Coastal upwelling dynamics influence spatial patterns of hypoxia and nearshore hypoxia events in the central basin of Lake Erie

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Introduction

Lake Erie sustains an important fishery and is a source of drinking water to millions of people, but hypoxia is detrimental to both of these ecosystem services. Hypoxia in the central basin of Lake Erie has been studied since the 1950's. Even so, spatial patterns of hypoxia, and episodes of hypoxia in nearshore areas where drinking water plant intakes are located, are not well characterized owing to limited observations. Hypoxia is ultimately caused by excessive nutrient loading, stimulating algal growth, and increased biochemical oxygen demand. In addition, physical processes have an important influence on the occurrence of hypoxia, especially processes that influence the thickness of the hypolimnion.

Hypoxia model and sensor network

We evaluated the ability of a relatively simple, physically-based, dissolved oxygen (DO) model to reproduce spatial and temporal patterns of hypoxia observed in Lake Erie. The DO model (Fig. 1) used assigned rates of sediment and water column oxygen demand (Mueller et al., 2012; Rucinski et al., 2010) that were temperature-dependent, but otherwise spatially and temporally uniform in the central basin. The DO initial condition was set to saturation with the atmosphere on April 1, a time when Lake Erie is vertically well-mixed. The DO model was linked to NOAA's Lake Erie Operational Forecasting System hydrodynamic model, an application of the Finite Volume Community Ocean Model (FVCOM) with 0.5-2 km horizontal resolution and 20 vertical layers. A hindcast simulation was run for 2016 using meteorology interpolated from stations surrounding the lake. In the summer of 2017, the model was run in a nowcast/forecast mode. A nowcast simulation was run every 24 hours, initialized from the previous-day nowcast, using interpolated meteorology, and a 14-day forecast simulation was run using meteorology from NOAA NDFD to day 5 and GFS model to day 14. Model DO was compared to observations from real-time sensor networks maintained by GLOS, LimnoTech, and MOECC Ontario Canada, in addition to an array of moored sensors that we deployed in 2017. In 2016, an array of temperature and DO sensors was installed on the bottom of the central basin by US Environmental Protection Agency and Purdue University (Sea Grant).
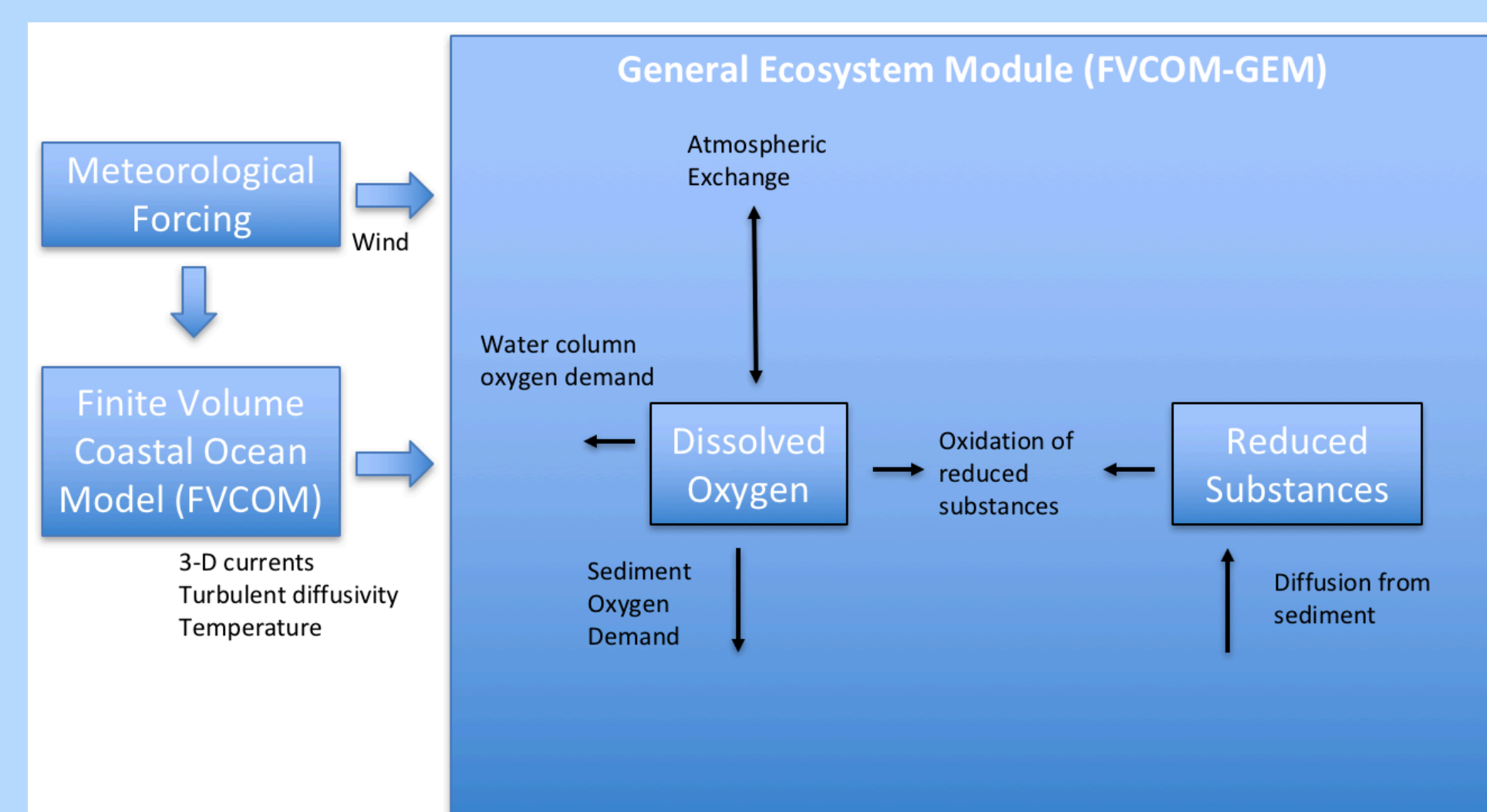

Figure 1. Process diagram of the dissolved oxygen model linked to the Lake Erie Operational Forecasting System: https://tidesandcurrents.noaa.gov/ofs/leofs/leofs.html
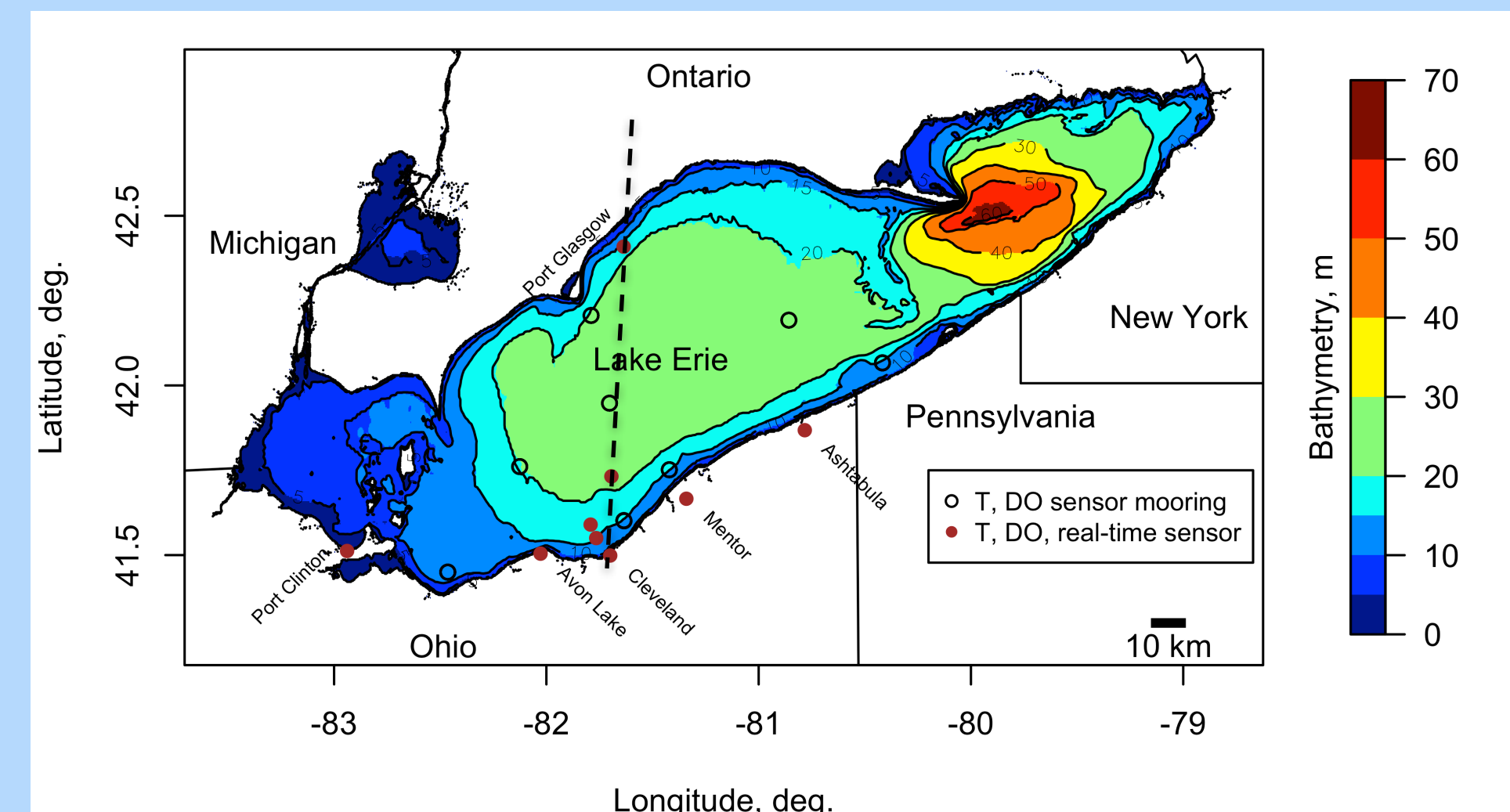

Figure 2. Map of Lake Erie, showing bathymetry and locations of real-time sensors (GLOS, LimnoTech) and sensor moorings installed as part of this study.

The dashed line indicates the cross-sectional view from Cleveland to Port Glasgow shown in Figures 4-6.

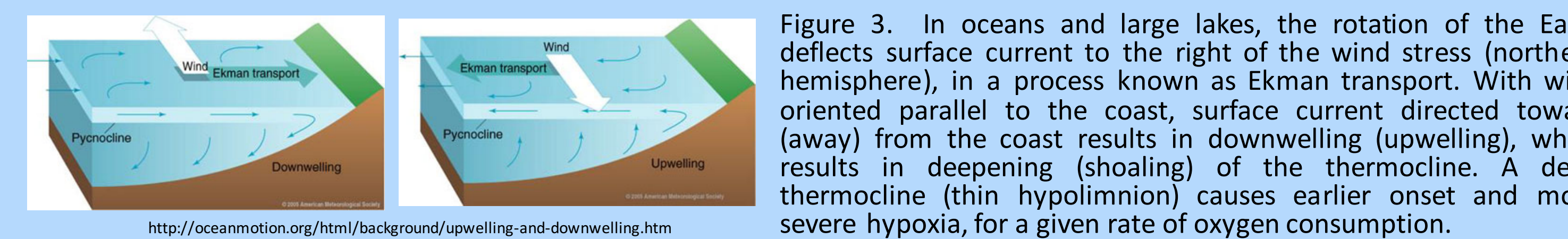## Influence of coastal upwelling on hypoxia in Lake Erie

Figure 3. In oceans and large lakes, the rotation of the Earth deflects surface current to the right of the wind stress (northern hemisphere), in a process known as Ekman transport. With wind oriented parallel to the coast, surface current directed toward (away) from the coast results in downwelling (upwelling), which results in deepening (shoaling) of the thermocline. A deep thermocline (thin hypolimnion) causes earlier onset and more severe hypoxia, for a given rate of oxygen consumption.
http://oceanmotion.org/html/background/upwelling-and-downwelling.htm
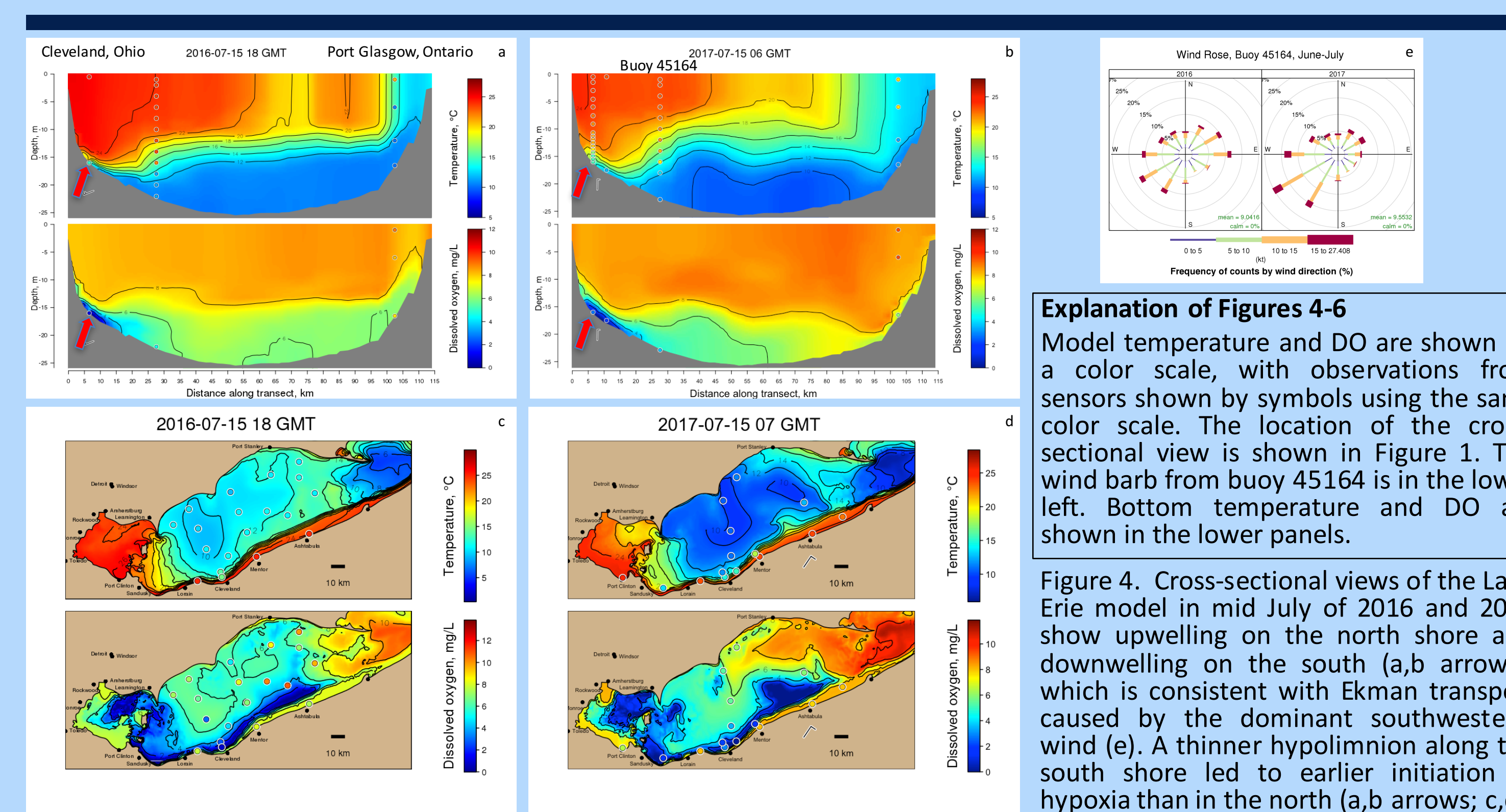
Explanation of Figures 4-6
Model temperature and DO are shown on a color scale, with observations from sensors shown by symbols using the same color scale. The location of the cross-sectional view is shown in Figure 1. The wind barb from buoy 45164 is in the lower left. Bottom temperature and DO are shown in the lower panels.

Figure 4. Cross-sectional views of the Lake Erie model in mid July of 2016 and 2017 show upwelling on the north shore and downwelling on the south (a,b arrows), which is consistent with Ekman transport caused by the dominant southwesterly wind (e). A thinner hypolimnion along the south shore led to earlier initiation of hypoxia than in the north (a,b arrows; c,d).
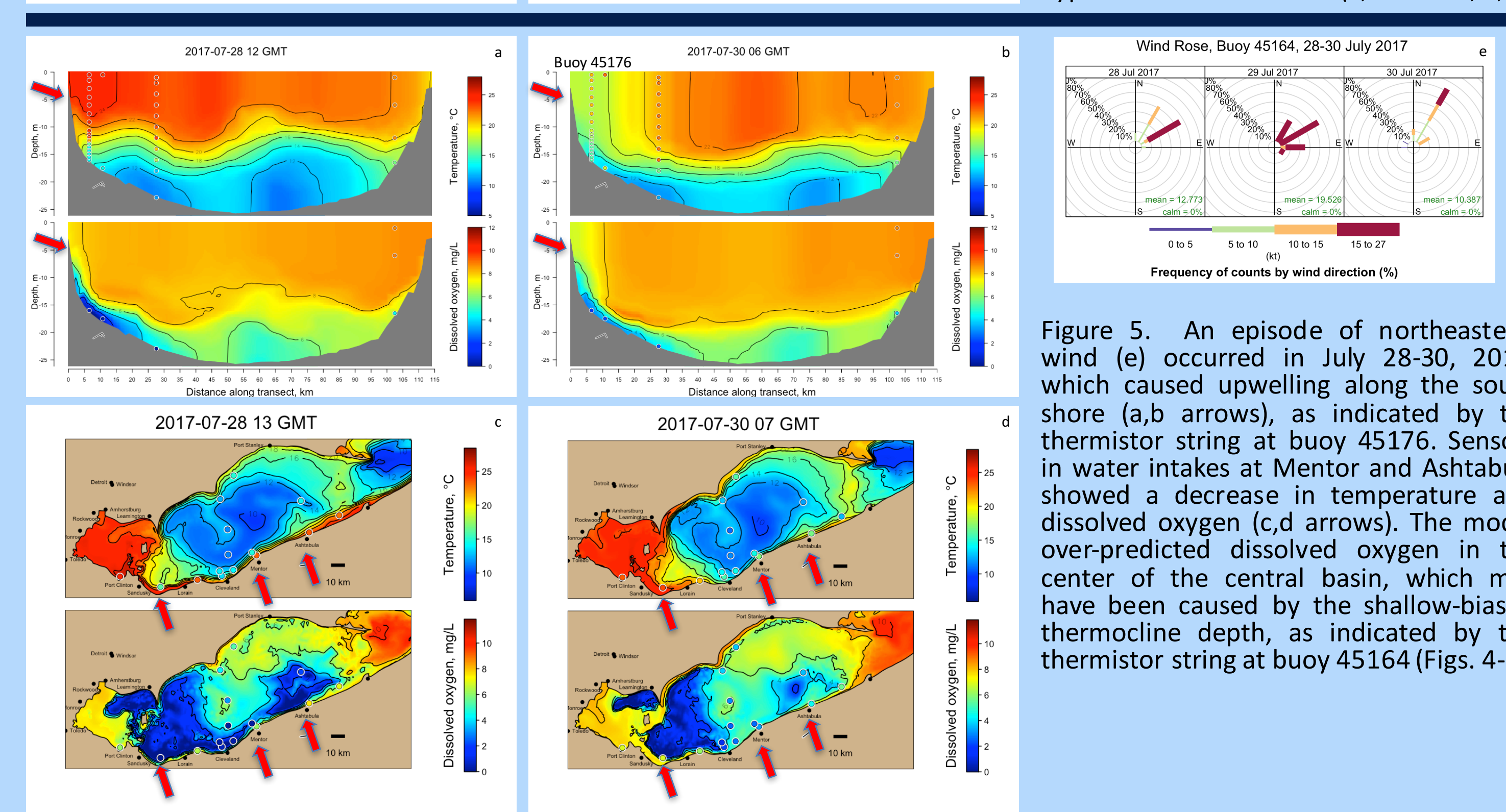

Figure 5. An episode of northeasterly wind (e) occurred in July 28-30, 2017, which caused upwelling along the south shore (a,b arrows), as indicated by the thermistor string at buoy 45176. Sensors in water intakes at Mentor and Ashtabula showed a decrease in temperature and dissolved oxygen (c,d arrows). The model over-predicted dissolved oxygen in the center of the central basin, which may have been caused by the shallow-biased thermocline depth, as indicated by the thermistor string at buoy 45164 (Figs. 4-6).
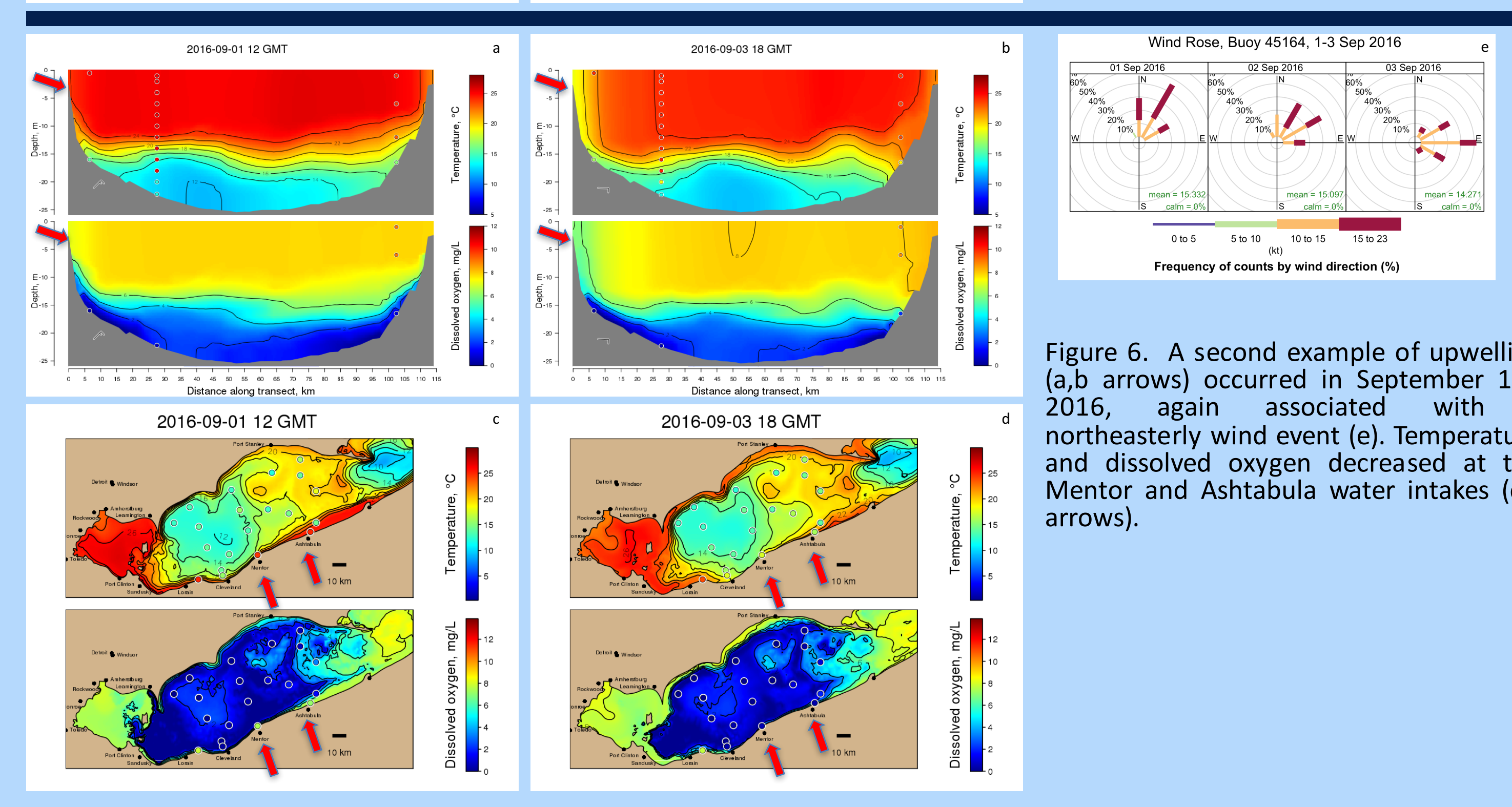

Figure 6. A second example of upwelling (a,b arrows) occurred in September 1-3, 2016, again associated with a northeasterly wind event (e). Temperature and dissolved oxygen decreased at the Mentor and Ashtabula water intakes (c,d arrows).

Dominant southwesterly winds caused persistent downwelling along the south shore, which resulted in a thinner hypolimnion and earlier initiation of hypoxia along the south shore than in the north in both 2016 and 2017 (Figure 4). Occasional winds from the northeast temporarily reversed this pattern, causing upwelling along the south shore that brought hypoxic water to nearshore water intakes (Figures 5-6).

We used archived nowcast and forecast model runs from 2017 to evaluate model skill in predicting rapid changes in temperature and dissolved oxygen at six drinking water intakes (Avon Lake, three intakes at Cleveland, Mentor, and Ashtabula). Low DO itself is not an issue for water treatment, but hypoxic water is associated with low pH and reduced substances (Mn, Fe) that can cause issues for water treatment. DO and pH were correlated, with DO < 4 mg/L being associated with pH < 7.5, an action threshold for water treatment, > 60% of the time (Figure 7). For skill assessment, we defined events as DO < 4 mg/L or a drop in hourly temperature of > 3 °C compared to the maximum temperature over the preceding 24 hours. The Pierce skill score gives the probability of a correct prediction, given that an event occurred, minus the probability of a false positive, given a non-event (Hogan and Mason, 2012). A persistence forecast was selected as a benchmark, representing the assumption of no change from the most recent observation and the best available information in the absence of a model. The persistence forecast is, by definition, perfect for the nowcast (day 0), but the model skill exceeded that of the persistence forecast for forecast days 3-12 (Figures 8-9).
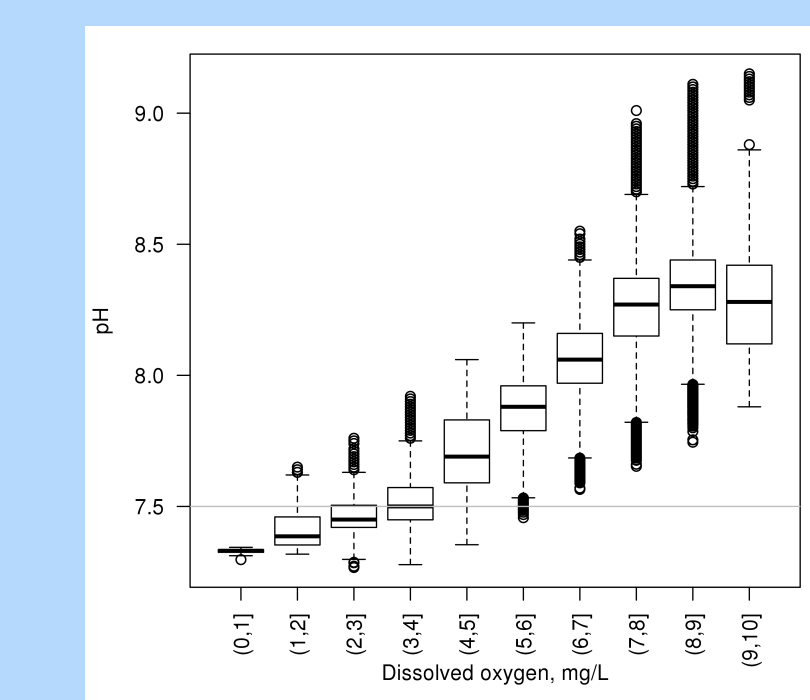

Figure 7. Association between pH and dissolved oxygen, measured at six drinking water intakes in 2017.
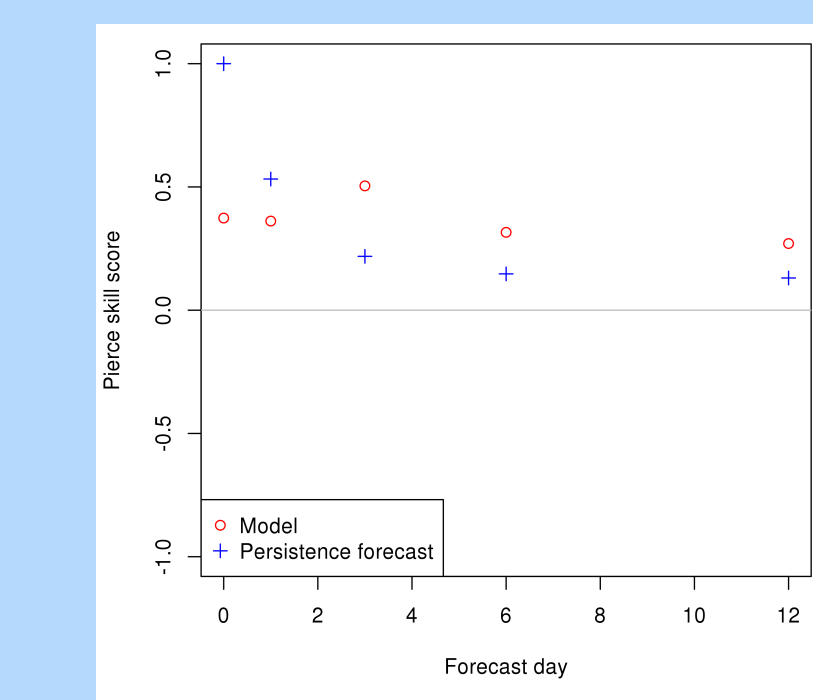
Figure 8. Skill scores for the model and a persistence forecast in predicting events of DO < 4 mg/L at six drinking water intakes in 2017.
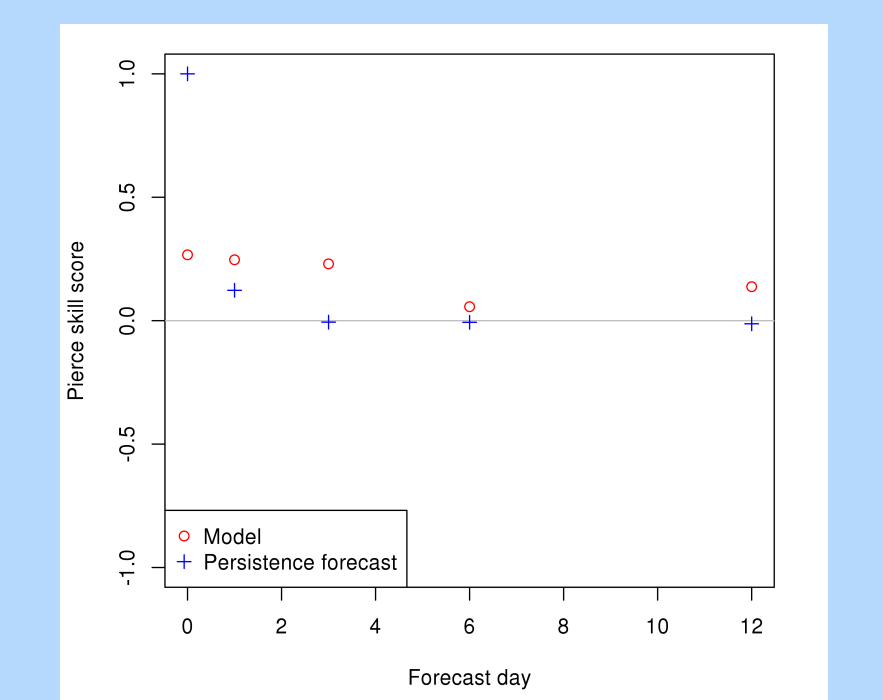
Figure 9. Skill scores for the model and a persistence forecast in predicting events of 3 °C temperature drop in 24 hours at six drinking water intakes in 2017.

Conclusion

Earlier onset of hypoxia along the south shore of Lake Erie, compared to the north, was associated with predominant southwesterly winds that caused a thinner hypolimnion in the south due to downwelling associated with Ekman transport. This spatial pattern of hypoxia was simulated by a model that used spatially-uniform rates of oxygen demand, indicating that spatiotemporal variation in oxygen demand is not necessary to explain this pattern.

Low temperature and dissolved oxygen events at nearshore water intakes in Ohio were associated with upwelling caused by northeasterly winds and associated Ekman transport. Such events were forecast by the model in 2017 with greater skill than a persistence forecast 3-12 days in advance.

Acknowledgements & References

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Hogan, R. J., and I. B. Mason (2012), Deterministic forecasts of binary events, in Forecast Verification: A Practitioner's Guide in Atmospheric Science, 2nd ed., pp. 31–59, John Wiley & Sons, Ltd., West Sussex, U. K.