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Meteorological drivers of hypolimnetic anoxia in a eutrophic, north temperate lake

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ABSTRACT

Oxygen concentration is both an indicator and driver of water quality in lakes. Decreases in oxygen concentration leads to altered ecosystem function as well as harmful consequences for aquatic biota, such as fishes. The responses of oxygen dynamics in lakes to climate-related drivers, such as temperature and wind speed, are well documented for lake surface waters. However, much less is known about how the oxic environment of bottom waters, especially the timing and magnitude of anoxia in eutrophic lakes, responds to changes in climate drivers. Understanding how important ecosystem states, such as hypolimnetic anoxia, may respond to differing climate scenarios requires a model that couples physical-biological conditions and sufficiently captures the density stratification that leads to strong oxygen gradients. Here, we analyzed the effects of changes in three important meteorological drivers (air temperature, wind speed, and relative humidity) on hypolimnetic anoxia in a eutrophic, north temperate lake using the anoxic factor as an index that captures both the temporal and spatial extent of anoxia. Air temperature and relative humidity were found to have a positive correlation with anoxic factor, while wind speed had a negative correlation. Air temperature was found to have the greatest potential impact of the three drivers on the anoxic factor, followed by wind speed and then relative humidity. Across the scenarios of climate variability, variation in the simulated anoxic factor was primarily due to changes in the timing of onset and decay of stratification. Given the potential for future changes in climate, especially increases in air temperature, this study provides important insight into how these changes will alter lake water quality.

1. Introduction

Lake eutrophication has led to degradation of water quality in lakes and reservoirs at a global scale (Diaz 2001; Carpenter et al., 2011; Trolle et al., 2011; Kara et al., 2012). An important consequence of elevated productivity in eutrophic systems is anoxia (<1 mg O_2 L^{-1}) in lake bottom waters (the hypolimnion), which arises from increased microbial metabolism of degradable organic matter (OM) (Hanson et al., 2004; Cooke et al., 2005; Bouffard et al., 2013). In thermally stratified lakes, in which the hypolimnetic waters are effectively isolated from atmospheric and photosynthetic oxygen sources in the epilimnetic surface waters, hypolimnetic dissolved oxygen (DO) consumption by microbial respiration leads to oxygen depletion and eventually anoxia (Robertson and Imberger 1994; Nürnberg 1995; Foley et al., 2012). Anoxia is a serious environmental threat, as it leads to the release of nutrients such as phosphorus (P) and metals from the sediments into the water column, and has negative consequences for fish and macroinvertebrates, including altered spatial distribution of species, changes in physiological processes and predator-prey interactions, and potentially death (Arend et al., 2011; Foley et al., 2012).

Projected changes in meteorological drivers over the next century are likely to cause further deterioration of water quality globally and may undermine management strategies intended to decrease anoxia (Jeppesen et al., 2007, 2009; Williamson et al., 2009; Trolle et al., 2011). Changes in water temperature and oxygen dynamics are occurring in many lakes worldwide (e.g. Hampton

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et al., 2008; Williamson et al., 2009; Schneider and Hook 2010; Foley et al., 2012; Palmer et al., 2014; North et al., 2014). However, the links between meteorological drivers and lake responses are complex. In some studies, there is evidence of diurnally asymmetric effects (i.e., a differing effect in the magnitude between daytime and nighttime) of meteorological drivers such as air temperature or wind speed (Livingstone 2003; Wilhelm et al., 2006; Kerimoglu and Rinke, 2013). Other studies, using model forecasts, have predicted increased stratification strength and duration, which would likely lead to increased extent of anoxia in the future (Mackay et al., 2009; Samal et al., 2012). Consequently, it is important to understand how changes in multiple meteorological drivers interact to affect important seasonal oxygen dynamics.

In linking meteorological drivers to water quality in lake ecosystems, most work has focused on the relationships between air temperature, longwave radiation, and lake thermal structure (Trolle et al., 2011; Samal et al., 2012), and there is still a need for investigating the effects and interactions of other meteorological drivers, such as wind speed, on thermal structure, as well as the subsequent chemical and biological responses to altered thermal structure (Wilhelm et al., 2006; Mackay et al., 2009; Kerimoglu and Rinke, 2013). For example, increased wind speeds cause increased surface turbulence, acting to decrease thermal stability. This can lead to delayed stratification and induce earlier fall turnover, potentially shortening anoxia duration. The complex interactions between exogenous forcings and lake anoxia are challenging to understand and require an analytical framework that both couples physics and biology within lakes and accounts for vertical thermal and chemical gradients.

Process-based numerical simulation models are appropriate for studies of meteorological scenarios because lakes have complex physical-biological coupling and substantial temporal variance (Arhonditsis et al., 2006; Kara et al., 2012). A number of factors may determine the spatial extent and duration of hypolimnetic anoxia, including epilimnetic productivity, duration of thermal stratification, thermal stability, hypolimnetic temperature, and hypolimnetic volume (Foley et al., 2012; Müller et al., 2012; Bouffard et al., 2013). Additionally, these processes are not independent of each other and may affect hypolimnetic anoxia in contrasting ways. As an example, higher hypolimnetic water temperatures can favor increased microbial metabolism rates and thus increased anoxia duration (i.e. earlier anoxia onset) (Foley et al., 2012), but they can also lead to decreased thermal stability, thereby decreasing the spatial extent and duration of anoxia (Nürnberg, 1988). Further, many heat-flux processes controlling thermal structure, and thus influencing chemical and biological processes throughout the water column, are non-linear (Wilhelm et al., 2006). Process-based numerical models are able to simulate these complex interactions and feedbacks between physics and biogeochemistry (Hamilton and Schladow, 1997), and thus are well-suited to provide insight into how oxygen dynamics may change under a gradient of meteorological scenarios.

How do meteorological drivers affect hypolimnetic oxygen dynamics in a eutrophic, north temperate lake? Does the timing of perturbations in meteorological drivers (day vs. night) influence their effect on oxygen dynamics? What are the projected impacts of changing climate on lake oxygen dynamics for the latter half of the 21st century? To explore these questions, we used a process-based, one-dimensional, hydrodynamic-biogeochemical lake model calibrated to observational data to independently test the influence of meteorological variables on lake anoxia, as well as explore meteorological scenarios that may be outside the bounds of available observational data. We applied this model to a well-studied eutrophic, north temperate lake (Lake Mendota, Wisconsin, USA) that routinely experiences hypolimnetic oxygen depletion during summer stratification. We examined relationships between changes in meteorological driving variables and emergent properties of the lake system using simple statistical models.

2. Methods

2.1. Study site description

Lake Mendota is a dimictic, eutrophic lake located in south-central Wisconsin, USA (43°7′N, 89°25′W). It has a surface area of 39.4 km^2 and a maximum depth of 25.3 m (Brock, 1985; Kitchell, 1992). Lake Mendota's major tributary, the Yahara River, accounts for approximately 70% of the total annual inflow. The hydraulic residence time is roughly 6 years. The lake is typically frozen from late December until early April, and stratifies June through early October. Due to its eutrophic status since the mid-1800s, Lake Mendota experiences intense phytoplankton blooms and hypolimnetic anoxia each summer (Brock, 1985).

2.2. Anoxic factor calculation

Anoxia is the state of extremely low DO, which can occur in the hypolimnion of a lake during thermal stratification when the bottom waters are isolated from atmospheric and photosynthetic oxygen sources in the surface waters. During this period, DO consumptive processes, or sinks, such as microbial respiration, exceed DO sources (downward transport from the surface waters via advection and diffusion), and DO decreases to very low concentrations. In this study, the anoxic threshold is defined as 1 mg L^{-1} (Nürnberg, 1995; Foley et al., 2012). The *anoxic factor (AF)* is an index that summarizes both the temporal duration and spatial extent of anoxia in a lake or reservoir into a single value for a specified length of time (e.g., a summer season) (Nürnberg, 1995). Anoxic factor (Nürnberg, 1995; Marcé et al., 2010) or other similar indices such as 'hypolimnetic anoxia' (Foley et al., 2012) and 'hypoxic factor' (North et al., 2014) have been used to track changes in hypolimnetic oxygen concentrations across varying meteorological conditions. The AF represents the amount of time (t) that a sediment area (a), normalized by the surface area of the lake (A_0), is overlain by anoxic waters (Eq. (1)).

$$AF = \frac{\sum_{i=1}^{n} t_i a_i}{A_o} \quad (1)$$

AF captures the spatial extent of anoxia by considering the anoxic depth in the water column (Fig. 1) and is normalized by lake surface area, allowing for comparison among lakes. AF is reported in time units (days), but is often described as days $year^{-1}$ or days $season^{-1}$ to specify whether winter anoxia (under ice) is included or excluded, respectively, in the AF calculation (Nürnberg, 1995). Because AF accounts for both the duration and spatial extent of anoxia, it is more indicative of the physiochemical and ecological impact of anoxia on a lake system than anoxia duration or the oxygen depletion rate. For example, if the time of stratification formation and decay were identical for two separate years for an idealized lake, but the oxycline depth differed, the measures of anoxia duration for the two years would be the same but the anoxic factor measures would differ.

2.3. Simulation model

We used a hydrodynamic-biogeochemical model to explore how changes in external forcing alter AF. While AF can be calculated directly from observational data, the model enabled us to explore gradients not represented in the observational data, the sensitivities of AF to relatively small changes in meteorology that may be masked by noise in the observational data, and to simulate the