

Hypoxic Intrusions to Puget Sound from the Ocean

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Abstract—Oceanic intrusions of dense, hypoxic water regularly occur at the entrance to Puget Sound, WA (USA), and may be significant to regional dissolved oxygen levels. Seabed observations at Admiralty Inlet from 2009 to 2013 show a strong correlation of low dissolved oxygen concentrations with high salinity, coincident with residual currents directed inward to Puget Sound. These intrusions of dense water to Puget Sound likely are related to estuarine exchange flows, which are expected to occur during conditions for minimal tidal mixing. Observations are consistent with minimal mixing, which occurs during the neap tides and maximum diurnal inequalities (and especially during solar equinoxes, when these effects are combined). However, tidal conditions alone cannot predict intrusions of hypoxic ocean water to Puget Sound. Coastal upwelling and Fraser River discharge influence the availability of dense, hypoxic water outside of Puget Sound. This likely is related to the larger-scale exchange flow in the Strait of Juan de Fuca, which connects Puget Sound to the North Pacific Ocean. This large scale process adds a strong seasonal modulation to the intrusion of hypoxic water. This paper develops a method to diagnose hypoxic intrusion events at Admiralty Inlet. The method is based, empirically, on seabed observations, but application of the method relies on operational data products. Using only tidal elevation datum and indices for coastal upwelling and river discharge, 100% of events with dissolved oxygen less than 4.0 mg/L are identified in the 3 year record.

I. INTRODUCTION

The waters of Puget Sound, WA (USA), are periodically subject to very low dissolved oxygen levels. These hypoxic events can be extremely harmful to biological life and consequentially to ecosystem-based industries like fishing and aquaculture. Within Puget Sound, Hood Canal is particularly susceptible to hypoxic events that lead to fish kills and to the decimation of populations of other marine life [1]. The origin of this low dissolved oxygen water can be attributed to two major forces. An obvious possible force is anthropogenic modulation. Runoff from farmland and other untreated wastewater that is high in nutrients can cause widespread algae blooms under certain conditions, which quickly consume dissolved oxygen in the water, reducing the concentration to hypoxic levels [1]. These anthropogenic forces may play a role in the modulation of dissolved oxygen levels in Puget Sound, but there is also an external forcing

factor. The external forcing is the natural modulation of dissolved oxygen concentration by oceanographic processes, particularly the intrusion of hypoxic water from the Pacific Ocean [1].

The overwhelming majority of the water leaving and entering Puget Sound does so through Admiralty Inlet, and thus our study focuses on this location. Admiralty Inlet has a unique bathymetry in that it has a long shallow sill compared to most glacially carved estuaries. The sill region is about 30 kilometers in length and has a minimum depth of about 60 meters with two major peaks along the region [2]. This distinctive geometry plays an important role in determining the physical behavior of the flow of water between the Strait of Juan de Fuca and Puget Sound. Another important characteristic in this region is the presence of strong tidal currents (> 3 m/s) [3].

The natural modulation of dissolved oxygen has not been studied enough to sufficiently understand the processes involved and its relative contribution to the overall modulation of dissolved oxygen levels in Puget Sound. It is understood that dense, low dissolved oxygen water can be upwelled from the deep ocean and carried through Admiralty Inlet into the Sound under certain tidal conditions [2]. This water then makes its way through the main basin and eventually may become involved in hypoxia events in certain areas of the Sound [4]. The relative importance of natural modulation compared to that of anthropogenic modulation is not well known. The driving forces involved in the availability and physical transport of these low dissolved oxygen water inflows require more explanation but are expected to include coastal upwelling, tidal currents, and river discharge.

Geyer and Cannon determined that high salinity intrusions into Puget Sound occur during periods of minimal mixing at Admiralty Inlet [2]. Consequently, they found that the two most important conditions favoring dense water inflow over the sill are the maximum diurnal inequality and the neap tides, which coincide at the equinoxes [2]. However, Geyer

and Cannon also note that the presence of these favorable conditions for dense water inflow do not guarantee that a high salinity intrusion will occur and that there are other forcing factors like increased river runoff that may account for availability of dense water [2]. Cannon, Holbrook, and Pashinski, discuss that coastal upwelling and downwelling may be important factors for availability as well [5]. In particular, Cannon, Holbrook, and Pashinski, observed that coastal storms in the winter, which cause downwelling, may suppress high salinity water intrusions [5]. They also calculated a strong negative correlation between bottom salinity near Admiralty Sill and wind measurements at N 48, W 125, with a lag in the bottom salinity of about 7.25 days following wind events [5].

In order to assess the seasonal availability of hypoxic water in the Strait of Juan de Fuca near Puget Sound, the persistence of coastal upwelling conditions and the discharge signal of the Fraser River must be quantified. The Fraser River is the primary source of fresh water into the Strait of Juan de Fuca [6]. Both upwelling and Fraser River discharge would influence the density difference between deep oceanic waters and fresher surface waters. An increase in this density difference could increase the strength of a two-layer exchange flow in the Strait [7]. Given Juan de Fuca conditions favorable for hypoxic availability, an intrusion at Admiralty Sill would then be expected to occur during neap tides with maximum diurnal inequality.

This paper presents a method to quantify the combined tidal and regional conditions necessary for hypoxic intrusion events. Section II describes seabed observations of hypoxic intrusions and develops indices for the relevant conditions. Section III applies these indices to predict (or rather, hindcast) the seabed observations and correctly identify hypoxic intrusion events. Section IV discusses implications and potential applications of the predictions for future events. Section V presents conclusions.

II. METHODS

A. Field Observations

Since August of 2009, a Seabird 16plusv2 CTDO (Conductivity, Temperature, Depth, Oxygen) sensor has been deployed on a Sea Spider tripod on the bottom of Admiralty Inlet off of Admiralty Head at approximately N 48 09.172, W 122 41.170. The water depth is approximately 55 m (ref. MLLW). The CTDO is mounted on the tripod 0.5 m above the seabed, and it samples every 30 minutes. The tripod is recovered and redeployed every 3 months, and each time the CTDO is replaced and calibrated.

A Nortek Continental ADCP (Acoustic Doppler Current Profiler) and a number of other sensors are also mounted to the tripod. (The tripod deployments are motivated originally by a tidal energy site characterization, see [3] [8]). The

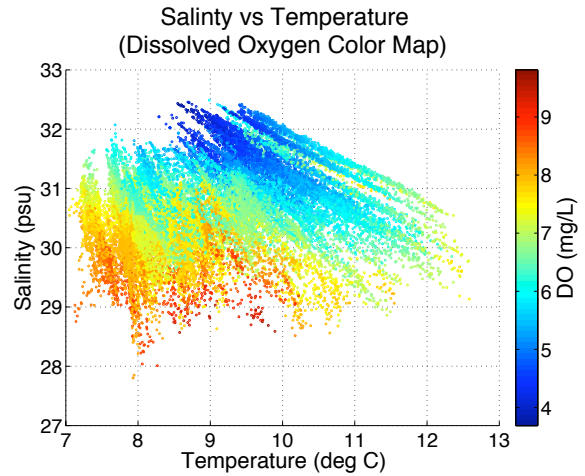
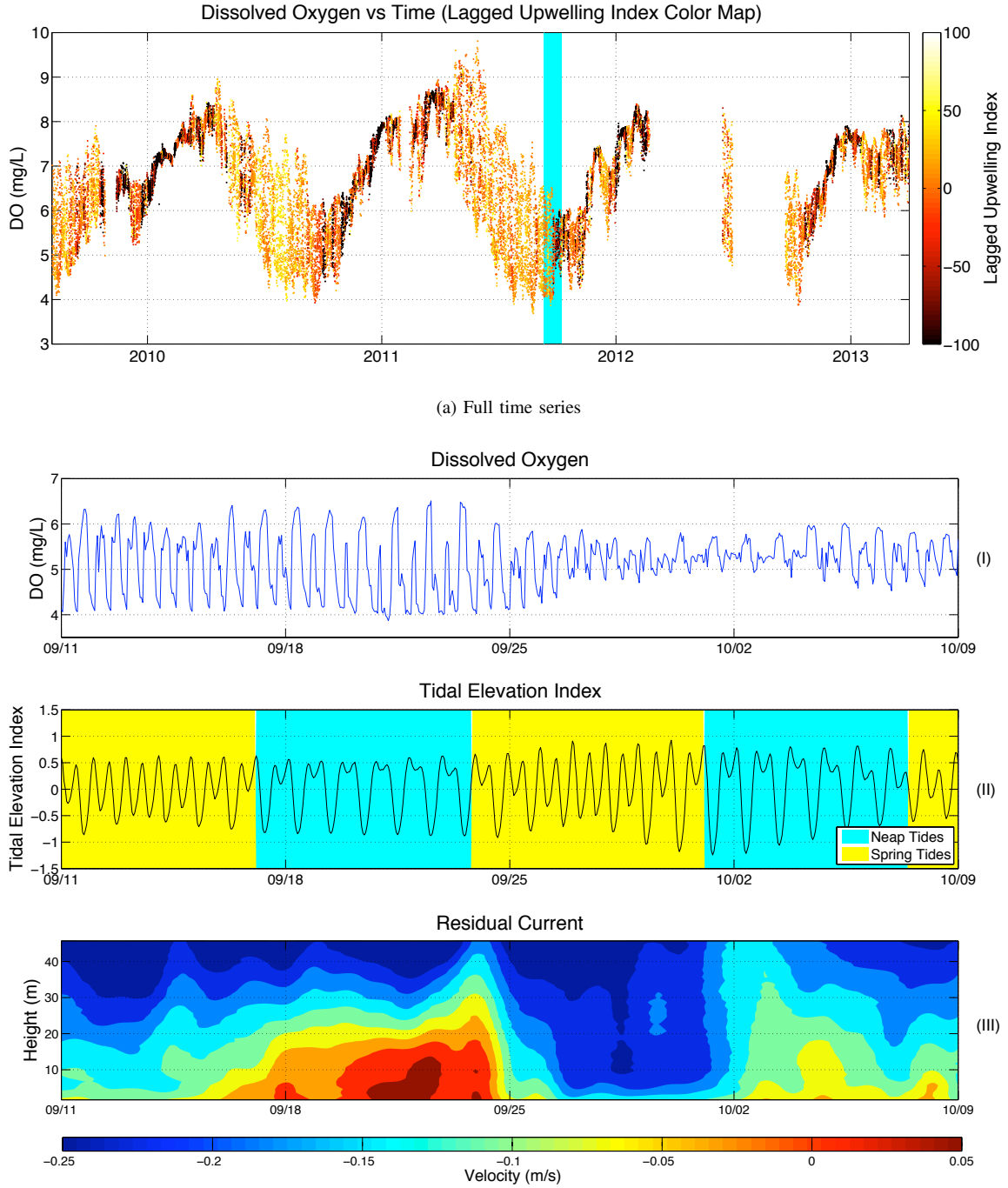


Fig. 1. Salinity (PSU) versus temperature (C) at Admiralty Inlet from August 2009 to April 2013. Data colored according to corresponding dissolved oxygen concentration (mg/L).

ADCP samples currents in 1 m bins from 1.7 to 50.7 m above the seabed and records ensemble averages every 1 minute. Prior to analysis, all CTDO and ADCP data are interpolated to a uniform hourly time base. This obscures the small scale variations, but provides high statistical confidence in resolving processes on tidal and seasonal time scales.

The CTDO sensor is a single point measurement, and thus cannot be used to estimate the flux of dissolved oxygen through the Inlet. Rather, we focus on diagnosing events of low dissolved oxygen and related conditions. Before other analysis, the collocated salinity and temperature readings are used to identify the water mass associated with low dissolved oxygen. As shown in Fig. 1, low dissolved oxygen levels measured at the site correspond with high salinity water and a narrow temperature range, suggesting an oceanic source (water from Puget Sound is expected to be fresher as result of the large river outflows). This confirms that occurrences of low dissolved oxygen water in Admiralty Inlet can be paired with the dynamics of dense water intrusions, which have been studied previously at this location [2].

The full time series from the CTDO sensor is shown in Fig. 2a, with a length of over three years. Missing sections of data are due to instrument failure or corrupted data. There is noticeable seasonality in the time series with the lowest dissolved oxygen levels occurring in the late summer and early autumn and higher levels occurring in the spring. There is also significant variance on shorter time scales. Fig. 2b(I) shows a four-week period in which dissolved oxygen levels are low and in which the tidal dynamics are theoretically favorable for exchange flow. In Fig. 2b(II), a Tidal Elevation Index derived via de-meaning and normalizing the pressure signal from the CTDO is shown in conjunction with the neap tides, which are



(b) Zoom-in of period shaded blue in full time series plot

Fig. 2. (a) Time series of dissolved oxygen concentration (mg/L) at Admiralty Inlet from August 2009 to December 2012. Data points colored according to an Upwelling Index obtained from the Pacific Fisheries Environmental Laboratory [9], linearly interpolated to an hourly time scale, and lagged 7.25 days (following [5]). (b) A four-week subset of data surrounding the 2011 autumnal equinox, showing: (I) dissolved oxygen concentration (mg/L), (II) Tidal Elevation Index (from demeaned pressure measurements), and (III) low-pass filtered residual currents (m/s), height measured from sea floor. Spring and neap tide periods are shaded for the Tidal Elevation Index time series.

shaded blue.

$$TEI = \frac{\text{demean}(Pressure)}{-MLLW} \quad (1)$$

As expected, the neap tides and the maximum diurnal inequality occur simultaneously during the equinox, and

thus there are protracted periods of weak tidal currents. The weak currents are associated with weak mixing, and thus exchange flow is strong. The residual currents, calculated using a low-pass filter $\mathcal{F}_{40}$ (low-pass filter notation) on the ADCP current velocity data with a half-amplitude period of 40 hours [8], show significant exchange flow occurring

coincident with the minima in dissolved oxygen (Fig. 2b(II)). It is clear that strong exchange flows and lower dissolved oxygen concentrations develop during periods of weak tidal amplitude. These flows and concentrations appear to be subsequently mixed out during periods of large tidal amplitude, consistent with Geyer and Cannon [2].

Related to this tidal modulation of exchange via mixing, there is a significant negative correlation between dissolved oxygen and tidal elevation during the period from August to November of 2011, an example of a period with a fairly constant background DO signal. While this correlation cannot be observed for the full data set due to seasonal trends, it suggests that tidal elevation may be a useful predictor of exchange flow conditions. However, whether low dissolved oxygen water is available to enter the Sound during these conditions likely depends on other forcing factors like coastal upwelling and river discharge. Revisiting Fig. 2a during the same time period, it appears that coastal downwelling is also initiated at the end of September 2011.

To examine this forcing, records of an Upwelling Index *UI* from the same longitude and latitude as the wind data used by Cannon, Holbrook, and Pashinski [5], were obtained from the Pacific Fisheries Environmental Laboratory [9], lagged by 7.25 days, and then compared with the dissolved oxygen time series from the mooring at Admiralty Inlet, as shown in Fig. 2a. This factor appears to play an important role in determining the availability of low dissolved oxygen water at Admiralty Inlet. Positive values indicate winds from the North that favor upwelling and negative values indicate winds from the South that favor downwelling. It appears that, on a seasonal time scale, downwelling conditions reduce of the availability of low dissolved oxygen water to be transported over the sill while upwelling conditions increase the availability of this dense water. This mechanism also seems to have an effect on dissolved oxygen availability on shorter time scales and appears to influence temporary changes in average dissolved oxygen concentrations.

B. Intrusion Event Index

An Intrusion Event Index is developed based on the ADCP data and is used to quantify the duration and magnitude of a bottom water intrusion event. This index is independent of dissolved oxygen levels and is solely intended to identify exchange flow into Puget Sound. Thus, the index is expected to modulate with spring-neap tidal cycles and diurnal inequality signals. Due to a new tripod location starting May 2010, only the time series from May 2010 to April 2013 will be considered in all subsequent intrusion analysis in order to preserve consistency in the index related to site-specific residual current patterns. Residual current data is first interpolated to create consistent bin sizes and heights between different ADCP deployments. Then residual current velocities are vertically averaged for all bins with positive

(into the Sound) current velocities from the seabed up to the zero crossing (i.e., where residual current velocity switches to negative [out of the Sound]). This depth-averaged intrusion velocity provides average positive current velocities of bottom water intrusions to the Sound and has a value of zero for all negative bottom current velocities, at each time step.

Next, the positive (inward) average bottom residual current velocities are integrated in time. Once this time-integral reaches a point where the depth-averaged intrusion velocity is zero or undefined, it resets to zero and remains so until the depth-averaged intrusion velocity is positive again and time-integration resumes. The result of this integral is a length scale representing the distance that a water parcel would travel under an assumption of homogenous flow. Comparing this length scale to the approximate $L = 30$ km length of Admiralty Sill [2], it can be assumed that if the time-integrated length of a bottom water intrusion is greater than 30 km, then a dense-water intrusion could potentially traverse all the way over the sill and into the main basin of Puget Sound. Thus, a non-dimensional intrusion index is given by

$$IEI = \frac{\int u dt}{L}, \quad (2)$$

in which any intrusion that exceeds one before resetting to zero is considered a major bottom water intrusion event, with the potential for bottom water to enter the deep basin of Puget Sound.

C. Neap Tide Index

The spring tide to neap tide cycle has a fortnightly period and is based on lunar orientation. Since spring tides reach their peak during the new moon and full moon and neap tides are prominent during periods of the quarter-moons [10], lunar phase data can be used as a basis for quantifying the neap-spring cycle. Daily lunar phase data downloaded from the Astronomical Applications Department of the US Naval Observatory provide a strong historical and predictive record for this application [11]. This daily raw data is formatted on a scale where a full moon has a value of 1, a quarter moon has a value of 0.5, and a new moon has a value of 0. The equation in (3) is used in order to convert this raw scale into the Neap Tide Index, a form where a value of 1 represents peak neap period and a value of 0 represents peak spring period.

$$NTI = (-2 \times |LunarPhase - 0.5|) + 1 \quad (3)$$

Since the NTI has a period of about 14 days, it does not need to be filtered to remove a tidal signal in order to be compared with residual current data or the Intrusion Event Index.

D. Diurnal Inequality Index

The maximum diurnal inequality occurs when the difference between the semidiurnal tidal amplitudes is largest. This means that there is about a half-day period of very gradual change

in tidal elevation followed by about a half-day period of very rapid change in tidal elevation, as can be seen in Fig. 2b(II). During the small-amplitude portion of the signal, tidal currents are weak with minimal mixing. Therefore, during the maximum diurnal inequality, average daily tidal elevation changes are moderated by these slow elevation-change periods. Conversely, during periods of diurnal equality, large-amplitudes dominate the entire signal and tidal currents are strong with maximal mixing. In order to capture this phenomena and its subtidal signal, the absolute value of the time gradient of the Tidal Elevation Index is low-pass filtered. The sign of the result is reversed for maximum values to indicate periods of maximum diurnal inequality and then normalized on a scale from 0 to 1 for the given time series, producing the Diurnal Inequality Index.

$$DII = -\mathcal{F}_{40} \left(\left| \frac{d}{dt} TEI \right| \right) \quad (4)$$

Values closer to 1 suggest the tidal elevation signal is in a period of maximum diurnal inequality, characterized by minimal average mixing, while values closer to 0 suggest the tidal elevation signal is in a period of near-diurnal-equality, characterized by strong mixing. Strong exchanges can happen during spring tides, but only during the lesser flood tide of a diurnal cycle. A subsequent greater ebb will cause mixing, and the exchanges are not sustained unless the diurnal inequality and the neap tide are coincident.

E. Upwelling Persistence Index

Persistent periods of upwelling or downwelling at the mouth of the Strait of Juan de Fuca influence a seasonal trend in dissolved oxygen concentration at Admiralty Inlet (Fig. 2a). A new index is defined in order to capture the influence of sustained upwelling or downwelling conditions over time. Since the upwelling index has a much greater average magnitude during downwelling conditions than during upwelling conditions (due to more intense storms in the winter than summer), a conditional time integral is used to capture this persistence signal. First, the 7.25 day lagged Upwelling Index UI from PFEL is low-pass filtered. Second, the filtered result is set to +1 if positive (upwelling condition) and -1 if negative. Third, this binary result is time-integrated over the series. Finally, the integrated result is demeaned and termed the Upwelling Persistence Index:

$$UPI = \text{demean} \left(\int \text{sign} [\mathcal{F}_{40} (UI - 7.25\text{days})] dt \right) \quad (5)$$

F. Fraser River Discharge Index

Discharge data D for the Fraser River measured at Hope, British Columbia, Canada, were obtained from the Water Survey of Canada website [12]. This station was the nearest main-channel station to the Strait of Juan de Fuca for the Fraser River that had complete discharge data for the appropriate time period. The data obtained was linearly interpolated to an

hourly time scale, then low-pass filtered with $\mathcal{F}_{40}$, and finally normalized to a scale of 0 to 1.

$$FRDI = \frac{\mathcal{F}_{40}(D)}{\max[\mathcal{F}_{40}(D)]} \quad (6)$$

The resulting time series is the Fraser River Discharge Index.

G. Dissolved Oxygen Deficit

A Dissolved Oxygen Deficit index is defined to quantify temporary decreases in dissolved oxygen concentration from the background seasonal modulation of the dissolved oxygen. First, the measured dissolved oxygen is low-pass filtered by $\mathcal{F}_{40}$ with the same 40 hour half-amplitude period as the other signals. Then, the result is filtered again with a 610 hour half-amplitude period filter $\mathcal{F}_{610}$ that is chosen as 1.6 times the maximum observed intrusion event duration (the distinct time period in which the IEI is positive, from initiation to termination of an event). The Dissolved Oxygen Deficit (DOD) is determined by the difference in these signals:

$$DOD = \mathcal{F}_{610}(DO) - \mathcal{F}_{40}(DO) \quad (7)$$

The Dissolved Oxygen Deficit value will be positive during an intrusion event and will indicate a hypoxic intrusion if the observed seasonal dissolved oxygen signal $\mathcal{F}_{610}$ is low at that time.

III. RESULTS

This section presents the two-part prediction developed to determine whether a hypoxic bottom water intrusion into Puget Sound is expected to occur in Admiralty Inlet at a given time. The prediction methods are based solely on indices that can be accurately determined without any in situ data collection in Admiralty Inlet. The first part of the method uses the Neap Tide Index NTI and Diurnal Inequality Index DII to conditionally predict that a major bottom water intrusion event is likely. The second part of the method uses the Upwelling Persistence Index UPI and Fraser River Discharge Index $FRDI$ to empirically predict availability of hypoxic water. When both the tidal and availability conditions are met, hypoxic intrusions are successfully identified.

A. Intrusion Event Predictions

All observed intrusion events that reach an Intrusion Event Index IEI of at least 0.5 are shown in Fig. 3a as a function of time during the event (i.e., from intrusion initiation to intrusion termination). The middle panels of Fig. 3 show the Neap Tide Index (c) and the Diurnal Inequality Index (b) signals during these large intrusion events. Both the Neap Tide Index and the Diurnal Inequality Index must be elevated at the same time in order for an large intrusion event to develop and be sustained. Events evolve according to these indices, such that intrusions terminate as soon as tidal conditions are no longer favorable (i.e., when tides become stronger and mixing becomes dominant). Other variables, such as local winds,

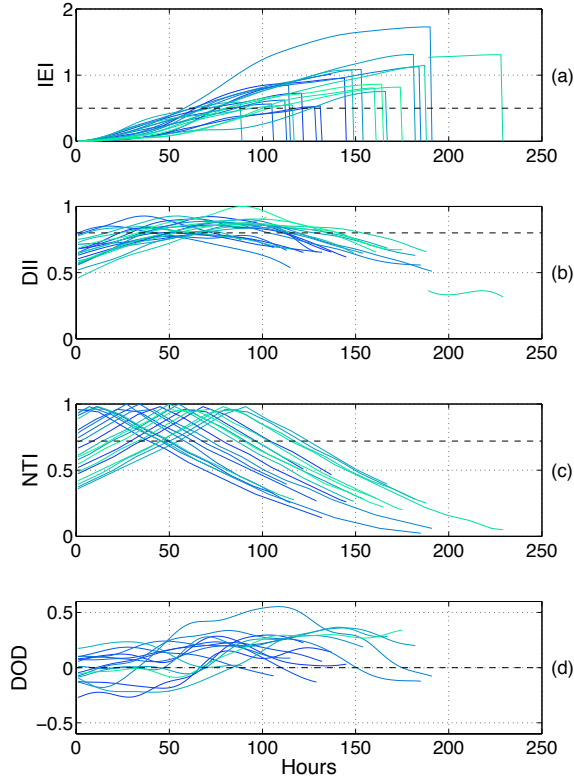


Fig. 3. Composite in time of intrusion events that obtain an IEI value of at least 0.5, showing the signals of (a) Intrusion Event Index, (b) Diurnal Inequality Index, (c) Neap Tide Index, and (d) Dissolved Oxygen Deficit.

and discharge from the major rivers into Puget Sound, and lagged Upwelling Index do not have noticeable patterns during Intrusion Events. Thus, Intrusion Events are predicted solely based on choosing thresholds in NTI and DII :

$$\text{If } NTI > 0.8 \ \& \ DII > 0.72, \text{ Intrusion} = 1 \quad (8)$$

Dashed black lines in Fig. 3 mark these threshold values. As is shown in TABLE I, using these two conditional thresholds achieves a high success rate for correctly identifying an observed intrusion event at at least one time-step in its duration. In fact, these threshold conditions can correctly identify all events that reach an Intrusion Event Index of at least 0.5. Furthermore, using these threshold conditions only produce a false positive prediction 1.74 % of the times that the true Intrusion Event Index is observed to be zero.

B. Empirical Prediction of Seasonal DO Availability

The second portion of the method requires an empirical prediction of the background (seasonal) dissolved oxygen signal. Fig. 3d supports the hypothesis that intrusion events cause a deficit in dissolved oxygen levels compared with the background, availability-driven seasonal signal of dissolved oxygen. The deficit only produces hypoxia if the background levels are already low, and thus a prediction of background levels is necessary to combine with predictions of intrusions.

TABLE I
INTRUSION EVENT PREDICTION RESULTS

Intrusion Events with IEI	Number of Events	Percent Identified
greater/equal to 1.0	8	100
greater/equal to 0.9	9	100
greater/equal to 0.8	13	100
greater/equal to 0.5	21	100
greater/equal to 0.4	24	91.67
greater/equal to 0.3	28	85.71
greater/equal to 0.2	31	80.65
greater/equal to 0.1	42	71.43
greater than 0.0	78	42.31

The Upwelling Persistence Index and the Fraser River Discharge Index are regressed against observed dissolved oxygen levels to determine an empirical equation for prediction of seasonal dissolved oxygen trends. Fig. 4 shows that the Upwelling Persistence Index follows the reverse seasonal signal of the seasonally filtered ($\mathcal{F}_{610}$) dissolved oxygen data, consistent with the mechanism of upwelling bringing low dissolved oxygen up from the deep ocean and into the Strait of Juan de Fuca. However, there is a lag in the correlation and the Fraser River Discharge Index (also shown in Fig. 4) may modulate the signal. The mid-year peak in river discharge would decrease the surface salinity, increasing the density difference between the two-layers of the exchange flow in the Strait of Juan de Fuca, and therefore making the exchange flow stronger, increasing availability of hypoxic waters in Puget Sound, despite the lag in upwelling persistence.

Performing a multi-linear regression, the Upwelling Persistence Index and the Fraser River Discharge Index fit the observed seasonal dissolved oxygen data as

$$DO_{AP} = 7.114 - [0.0013 \times UPI] - [2.877 \times FDI], \quad (9)$$

where the R-squared correlation value is 0.74. The resultant empirical Dissolved Oxygen Availability Prediction DO_{AP} is shown in Fig. 4c, where it is compared with the observed seasonal dissolved oxygen pattern. While this DO Availability Prediction does not precisely predict the observed seasonally filtered DO data, it does perform adequately in reproducing a similar trend, which is important in assessing the availability of hypoxic water for a given intrusion prediction. The availability prediction was not designed to follow the observed hourly DO time series because there is too much local variance for a regression to be accurate and because this prediction is meant to address the availability question and therefore must model seasonal dissolved oxygen trends. This is where the relationship between the DOD and IEI becomes important for predicting reductions in dissolved oxygen concentration from the background availability.

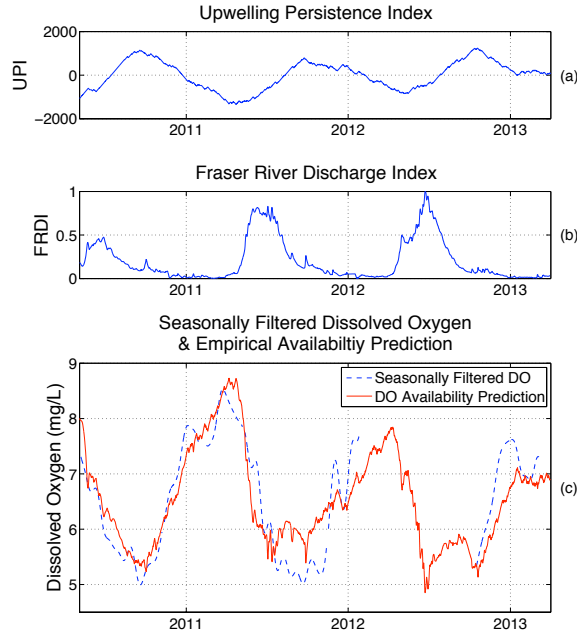


Fig. 4. (a) Upwelling Persistence Index time series from May 2010 to April 2013. (b) Fraser River Discharge Index time series from May 2010 to April 2013; (c) Time Series of observed seasonally filtered DO from May 2010 to April 2013 and the Dissolved Oxygen Availability Prediction constructed through regression.

C. Hypoxic Intrusion Event Predictions

Finally, a combined set of thresholds is established, empirically, to predict hypoxic intrusion events. If an Intrusion Event Prediction from the first part of the method coincides with an empirical Dissolved Oxygen Availability Prediction less than or equal to 6.4 mg/L, this predicted intrusion event is expected to be characterized by hypoxic water (less than 4.0 mg/L).

$$\text{If } NTI > 0.8 \quad \& \quad DII > 0.72 \quad (10) \\ \& \quad DO_{AP} < 6.4, \quad \text{Hypoxic Intrusion Event} = 1$$

Conditions are regarded as favorable for dissolved oxygen to drop to hypoxic levels in any time period of 8 days before or after an Intrusion Event Prediction that has a Dissolved Oxygen Availability Prediction below this threshold. The combined result is shown in Fig. 5 and TABLE II, in which identified events are shaded in blue and percent identification is listed, respectively.¹ The top panel shows the observed Intrusion Event Index over the time series and marks when the tidal condition indices are both above the chosen threshold. The lower panel shows the observed dissolved oxygen and predicted events. Fig. 5 demonstrates the success of this two-part method for predicting intrusion events characterized by hypoxic water. Observed dissolved oxygen data less than or equal to 4.5 mg/L is marked red to highlight near-hypoxic dissolved oxygen measurements at

¹Dissolved oxygen data that is within 8 days before or after periods of no raw DO data collection or undefined NTI and DII points are removed in order to remove bias due to gaps in data.

TABLE II
HYPOXIC INTRUSION EVENT PREDICTION RESULTS.

Observed DO Below	Percent of Points Identified
4.0	100
4.25	95.05
4.50	90.81
4.75	87.69
5.0	84.09
5.25	80.37
5.5	77.89
5.75	74.54
6.0	72.17
6.25	68.81
6.5	64.53

the mooring site. As TABLE II demonstrates, the predicted hypoxic intrusion event favorable periods encompass 90 % of observed DO concentrations below 4.5 mg/L and 100 % of observed DO concentrations below 4.0 mg/L. These hypoxic intrusion favorable periods do include many DO observations above 4.5 mg/L, but this is because the predictions are based on a sub-tidal time-scale, making these false positives an inevitable part of the prediction. This is why a hypoxic intrusion favorable period is only meant to indicate when Puget Sound is at “high risk” for a near-hypoxic intrusion event.

IV. DISCUSSION

This two-part method for prediction of hypoxic intrusions to Puget Sound can be used to assess the likelihood that low dissolved oxygen water will be transported over the sill at Admiralty Inlet and into the main basin of Puget Sound at a given time. The first part of the method is valuable independently for predicting any major bottom water intrusion events (which may carry nutrients or other water properties of interest). A key aspect of the approach is the use of readily available information from standard tide datums, rather than detailed in situ measurements. Lunar phase data (for *NTI*) and tidal elevation data (for *DII*) have enough skill to identify exchange flow events, so ADCP data may not significantly increase the predictability. However, ADCP data does allow for the ability to observe the duration and magnitude of events which provide a better indication of whether a given bottom water intrusion is capable of making it into the main basin of the Sound. The limitation of the present method is that it only identifies events; it does not prescribe the severity.

The second part is specific to the question of hypoxia in Puget Sound and may help to better understand the natural forcing of dissolved oxygen levels in the Sound. This part of the method also uses publicly available datum (Upwelling Index and Fraser River Discharge) and does not require in situ observations. However, a similar limitation to event identification remains; the present method does not prescribe the

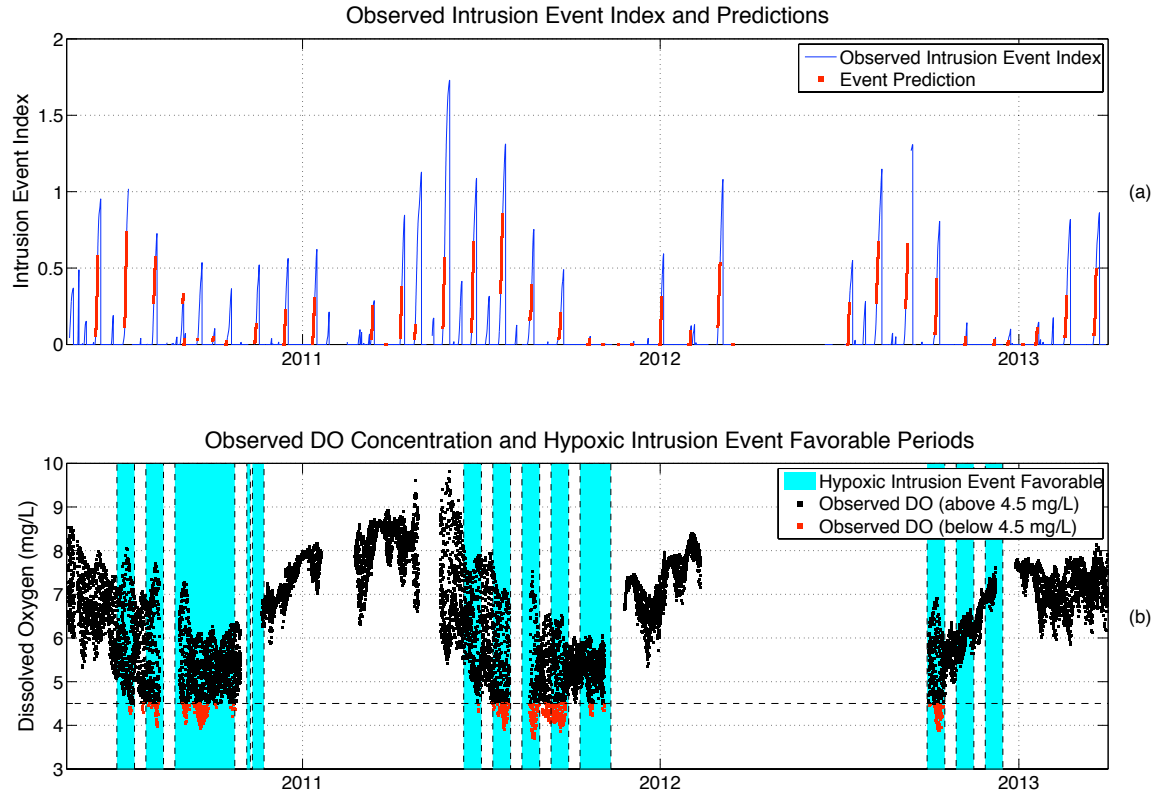


Fig. 5. (a) The observed Intrusion Event Index time series from May 2010 to April 2013 with marks indicating when the tidal condition indices are both above the proposed threshold for prediction ($NTI > 0.8$, $DII > 0.72$). (b) Hourly Dissolved Oxygen Data (points less than or equal to 4.5 mg/L marked red) from May 2010 to April 2013, with background shaded blue for Hypoxic Intrusion Event Favorable Periods.

severity of the hypoxic intrusion or the overall impact to Puget Sound water quality. It is likely that such details will always require comprehensive in situ monitoring and hydrodynamic modeling. Such efforts can be guided and optimized by the dominant variables identified herein.

It is a complicated task to determine where low dissolved oxygen water flows after it traverses the Admiralty Inlet sill. Literature proposes that, after inflow, the dense water is no longer governed by strong tidal currents and acts as a gravity current that carries this water through the main basin until it is eventually mixed by other processes [1] [2] [4]. This could be investigated by looking for a low dissolved oxygen signature at other locations in the Sound after low dissolved oxygen inflows occur at Admiralty Inlet. The spatial and temporal dynamics of the main-basin-transport will be important to understand if the methods developed here are to be useful in decisions and policy making for water quality management.

V. CONCLUSION

Low dissolved oxygen water measured at the mouth of Puget Sound is associated with deep ocean water masses, as determined by temperature and salinity. This ocean water can intrude into Puget Sound at the seabed under exchange flow conditions of minimal mixing, nominally coincident

maximum diurnal inequality and neap tides during equinoxes. Tidal elevation data can be used as an indicator for exchange flow, as shown by the use of combined Neap Tide Index and Diurnal Inequality Index thresholds. Residual current analysis from ADCP data validates the threshold basis for identifying intrusions, but this alone is not sufficient to identify hypoxic events. Hypoxic events also are controlled by coastal upwelling and river discharge, which set the availability of dense, low dissolved oxygen water in the Strait of Juan de Fuca. A regression of dissolved oxygen background levels to an Upwelling Persistence Index and Fraser River Discharge Index results in empirical Dissolved Oxygen Availability Prediction that is well correlated with observations. Ultimately, an Intrusion Event prediction combines the background oxygen levels and intrusion predictions to successfully identify 100% of all events with $DO < 4.0$ mg/L and 90% of all events with $DO < 4.5$ mg/L over a three year time series.

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REFERENCES

- [1] T. Khangaonkar, B. Sackmann, W. Long, T. Mohamedali, and M. Roberts, "Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and do in Puget Sound using an unstructured grid model," *Ocean Dynamics*, vol. 62, pp. 1353–1379, 2012.
- [2] W. R. Geyer and G. A. Cannon, "Sill processes related to deep water renewal in a fjord," *Journal of Geophysical Research*, vol. 87, no. C10, pp. 7985–7996, 1982.
- [3] J. Thomson, B. Polagye, V. Durgesh, and M. Richmond, "Measurements of turbulence at two tidal energy sites in Puget Sound, WA," *Journal of Oceanic Engineering*, vol. 37, no. 3, pp. 363–374, 2012.
- [4] C. A. Barnes and E. E. Collias, "Some considerations of oxygen utilization rates in Puget Sound," *Journal of Marine Research*, vol. 17, pp. 68–80, 1958.
- [5] G. A. Cannon, J. R. Holbrook, and D. J. Pashinski, "Variations in the onset of bottom-water intrusions over the entrance sill of a fjord," *Estuaries*, vol. 13, no. 1, pp. 31–42, 1990.
- [6] R. E. Thomson, "Physical oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait system," in *Review of the Marine Environment and Biota of Strait of Georgia, Puget Sound and Juan de Fuca Strait. Proceedings of the BC/Washington Symposium on the Marine Environment. Canadian Technical Report of Fisheries and Aquatic Science, NO.1948*, R. Wilson, R. Beamish, F. Aitkens, and J. Bell, Eds., 1994, pp. 36–100.
- [7] K. R. Helfrich, "Time-dependent two-layer hydraulic exchange flows," *Journal of Physical Oceanography*, vol. 25, pp. 359–373, 1995.
- [8] B. Polagye and J. Thomson, "Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, WA (USA)," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 227, no. 3, pp. 352–367, 2013.
- [9] N. O. A. A. Pacific Fisheries Environmental Laboratory. Index values at 48N 125W (1967-present). [Online]. Available: <http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html>
- [10] S. D. Hicks, R. L. Sillcox, C. R. Nichols, B. Via, and E. C. Mccray, "Tide and current glossary. Silver Spring, MD: NOAA National Ocean Service," *Center for Operational Oceanographic Products and Services*, pp. 1–29, 2000.
- [11] U. S. N. O. Astronomical Applications Department. Fraction of the moon illuminated. [Online]. Available: <http://aa.usno.navy.mil/data/docs/MoonFraction.php>
- [12] E. C. Water Survey of Canada. Hydrometric data. [Online]. Available: <http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm>