to

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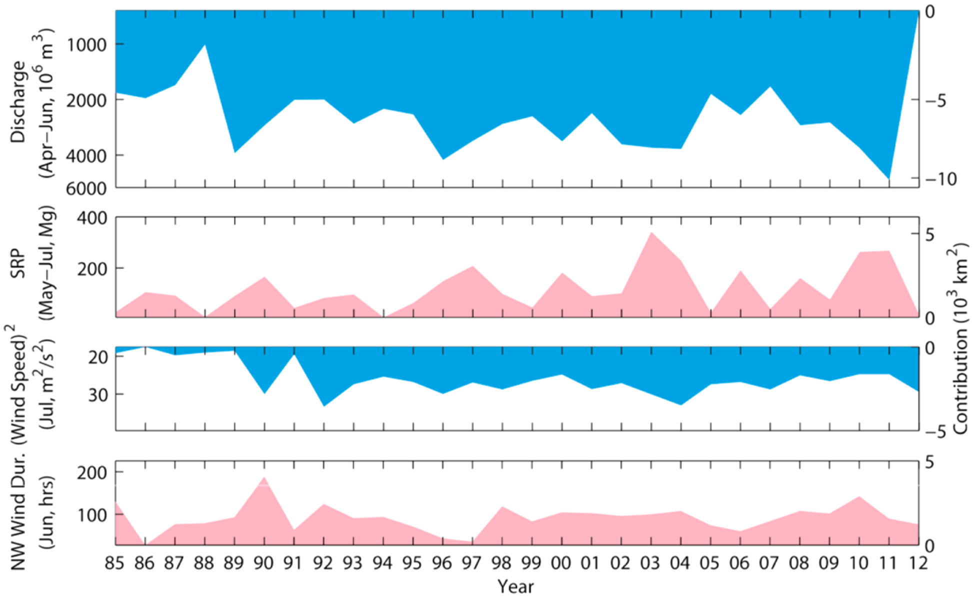

Figure 3. Historical record of variables contributing to the model of seasonally averaged hypoxic extent interannual variability, and their contribution to the model for each year. The contributions are based on the model presented in eq 3, and illustrated here relative to the year of minimum impact for each variable. Variables associated with a relative reduction in hypoxic area are presented as blue areas, whereas variables associated with a relative increase in hypoxic area are presented as pink areas. Note the sign differences for the "Contribution" axis between these two variable categories, and the logarithmic scale for discharge.

reliably represent summertime hypoxic conditions in the central basin, neither in space nor in time.

Model of Interannual Variability. A model ($\hat{y}$, 10^3 km^2) composed of just four variables is found to explain 82% of the interannual variability in the seasonally averaged hypoxic extents (Figures 2, 3):

$$\hat{\mathbf{y}} = 43.00 - 4.79 \cdot \ln(D_{\mathrm{Apr-Jun}}) + 0.0153 \cdot SRP_{\mathrm{May-Jul}} - 0.225 \cdot WS_{\mathrm{Jul}}^2 + 0.0251 \cdot WD_{\mathrm{NW,Jun}} \quad (3)$$

where $D_{\mathrm{Apr-Jun}}$ (10^6 m^3) is the total river discharge to the Western and Central basins from the Maumee, Raisin, Sandusky, Cuyahoga, and Grand Rivers from April to June, $SRP_{\mathrm{May-Jul}}$ (Mg) is the total *SRP* load to the Western and Central basins from these same rivers from May to July, WS_{Jul}^2 (m^2/s^2) is the average squared hourly wind speed in July (a term proportional to wind stress), and $WD_{\mathrm{NW,Jun}}$ (hrs) is the total duration of June northwesterly winds (270° to 360°). The same four variables were identified when 2012, with its extreme hypoxic event, was excluded from the variable selection as a sensitivity test. A leave-one-out cross-validation using the four selected variables yielded $R^2 = 0.64$.

The model presented here is the result of an empirical retrospective statistical analysis of the interannual variability of hypoxic extents, with the inclusion of variables based on their explanatory power and a confirmation of the validity of linear assumptions (Figure 4). The selected variables and their relationships to hypoxic extent do also provide insights into controlling processes in many cases. In others, they reveal the need for further process-based research to elucidate mechanistic linkages, and thereby illustrate the complementary benefits of statistical and mechanistic modeling strategies.

Previous studies have focused largely on anthropogenic phosphorus loading as the primary driver of central basin hypoxia,[6] but in this study, tributary inflow is found to explain the largest portion of the interannual variability of seasonally averaged hypoxic extent (Figure 3). The April to June period is similar to the March to June discharge time frame identified as critical for explaining bloom intensity of HABs in Lake Erie.[8] However, while higher discharge is found here to be associated with lower hypoxia, it has been shown to correlate with higher HAB intensity.[8] Mechanistically, higher discharge can lead to changes in circulation, residence time, and stratification. Further analysis showed that the combined discharge of all western and central basin tributaries is small relative to the volume of the central basin,[27] therefore its impact on residence time and stratification should be minimal. In addition, discharge from small tributaries has been shown to only affect circulation locally.[28] Although discharge from the Detroit River, the main inflow into Lake Erie, was also considered, it was not found to improve the model's explanatory power, likely due to its minimal interannual variability, resulting from the fact that it represents the discharge from Lake St. Clair and the upstream Great Lakes and is therefore not directly representative of hydrologic conditions in the Lake Erie watershed. It is also possible, therefore, that the significance of the tributary discharge term included here is representative of the impact of meteorological conditions that correlate with discharge but that are not represented in the candidate variables examined here. Overall, river discharge (i.e., flow) alone explains 39% of the interannual variability in hypoxic extents (Figure 4, top-left panel).

Results do also confirm that anthropogenic phosphorus loading, and specifically increased SRP loading, leads to larger hypoxic extents, all else being equal. We infer that it does so by leading to increased water column oxygen demand by stimulating primary productivity, as there is little variability in measured sediment oxygen demand.[29] Consistent with previous studies,[15,30] SRP loading is more closely associated with hypoxia than is TP. Furthermore, we do not find evidence that the previous year's phosphorus load is a significant factor, as had been suggested previously.[31] If the previous year's loading had been significant, then this would have indicated residual impacts

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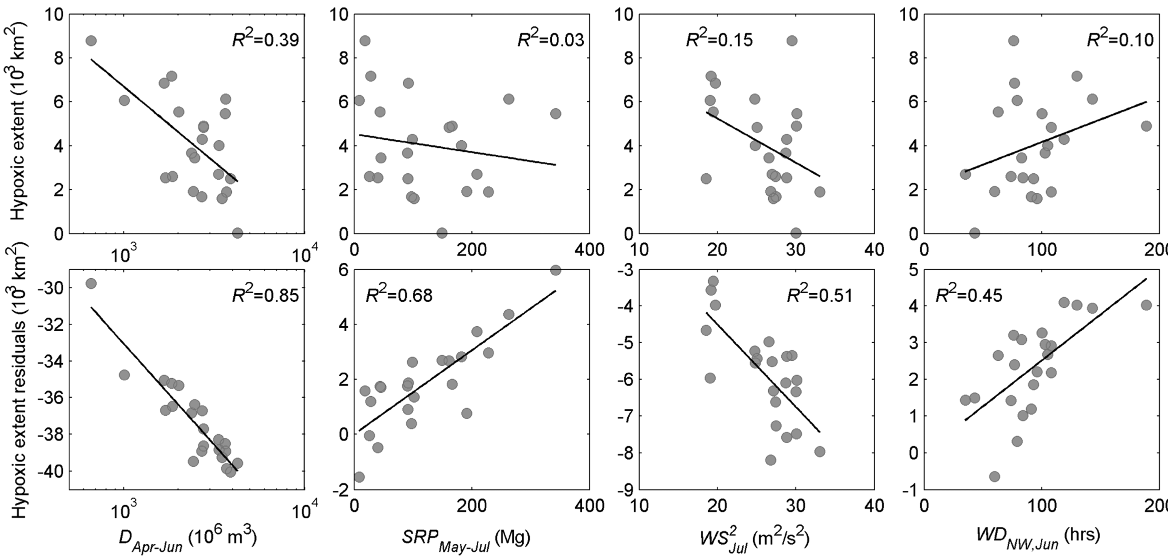

Figure 4. Relationship between hypoxic extent and explanatory variables in the selected model. Scatterplots of seasonally averaged hypoxic extent and each selected variable (first row), and scatterplots of hypoxic extent residuals from final multiple linear regression with one variable removed and this individual variable (second row). $D_{\mathrm{Apr-Jun}}$ (10^6 m^3) is the total tributary discharge from the Maumee, Raisin, Sandusky, Cuyahoga, and Grand Rivers from April to June, $SRP_{\mathrm{May-Jul}}$ (Mg) is the total *SRP* load from these same rivers from May to July, WS^2_{Jul} (m^2/s^2) is the average squared hourly wind speed in July, and $WD_{\mathrm{NW,Jun}}$ (hrs) is the total duration of June northwesterly winds. Note that the river discharge plots are on a logarithmic scale. These scatterplots confirm that the relationships between the hypoxic extent and individual variables are relatively weak, but that the hypoxic extent residuals are indeed well represented by a linear model with each variable.

of high loading, or could have indirectly accounted for an impact from a previous year's HAB. The impact of HABs on the following year's hypoxia cannot be directly assessed, as quantitative estimates of HAB size and intensity only cover a limited subset of the period examined here,[8,9] but an analysis of recent years confirmed no clear relationship. Also, whereas the impact of loading to the western basin on hypoxia has previously been highlighted,[6] we find that the total loading to both the western and central basin is a stronger determinant of hypoxic extent in the central basin. The critical May to July period is somewhat later than the March to June period found to best explain HAB intensity,[8] suggesting that the timing of loading may differentially affect HAB and hypoxia formation.

Increased wind stress in July, the month preceding the typical August to September hypoxic season in Lake Erie, is associated with a reduction in hypoxia, a relationship expected based on its impact on stratification and hypolimnion thickness. Variations in the thickness of the hypolimnion have previously been shown to have a direct impact on intraseasonal variability in hypoxic conditions in the lake, with a thinning thermocline associated with a reduction in hypoxic extent.[5] Lam et al.[32] had in turn noted a possible relationship between windy conditions and higher oxygen concentrations for two specific years in the 1970s. Recent work[15,33,34] has also shown that higher wind stress leads to a deepening of the mixed layer and a thinning of the hypolimnion, but whereas some have suggested that wind leads to lower dissolved oxygen concentrations in the hypolimnion layer,[33] others suggest that higher winds instead increase oxygen concentrations by increasing the dissolved oxygen fluxes through the thermocline.[34] Results shown here are more consistent with the latter scenario, showing a relationship between increased wind stress and a reduction in hypoxic extent.

We hypothesize that the significance of northwesterly wind duration in June, two months prior to the onset of the hypoxic season, is related to its role in producing strong eastward flow along the southern shore of the western basin, and therefore aiding in the delivery of nutrients from the Maumee and Sandusky Rivers to the central basin. Given the orientation of the south coast of the western basin (Figure 1), northwesterly winds are expected to produce eastward coastal flow.[35] The wind duration from other directions and during other months yielded substantially lower explanatory power (additional details in SI), and wind direction in June is unlikely to affect hypoxia by influencing stratification, because Lake Erie hypoxia usually appears only in late July or August. To test the hypothesis about June northwesterly winds affecting eastward flow of nutrient-rich water, we use simulations of Lake Erie circulation (see SI for details) for several prototypical years (2004, 2005, 2007, 2009, 2010, and 2011). Results show a systematic increase in June flow along the southern lake boundary from the western to the central basin as the duration of northwesterly winds increases. The flow in the strait south of South Bass Island (Figure 5), which is a good indicator of the strength of the south coast flow into the central basin, was found to be highly correlated with northwesterly wind duration (R^2=0.75) for the six examined years. The difference in June circulation between the year with the highest (2010) and the lowest (2005) duration of northwesterly winds among the examined years (Figure 3) is illustrated in Figure 5, and shows the enhanced eastward flow in 2010. In the hydrodynamic model, the flow in 2005 was very weak and in some areas actually directed toward the Maumee River, unlike in 2010 when it was strongest among the examined years. The total flow south of South Bass Island was approximately 5-fold higher in 2010 (1582 m^3/s) than in 2005 (298 m^3/s), and 62% higher than average (974 m^3/s), while the duration of northwesterly winds was approximately double (143 h versus 74 h) in 2010 relative to 2005. Lake circulation patterns control transport of nutrients in Lake Erie,[36,37] and this increased transport from the western to the central basin in June coincides with the period identified as critical for SRP loading (May to July), and is well aligned to deliver nutrient-rich water from the Maumee and Sandusky rivers into the main portion of the central basin. Therefore, northwesterly

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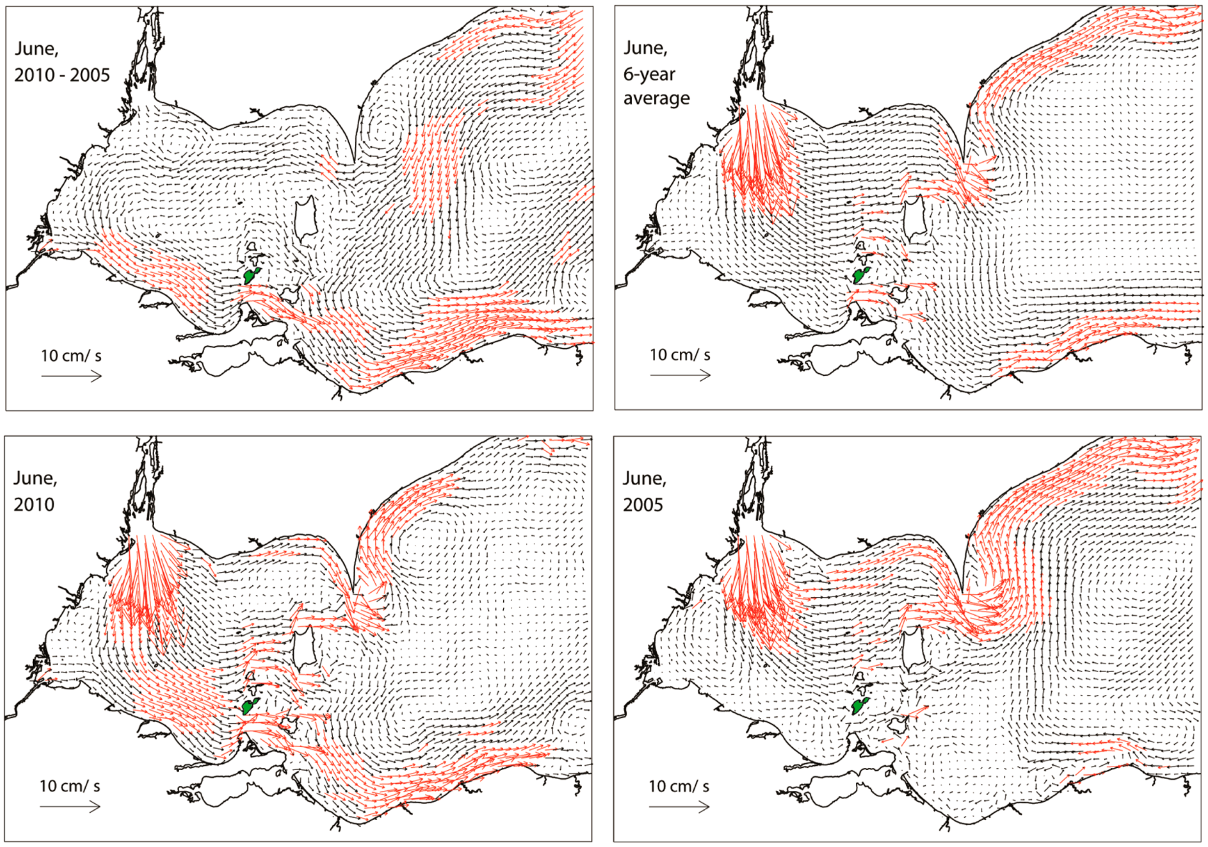

Figure 5. Difference between lake circulation (depth-average currents are shown) in June 2010 and 2005 (upper left), as well as 6-year average (upper right), 2010 (lower-left), and 2005 (lower-right) June circulations. Current speeds greater than 2 cm/s are in highlighted in red, and South Bass Island is highlighted in green. 2010 and 2005 are the years with highest and lowest duration of June northwesterly winds, respectively, among the years for which the lake circulation model is available (2004, 2005, 2007, 2009, 2010, and 2011). The difference in circulation shows enhanced eastward transport along the southern shore of the western basin (conducive to enhanced nutrient transport to the central basin) associated with increased northwesterly wind. Results for intermediate years are consistent with those shown here.

winds in June represent increased transport, and thus delivery of nutrients, into the central basin. Once in the central basin, this nutrient load can spread throughout the basin fairly quickly due to basin-wide circulation that greatly intensifies in July and remains strong through the rest of summer and fall.[38]

Overall, we find that April to June river discharge, May to July SRP loading, July wind stress, and the duration of June northwesterly winds together explain the interannual variability of seasonally averaged hypoxic extent in the central basin of Lake Erie (R^2 = 0.82). This result indicates that evolving meteorological conditions need to be considered in addition to nutrient loading in the development of management strategies for Lake Erie, and more broadly the Great Lakes system, especially as both extreme precipitation and drought become more frequent under a changing climate.

Hypoxia in 2011 and 2012. The newly developed model of interannual variability provides a clear picture of the explanatory factors of the record-setting hypoxic event in 2012 (Figure 2). Tributary discharge into the western and central basins was the lowest in the 28-year examined period (Figure 3). This observation is consistent with larger-scale records for 2012, which indicate that the Midwest and Northern United States experienced one of the most severe droughts on record.[39] More than a quarter of U.S. rivers saw less than 10% of normal discharge[40] and fish kills were rampant.[24,40] Although the reduced river discharge and lack of intense springtime discharge events[41] also led to low SRP loading during the May to July period (Figure 3, third lowest in the examined period), and the average July wind speed was the third highest on record, these mitigating factors were not sufficient to offset the low discharge (Figure 3). Finally, the duration of June northwesterly winds was low but not especially so. Overall, the 2012 drought and associated low tributary discharge were therefore the overwhelming explanatory factor for the record hypoxia observed in 2012.

The model of interannual variability also makes it possible to estimate the hypoxic extent for years when BWDO observations are not available during the early or late portion of the hypoxic season, namely 1986, 1992, 1994, 1995, 2009, and most notably during the summer of the record-breaking HAB of 2011 (Figure 2, SI Figure S2). Although the springtime SRP loading was the highest on record in 2011[7] and the loading during the critical May to July period identified here was the second highest on record, the lake also experienced the highest tributary discharge over the examined 28-year record during the identified critical April to June period, which more than offset the impact of increased SRP loading. Neither the July wind speed nor the duration of northwesterly winds in June was noteworthy (Figure 3). Overall, the model of interannual variability (Figure 2) indicates that the hypoxia during summer 2011 was either of short duration or covered a small area, yielding a seasonally averaged extent in the lowest quartile of the 28-year analysis period.

The juxtaposition of a massive HAB and small estimated hypoxic zone in 2011, and a small HAB and massive hypoxic zone in 2012 suggests that river discharge and the timing of nutrient

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input affect these two types of impacts in different ways in Lake Erie. Whereas the intensity of HABs and hypoxia are both linked to anthropogenic nutrient input and correlate positively with SRP loading, results presented here suggest that the timing of loading matters, with earlier spring loading more closely associated with HABs, while later spring and early summer loading more closely associated with increases in hypoxic extent. This difference in impacts may be further affected by river discharge, as higher river discharge is correlated with larger HABs but smaller hypoxic extent.

Overall, we find that the 2012 North American drought was associated with a record-breaking hypoxic event in Lake Erie. Drought conditions are expected to occur more frequently in the future,[13] and the results of this study imply that this will have a direct impact on anthropogenically mediated eutrophication through the exacerbation of hypoxic conditions. We further estimate that the record-breaking HAB that occurred in Lake Erie in 2011 was not associated with a correspondingly large hypoxic event, calling for further research into interactions between these two consequences of anthropogenic nutrient loading to freshwater systems.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

(S1) Dissolved oxygen observations and auxiliary variables for estimating hypoxic extent, (S2) geostatistical approach for cruise-specific hypoxic extent and uncertainty quantification, (S3) candidate variables considered for modeling interannual variability of hypoxic extent, (S4) confidence intervals and prediction intervals of multiple linear regression model, (S5) Lake Erie hydrodynamic modeling, (S6) variable selection results for modeling interannual variability, and (S7) impact of wind direction. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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