Proceedings of the 7th International Conference on HydroScience and Engineering

Philadelphia, USA September 10-13, 2006 (ICHE 2006)

ISBN: 0977447405

Drexel University

College of Engineering

USE OF UnTRIM TO INVESTIGATE DISSOLVED OXYGEN TRANSPORT IN UPPER KLAMATH LAKE, OREGON

Tamara M. Wood[1] and Ralph T. Cheng[2]

ABSTRACT

The hydrodynamic and constituent transport model UnTRIM was used to simulate hydrodynamics in Upper Klamath Lake, a shallow, hypereutrophic lake in which currents are responsive primarily to wind forcing. A simplified version of a dissolved oxygen model was used to simulate the transport of oxygen-depleted water from a deep trench on the western shoreline into important fish habitat in the northern part of the lake. Two scenarios were tested: a strong prevailing wind scenario and a weak prevailing wind scenario. The weak prevailing wind scenario resulted in lower dissolved oxygen concentrations in the deep trench, but higher concentrations in the fish habitat area. In contrast, the strong prevailing wind scenario induced stronger circulation through the fish habitat area, which resulted in greater transport of oxygen-depleted water from the trench into the fish habitat area and lower concentrations there. The results suggest that strong prevailing winds are more likely to lead to the conditions preceding a fish die-off than weak prevailing winds, which contradicts some previous studies, but is consistent with observations made from 2002 and 2004, including a year of a small die-off in 2003. The explanation could be that the previous studies that show a correlation of fish die-off years with low wind speeds relied on a flawed dataset, or, wind speed could simply be of less importance than other variables.

1. INTRODUCTION

Upper Klamath Lake (Figure 1) is a large (surface area about 200 km^2), shallow lake in south central Oregon. Water movement and material transport in the lake are dominated by wind-driven circulation. The lake has been eutrophic for at least the last 1,000 years (Eilers et al., 2001), but in recent decades it has become hypereutrophic and now experiences annual occurrences of cyanobacterial blooms. Several large die-offs of endangered Lost River and shortnose suckers have been documented over the last several decades, including three in the mid-1990s and a relatively smaller die-off in 2003. These die-offs are believed to be triggered by the hypoxia that accompanies a crash in the cyanobacterial bloom. It is of interest to understand the factors that lead to a particularly severe water quality event in some years but not in others. In this paper we address the specific question of how the strength of the prevailing wind forcing affects dissolved oxygen in the northern part of the lake where the most important adult sucker habitat is located. There is some evidence that particularly low dissolved oxygen events are associated with lower-than-average wind

---

[1] Hydrologist, US Geological Survey, Portland, OR 97216, USA (tmwood@usgs.gov)
[2] Senior Research Hydrologist, US Geological Survey, Menlo Park, CA 94025, USA (rtcheng@usgs.gov)

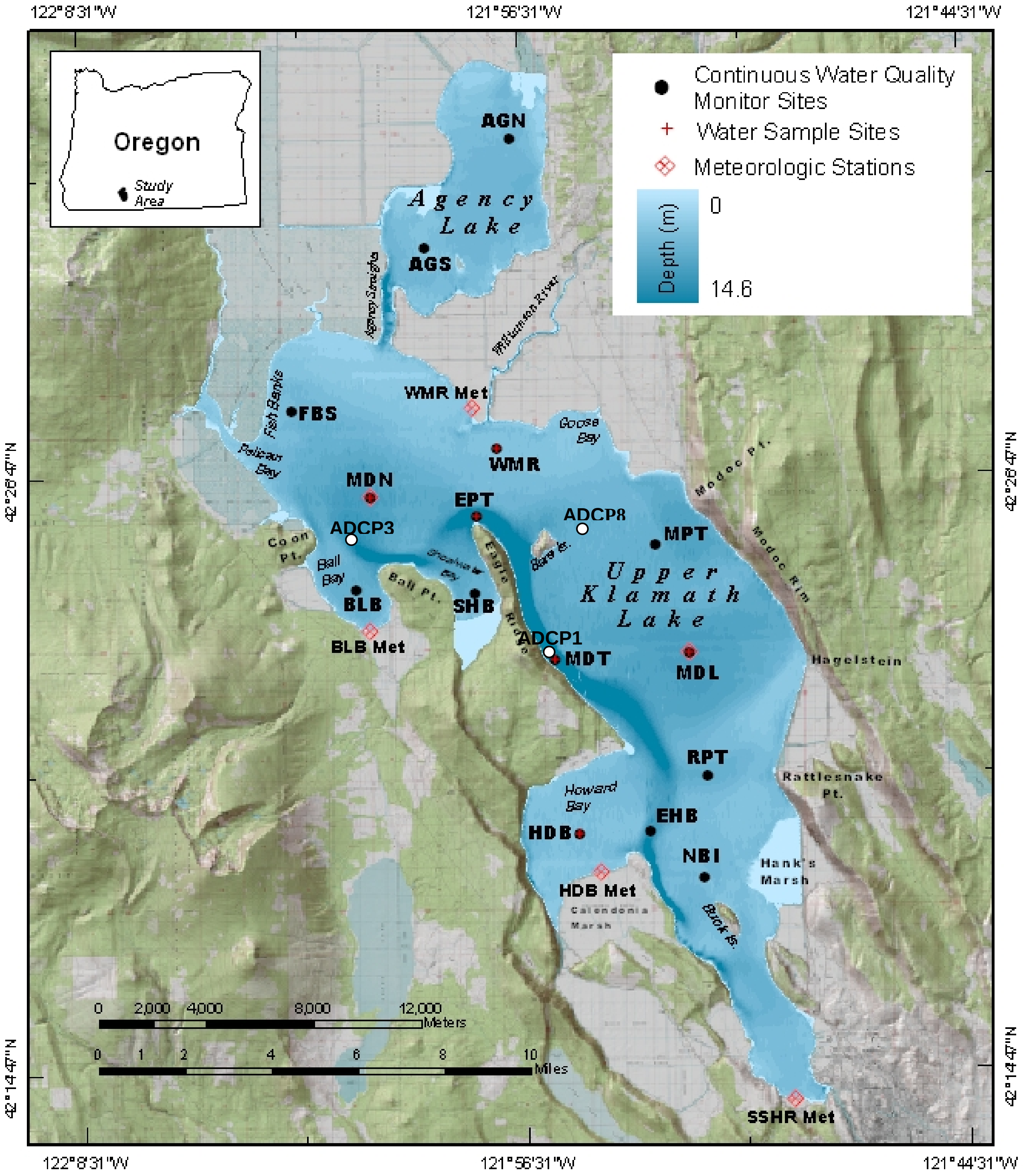

Figure 1 Map of Upper Klamath Lake, Oregon, showing water quality data collection sites and meteorological data collection sites from 2005. ADCP1 and ADCP3 were sites where acoustic Doppler current profilers (ADCPs) were placed in 2005, and ADCP8 was a site where an ADCP was placed in 2003.

speeds (Kann and Welch, 2005), and an association between fish die-off years and years of lower-than-average wind speed has been found in a historical wind dataset (Wood et al., 2006).

Observations from continuous dissolved oxygen monitors deployed in the lake between 2002 and 2005 indicate that, in the shallowest areas of the lake, oxygen production through photosynthesis dominates consumption through respiration and biochemical oxygen demand, and dissolved oxygen concentrations often are supersaturated. In the deep trench located along the western shoreline of the lake from Howard Bay to the tip of Eagle Ridge (Figure 1) the opposite is true. Thus the dissolved oxygen concentration in the trench is consistently lower than in the rest of the lake, and often is undersaturated. When the most severe low dissolved oxygen events occur in the northern part of Upper Klamath Lake, the dissolved oxygen concentration in the trench is a few milligrams per liter or less, while concentrations remain at or above saturation over much of the shallow eastern and southern parts of the lake. UnTRIM (Casulli and Zanolli, 2002) has been used to simulate hydrodynamics (Cheng et al., 2005) and heat transport in Upper Klamath Lake, and in this study is used to investigate the influence of the transport through the trench on dissolved oxygen concentration at site Midnorth (MDN, Figure 1), which is centrally located in the fish habitat area.

2. UPPER KLAMATH LAKE PREVAILING WINDS AND CIRCULATION

The circulation in Upper Klamath Lake is determined by wind forcing and the bathymetry of the lake. The lake is mostly shallow (<3.5 m depth) with the exception of a narrow trench (>10 m depth) that runs along the western shoreline (Figure 1). The prevailing winds over Upper Klamath Lake are westerly (between approximately 250 and 315 degrees) over the northern part of the lake and then are constrained by the surrounding land topography to a northwesterly direction (between approximately 315 and 360 degrees) over the southern part of the lake (Figure 2). Current velocity measurements made with acoustic Doppler current profilers (ADCPs, Wood et al., 2006) and the hydrodynamic modeling effort (Cheng et al., 2005) have confirmed that during periods of prevailing winds, the circulation is clockwise around the lake, consisting of a broad and shallow southward flow through most of the lake and along the northern and eastern shorelines, and a narrow, deep, northward flow through the trench along the western shoreline (Figure 3). The current direction in the trench is tightly constrained by the bathymetry to flow to the northwest at approximately 320 degrees; occasional reversals are associated with reversals in the wind direction, and demonstrate that the response of the currents to a change in wind direction is rapid, within a few hours (Figure 4). Some of the water exiting the trench just west of Bare Island continues clockwise around the island, and the rest turns west around Eagle Point, generating a clockwise circulation within the northern third of the lake (Figure 3).

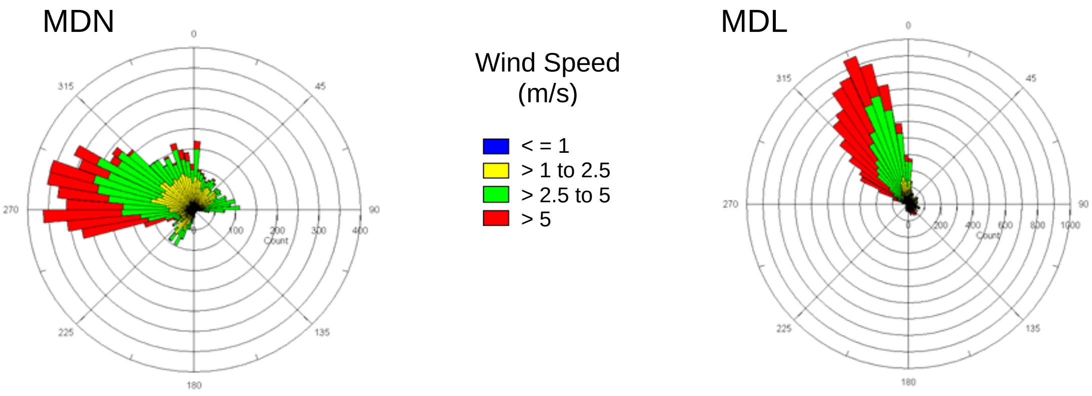

Figure 2 Wind histograms of wind vector data from sites MDN where prevailing winds are westerly, and MDL where prevailing winds are northwesterly, on Upper Klamath Lake, June-October, 2005. The direction shown is the direction from which the wind is blowing.

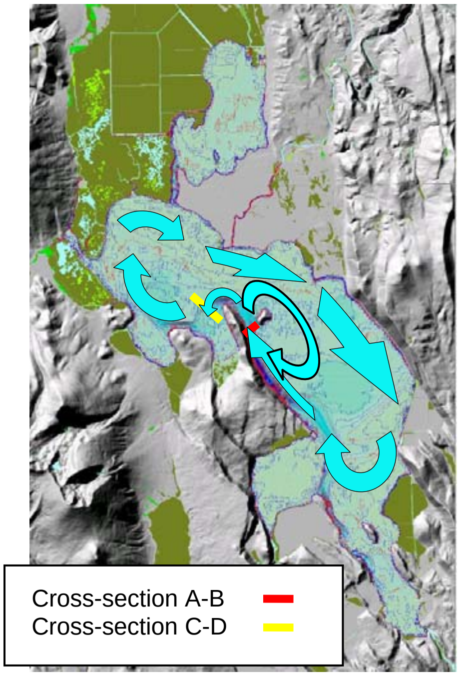

Figure 3 Schematic of the circulation pattern in Upper Klamath Lake under prevailing wind conditions.

The UnTRIM model of Upper Klamath Lake confirms the close coupling between lake currents and wind forcing at the surface. This 3-dimensional model runs on an unstructured, boundary-fitted grid with 8,389 computational cells that vary in size from about 40 to 250 m, and 22 computational layers. The boundary conditions include major tributary inputs and outflow at the southern end of the lake. The model includes heat transport and temperature-dependent density. The model was initially run using wind data from 2003, which was collected at site MDN in the northern part of the lake (Figure 1, Cheng et al., 2005). Based on that study, it was recognized that because the currents are so responsive to the wind forcing, a realistic, spatially variable wind field forcing might improve the accuracy of the simulated hydrodynamics. More meteorological sites were added around the shoreline of the lake in 2005 (Figure 1); all were in place and collecting good data by August 18. An atmospheric boundary layer model was developed to interpolate among the two sites on the lake and four sites on the shoreline of the lake, taking into account local mass conservation and the regional land topography, in order to create a spatially variable wind field with which to force the lake circulation (Ludwig et al, 1991,1997). Modeled currents were in better agreement with the observed currents when the spatially variable wind field was used, as compared to the spatially uniform wind field (Figure 5). This was particularly true in the northern third of the lake that is the most important focus of this study. Therefore we used a spatially variable wind forcing to investigate the relation between the strength of the wind forcing and the transport in the northern third of the lake.

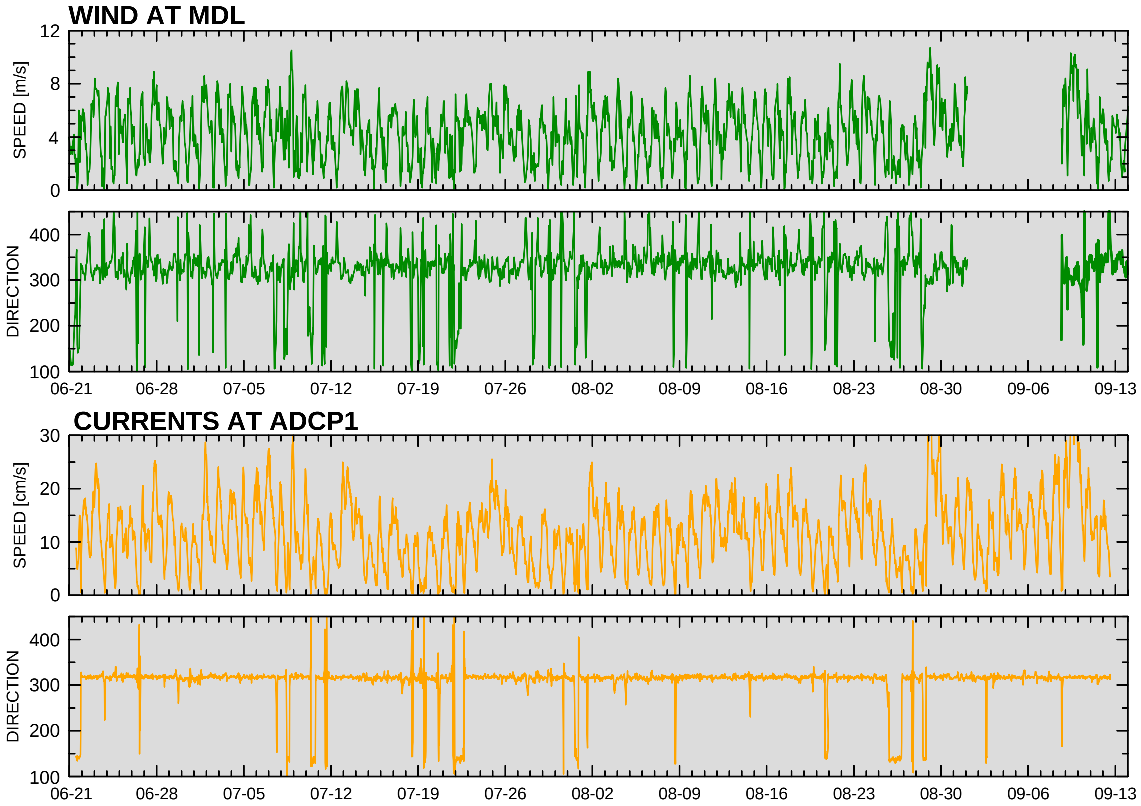

Figure 4 Wind speed and direction observed at MDL, and depth-averaged current speed and direction observed at ADCP1, 2005. Current direction is the direction toward which the current vector points. Both wind and current direction are plotted on a scale from 100 to 460 degrees, because 360 degrees were added to direction values less than 100 degrees. This removed many transitions between 0 and 360 degrees, and makes the graphs easier to read.

3. APPROACH

The UnTRIM hydrodynamic model of Upper Klamath Lake was used in an experimental mode to investigate the relation between wind speed and water quality, in particular dissolved oxygen concentration, in the northern part of the lake. This was not an attempt to accurately re-create observations of dissolved oxygen during any particular time period as a result of observed wind forcing, but rather to simplify the situation enough to isolate one particular aspect of the relation between wind speed and dissolved oxygen—the transport of relatively oxygen-depleted water from the trench into the fish habitat in the northern third of the lake. By taking this first experimental modeling step, some insight is gained that is difficult to achieve by going directly to a more complicated dissolved oxygen model that includes all the non-conservative terms contributing to the dissolved oxygen budget, and has the objective of accurately reproducing observations. Consistent with this approach, we use idealized versions of wind forcing that represent two extremes—one in which a very strong prevailing wind persists uninterrupted for up to two weeks, and another in which a very weak prevailing wind persists uninterrupted for up to two weeks. In reality, the wind observed around Upper Klamath Lake is more variable than this, and neither of these extremes in conditions normally persists for more than a day or two; nonetheless, these two idealized time series bracket the range that is possible in the distribution of the wind vectors over the lake on time scales of one or two weeks.

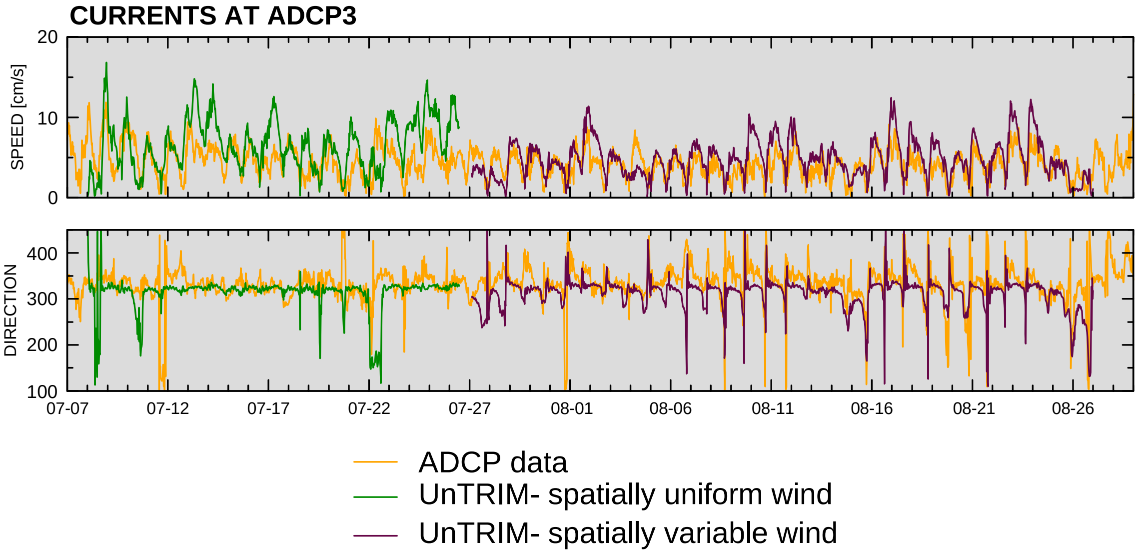

Figure 5 Comparison of observed depth-averaged current speed and direction at ADCP3 to model simulation. Current direction is the direction toward which the current vector points. Prior to July 25, the model was forced with a uniform wind as observed at MDL; after July 25, the model was forced with a spatially variable wind interpolated from five sites around the lake. Current direction is plotted from 100 to 460 degrees because 360 degrees were added to direction values less than 100 degrees. This removed transitions between 0 and 360 degrees, and makes the graphs easier to read.

A time series of spatially variable wind over the lake representative of "strong" and "weak" prevailing conditions was constructed by first examining the wind time series at a single site (MDL was chosen because it is over the lake and prevailing winds through the site have a long fetch) and the observed currents at ADCP1. Because the wind over the lake is interpolated among several meteorological data collection sites, only the time period when data from all sites were available was considered, which limited the period under consideration to July 25 through October 12 when the meteorological stations on the lake were removed. A 2-day period of strong prevailing winds was identified that occurred on September 9 and 10, as evidenced by the high wind speed, very steady wind direction, and the corresponding strong and steady currents that occurred in the trench during that time (Figure 6). This 2-day period was isolated and then repeated multiple times in order to create a long time series of strong prevailing winds that preserved a realistic diurnal pattern. Similarly, a 2-day period of weak prevailing winds on August 19 and 20 was identified by moderate wind speeds and wind direction that was steady in the prevailing direction during the maximum wind speeds, with a clockwise rotation during the time of day of the weakest wind speeds. This typical diurnal pattern during weak winds results in moderate currents in the trench steadily northward except for a brief reversal of an hour or so during the day (Figure 7). This 2-day period of weak prevailing winds was isolated from the time series and repeated to create a longer time series of weak prevailing winds.

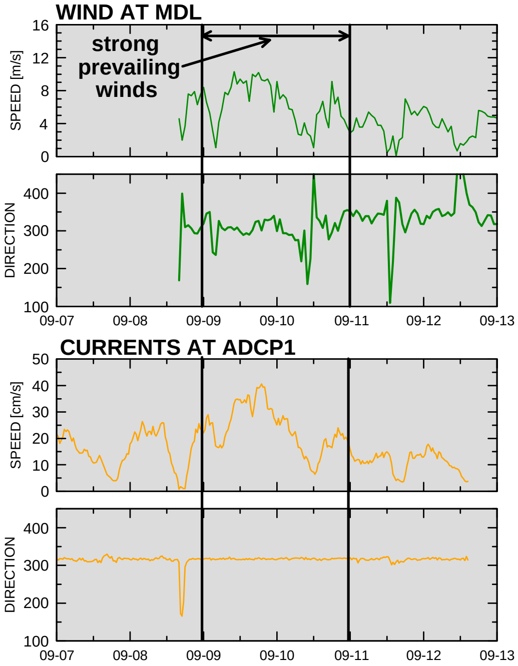

Figure 6 Observed wind speed and direction at MDL and observed currents at ADCP1 during a period of strong prevailing winds, September 9-11, 2005.

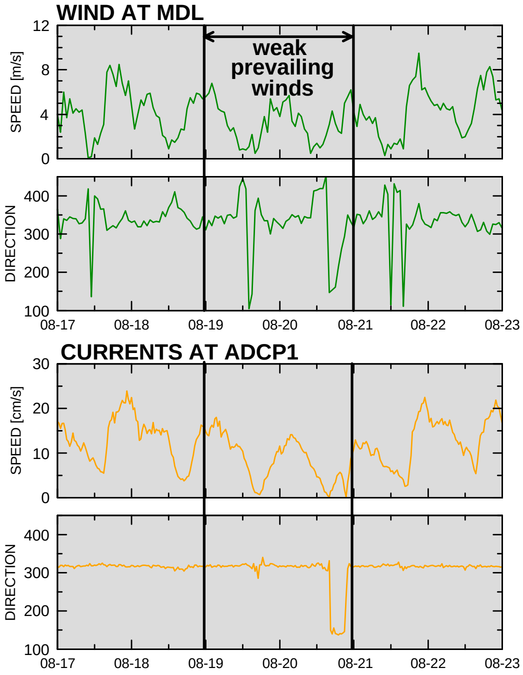

Figure 7 Observed wind speed and direction at MDL and observed currents at ADCP1 during a period of weak prevailing winds, August 19-21, 2005.

In order to investigate the relation between wind speed and dissolved oxygen in the northern third of the lake, the following numerical experiment was conducted. Concentrations of dissolved oxygen were initialized to 10 mg/L everywhere in the model. A zero-order decay of 5 mg/L day^{-1} was applied only in those areas of the model with a water column depth greater than 4.5 m. (Figure 8). No other production or consumption terms were included in this model. The initial conditions and decay represent a much simplified model of dissolved oxygen in which concentrations are supersaturated in shallow areas that comprise most of the lake, and in which decay processes exceed photosynthetic production in the deeper areas of the lake, located in the trench along the western shoreline. The numerical simulation was run forward for 10 days (approximately the time scale of very low dissolved oxygen events in the lake), starting with initial conditions saved from a previous model simulation, thus eliminating the initial adjustment from static to dynamic conditions. Two 10-day simulations were produced, starting with the same set of initial conditions, first using a 10-day time series of the weak prevailing wind forcing function, and then using a 10-day time series of the strong prevailing wind forcing function. All other forcing functions and boundary conditions were as observed for the time period July 10-20, 2005, ensuring that they were realistic for the mid- to late July time period that tends to be most crucial for water quality in the lake. The decay term was turned off in a grid cell if all of the oxygen was depleted, with the result that the concentration was allowed to be zero but was not allowed to become negative.

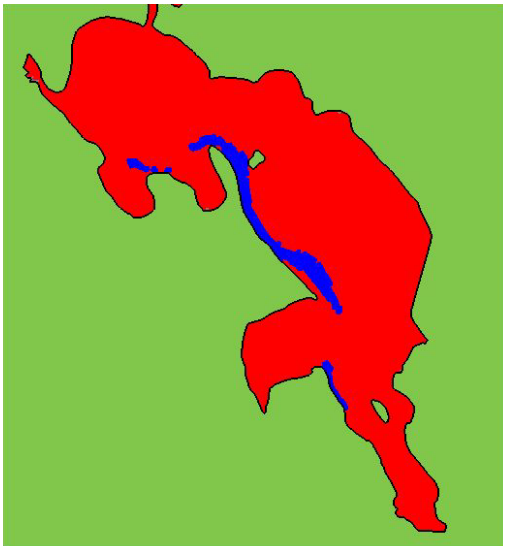

Figure 8 Map of Upper Klamath Lake showing areas of the UnTRIM model grid (in blue) where a zero-order decay term was applied to dissolved oxygen concentrations.

4. RESULTS

The simulations demonstrate that the strength of the wind and the resultant circulation pattern affect the dissolved oxygen concentration at MDN (Figure 9). Concentrations at MDN are more variable over the day, particularly in the lower water column, under the weak prevailing wind scenario. The upper water column and daily maximum concentrations, however, are lower at MDN under the strong prevailing wind scenario. Concentrations in the trench (at site MDT) are depleted faster under the weak prevailing wind scenario (Figure 10) because the residence time in the trench is greater, but the concentration in the trench is more similar to the concentration at MDN under the strong prevailing wind scenario. Strong prevailing winds produce a stronger clockwise circulation around the northern part of the lake that carries relatively more of the oxygen-depleted water from the trench into the fish habitat area. In contrast to the concentration at MDN, the concentration at ADCP8, which is to the east of Bare Island and in the smaller circulation loop that circles the island (Figure 4), is lower under the weak prevailing wind scenario (Figure 11), indicating more influence of the trench at that site under the weak prevailing wind scenario than under the strong prevailing wind scenario. The fact that the concentration trends downward indefinitely at all the sites is an artifact of the lack of any photosynthetic production terms in the model to balance the loss of oxygen in the trench.

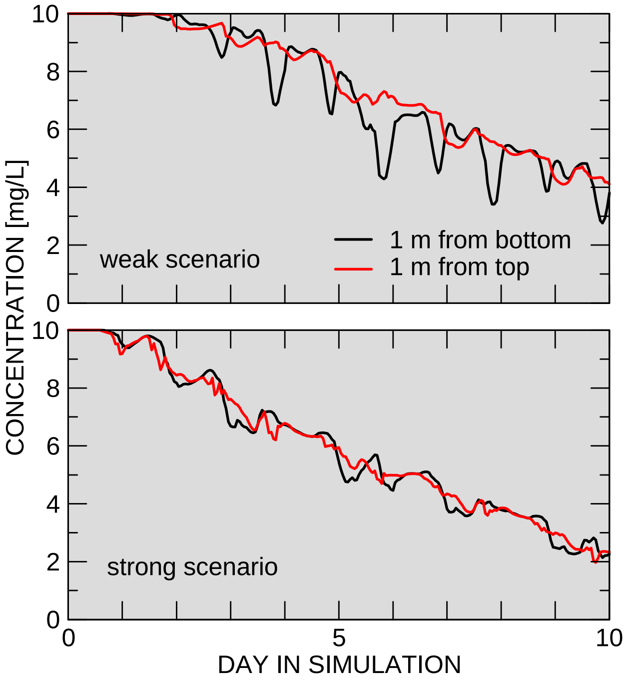

Figure 9 Simulated dissolved oxygen concentration at MDN.

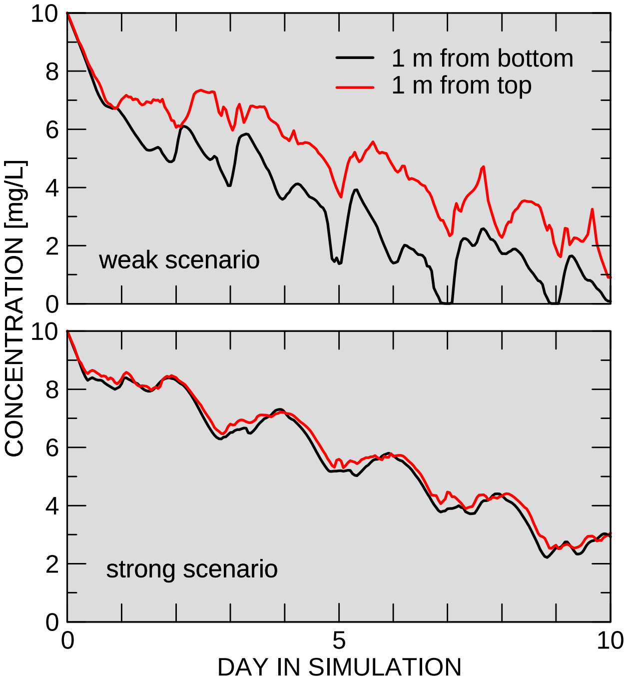

Figure 10 Simulated dissolved oxygen concentration at MDT.

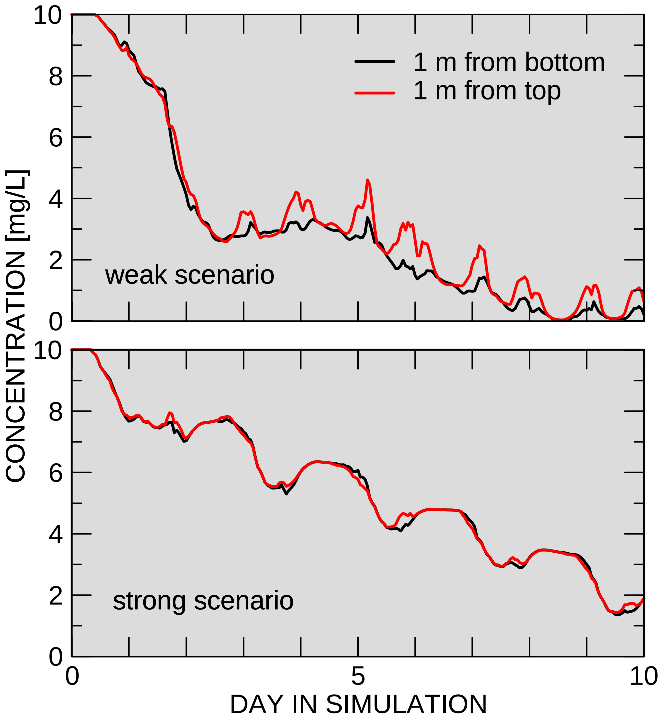

Figure 11 Simulated dissolved oxygen concentration at ADCP8.

In both scenarios, some of the water coming through cross-section A-B (Figure 3) turns clockwise around Bare Island and moves southward without ever entering the northern part of the lake. This is clearly seen in the accompanying movies as the spread of the plume from the trench both to the west around Eagle Point and around the eastern side of Bare Island. The circulation produced by weak prevailing winds sends proportionately more water around Bare Island and back to the south than does the circulation produced by strong prevailing winds. Strong prevailing winds send proportionately more water west around Eagle Point and across the entrance to Shoalwater Bay, represented by cross-section C-D (Figures 3, 12, and 13).

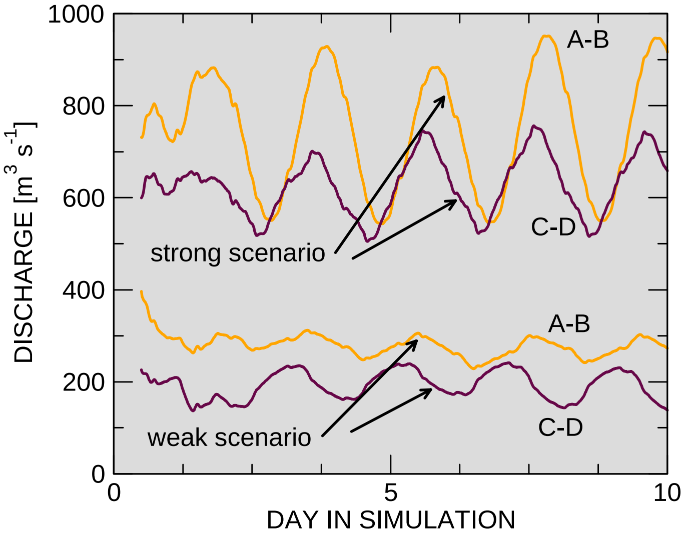

Figure 12 Simulated discharge through cross-sections A-B and C-D.

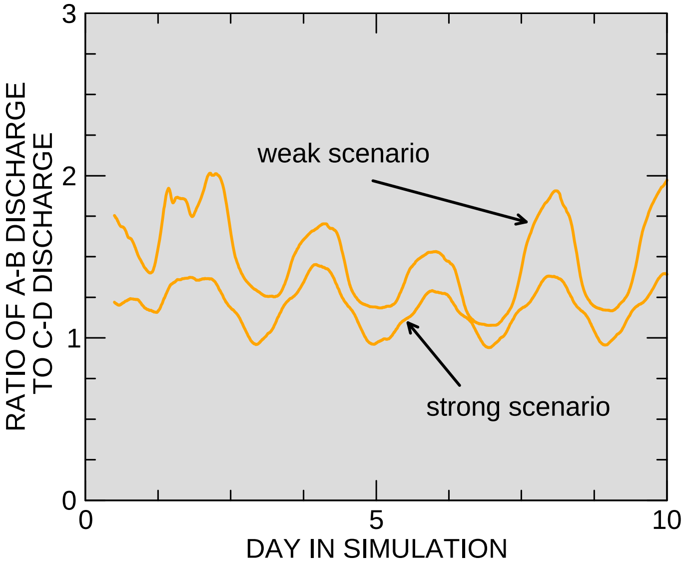

Figure 13 Ratio of simulated discharge through cross-section A-B to simulated discharge through cross-section C-D.

5. DISCUSSION

The water quality observed at MDN, a site centrally located in the area occupied by endangered fish species, is a complicated function of the lake circulation and the sources and sinks that affect the concentration of a nonconservative quantity like dissolved oxygen. Nonetheless, by considering a simplified version of a dissolved oxygen model we can gain some understanding of the relation between wind strength and dissolved oxygen that might be lost in going directly to a more complicated model incorporating all of the relevant nonconservative processes. In this simplified model, two important and competing effects of varying wind speed are demonstrated. A weaker prevailing wind generates a weaker circulation pattern, which increases the residence time of any given parcel of water in the trench and therefore increases the time available for decay processes to consume dissolved oxygen, resulting in much lower concentrations in the water leaving the trench. At the same time, because the overall circulation and currents are weaker, more of the water leaving the trench west of Bare Island turns eastward around the island and then south without entering the northern part of the lake. Because relatively more of the low-concentration water is diverted away from the northern part of the lake, the concentration at MDN is higher under the weak prevailing wind scenario than under the strong prevailing wind scenario, even though the dissolved oxygen in the trench is depleted more rapidly under the weak prevailing wind scenario. Strong prevailing winds are more effective at forcing the water in the trench into the important fish habitat area in the northern part of the lake.

Awareness of the relation between wind forcing and dissolved oxygen in Upper Klamath Lake will help researchers understand why fish die-offs have occurred in the past and under what conditions they are likely to occur in the future. The results presented here are at odds with past interpretations of this relation. This can be explained in part by an overestimate of the importance of stratification in generating low dissolved oxygen events in this lake (Wood et al., 2006), but the correspondence between lower-than-average wind speed and fish die-off years has been noted based on empirical relations between variables (Kann and Welch, 2005) and based on an analysis of variance (ANOVA) of a historical dataset of climate variables collected at the Klamath Falls Airport by the National Oceanic and Atmospheric Administration (NOAA) since 1990 (Wood et al., 2006).

It may be that quality of the NOAA wind dataset was insufficient for the statistical techniques that were used, because other lines of evidence support the results presented here. For example, Wood et al. (2006) noted that the ANOVA analysis of wind speed in the NOAA dataset was inconsistent in important ways with a similar analysis of a shorter but higher quality dataset collected by the Bureau of Reclamation at a site near Agency Lake. Furthermore, the relation between dissolved oxygen concentration and wind speed presented here is consistent with observations made since 2002. Wood et al. (2006) noted that sometimes the concentrations observed in the trench are very similar to those observed at MDN, indicating that the trench has a large influence on the northern part of the lake, and sometimes the concentrations observed at MDN are quite different from those observed in the trench, indicating less direct influence of the water in the trench on the conditions to the north. When a severe low dissolved oxygen event lasting for several weeks and a small fish die-off occurred near the end of July in 2003, the concentrations measured at MDN were very similar to low concentrations measured in the trench. In 2004, a similar dip in the concentration was observed near the middle of August, but conditions as severe as those in the trench never reached MDN. Because wind measurements were made over the lake in those years, we can confirm that the wind speeds in July 2003 were higher than in July 2004. It also is possible that wind speed is just one, and maybe not the most important, of several variables that determine when conditions become bad enough to result in a fish die-off.

ACKNOWLEDGEMENTS

The authors wish to thank USGS colleague reviewers Stewart Rounds and Jerad Bales, and technical editor John Williams. The efforts of these reviewers greatly improved the final paper.

REFERENCES

Casulli, V., and Zanolli, P. (2002). “Semi-implicit Numerical Modeling of Non-hydrostatic Free-surface Flows for Environmental Problems”, Mathematical and Computer Modelling, vol. 36, pp. 1131-1149.

Cheng, R., Gartner, J., and Wood, T. (2005). “Modeling and Validation of Wind-Driven Circulation in Upper Klamath Lake, Oregon”. Proceedings of the 2005 World Water and Environmental Resources Congress, R. Walton (editor), EWRI/ASCE, May 15-19, 2005, Anchorage, Alaska.

Eilers, J., Kann, J., Cornett, J., Moser, K., St. Amand, A., and Gubala, C. (2001), “Recent Paleolimnology of Upper Klamath Lake, Oregon”, Roseburg, Oregon, Report submitted to the Bureau of Reclamation, Klamath Falls, Oregon by JC Headwaters, Inc., 44 p.

Kann, J. and Welch, E. B. (2005), Wind control on water quality in shallow, hypereutrophic Upper Klamath Lake, Oregon, Lake and Reservoir Management, vol. 21 (2), pp. 149-158.

Ludwig, F. L., Livingston, J. M., and Endlich, R. M. (1991), “Use of Mass Conservation and Critical Dividing Streamline Concepts for Efficient Objective Analysis of Wind in Complex Terrain”, J. Appl. Meteorol., Vol. 30, pp. 1490-1499.

Ludwig, F. L., Cheng, R. T., Feinstein, J., Sinton, D., and Becker, A. (1997), “An On-line Diagnostic Wind Model Applied to San Francisco Bay Region”, 13th Inter. Conf. on Interactive Information and Processing System (IIPS) for Meteorology, Oceanography and Hydrology, Am. Meteorological Society, February 2-7, 1997, pp. 344-347.

Wood, T., Hoilman, G., and Lindenberg, M. (2006), “Water Quality Conditions in Upper Klamath Lake, Oregon, 2002-2004”, US Geological Survey Scientific Investigations Report 2006-5209, 52 p.