

Predicting Deep Water Intrusions to Puget Sound, WA (USA), and the Seasonal Modulation of Dissolved Oxygen

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Abstract Observations and predictions regarding oceanic intrusions at the entrance to Puget Sound, WA (USA), are presented. Four years of seabed observations at Admiralty Inlet show episodic periods high salinity, coincident with landward residual currents near the seabed. The observed residual currents are consistent with an estuarine exchange flow during minimal tidal mixing, coincident with neap currents and maximum diurnal inequalities. These subtidal intrusions can carry dense water into Puget Sound and, thereby, renew the bottom water that is trapped landward of the sill. The oxygen concentration levels of these intrusions are often low, though not hypoxic, and may influence

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the oxygen levels in Puget Sound. The water mass properties of these intrusions are influenced strongly by regional dynamics, because the entrance to Puget Sound is connected to the open ocean via the Strait of Juan de Fuca. Coastal upwelling and discharge from the Fraser River discharge control the exchange flow in the Strait of Juan de Fuca and thus control the availability of dense water at the entrance to Puget Sound. The net effect of the tidal and regional dynamics is for intrusions with low oxygen levels to prevail in the late summer months. To predict intrusions in future years, an empirical method is developed and validated for daily application. The prediction method is based on publicly available operational data products and does not require in situ observations. In verification, 98% of intrusion events with dissolved oxygen less than 4.0 mg/L are successfully identified in a hindcast prediction for the 4-year observational record.

Keywords Dense intrusion · Puget sound · Exchange flow · Tidal currents · Estuary · Dissolved oxygen

Introduction

This study examines intrusions of dense ocean water, and the associated modulation of dissolved oxygen (DO) levels, at the entrance to Puget Sound, WA (USA). The dense intrusions are controlled by estuarine exchange and tidal dynamics. The dissolved oxygen levels are set by the water mass properties of the intrusion, which can renew the bottom water in Puget Sound and may thereby influence regional dissolved oxygen levels. Of course, dissolved oxygen levels within Puget Sound are forced by the balance of many processes (i.e., primary production, respiration, advection, mixing); the focus of the present study is solely on diagnosing and predicting the episodic intrusion of low-DO water at the entrance.

Puget Sound is part an estuary system often called the Salish Sea, which includes the Strait of Juan de Fuca, the Strait of Georgia, and Puget Sound. Within this system, the Strait of Juan de Fuca is the connection to the North Pacific Ocean by, as seen in Fig. 1a. Admiralty Inlet is the primary connection (98% of the tidal flow, according to Thomson 1994) from the Strait of Juan de Fuca to Puget Sound, and this study focuses on that location (Fig. 1b). Admiralty Inlet is a 6-km wide sill that is shallow (60 m) and relatively long (30 km) compared to most glacially carved estuaries. In close examination, the Inlet is really two sills, each roughly 100 m above the surrounding bathymetry (Geyer and Cannon 1982). This distinctive geometry plays an important role in the flow of water between the Strait



Fig. 1 a Bathymetric map of the Salish Sea region, including Puget Sound, the Strait of Juan de Fuca, and the Pacific Ocean, which are, respectivelty, east, north, and west, of the Olympic Peninsula. The boundaries of panel b are indicated with the *red box* in panel a. **b** Zoomed-in bathymetric map of Admiralty Inlet (*red cross*) at the mouth of Puget Sound. Included is the location of the tripod mooring, TS1 (*red triangle*), where observational data were collected collected by the University of Washington and Washington Ecology

of Juan de Fuca and Puget Sound. The region is characterized by high turbulence, especially with the strong (>3 m/s) currents that occur during spring tides (Gregg 2004; Greene et al. 2015; Thomson et al. 2012). Tidal flows are also strong in the Strait of Juan de Fuca; however, the estuarine circulation is of equal importance. This large-scale estuarine exchange is controlled by the Fraser River, which is the primary source of fresh water into the Salish Sea and sets much of density stratification and sea surface slope (Holbrook et al. 1980; Thomson 1994). The importance of these regional connections and dynamics was recently highlighted by Johannessen et al. (2014) in an analysis of dissolved oxygen modulation in the Strait of Georgia.

This study examines oceanic intrusions at Admiralty Inlet, with application to dissolved oxygen (DO) levels in Puget Sound. Dissolved oxygen is a key ecosystem parameter in Puget Sound, where regions as such Hood Canal are susceptible to hypoxic events with large fish kills (Newton et al. 2007; Palsson et al. 2008; Khangaonkar et al. 2012). The contribution of external oceanic forcing, relative to local sources and local processes causing hypoxia, is poorly constrained (Newton et al. 2007; Steinberg et al. 2011). It is understood that dense, low dissolved oxygen water can be upwelled from the ocean and funneled from deeper regions through the Juan de Fuca Canyon (Alford and MacCready 2014). Some of this low-DO oceanic water may be derived from the continental shelf, where periods of low-DO are common in the summer near the mouth of the Strait (Alford and MacCready 2014; Siedlecki et al. 2015). Under certain tidal conditions, the upwelled oceanic water can be carried through Admiralty Inlet into Puget Sound as part of a bottom intrusion (Geyer and Cannon 1982). A bottom intrusion over the sill constitutes the lower portion of a two-layer exchange flow in Admiralty Inlet, in which dense water flows into Puget Sound along the seabed. This water can then make its way into the Main Basin and Hood Canal. Once inside Puget Sound, the intrusion may eventually contribute to hypoxic events indirectly, by displacing existing bottom water that is both hypoxic and less dense than the intrusion (Barnes and Collias 1958; Feely et al. 2010). In this cycle, the intrusion renews the bottom water and then becomes the resident bottom water to be displaced in some future event. The controlling parameters for these intrusions are expected to be tidal mixing conditions (due to springneap cycles) and estuarine exchange strength (due coastal upwelling and river discharge).

In this study, observations and forcing parameters are used to develop a predictive method for identifying time periods in which conditions are favorable for low-DO (less than 4 mg/L) intrusions to occur. "Background" provides the background of previous analyses regarding the dynamics of dense-water intrusions at Admiralty Inlet, and this prior work is used to guide the parameters for the Fig. 2 Flow chart outlining the prediction method for identifying low-DO intrusion events



new prediction method. "Intrusion Analysis and Prediction Indices for Admiralty Inlet" presents the field data collected and empirical indices developed for later use in the empirical prediction method. "Combined Intrusion and Low Dissolved Oxygen Prediction Method" details the twostep prediction method and tests it operationally (hindcast mode). The first part of the prediction method uses tidal conditions to identify intrusion events. The second part of the method predicts whether the intrusion will have low-DO water, based on the seasonal availability of low-DO in the Strait of Juan de Fuca. The availability prediction is based on upwelling at the mouth of the Strait of Juan de Fuca and discharge from the Fraser River. The prediction method (outlined in the flow chart in Fig. 2) does not require any in situ data and is operationally tested using readily available public data (updated daily). "Discussion of Prediction Outcomes" discusses potential applications of the predictions for future intrusion events. "Conclusions" section concludes with a summary of the predictions and relative skill.

Background

Geyer and Cannon (1982) determined that intrusions of high salinity (and thus relatively dense) water into Puget Sound occur during periods of minimal tidal mixing at Admiralty Inlet. The two important tidal conditions found were maximum diurnal inequality and neap tides.¹ These conditions coincide at the equinoxes, as discussed later in "Lunar Index (LI)". Geyer and Cannon (1982) also provide illustrations that demonstrate how the isopycnal structure progresses during the tidal cycle through the course of a dense water intrusion at Admiralty Inlet. Separately, Geyer and Cannon (1982) also mention that during the strongest spring tidal currents in a year (at the solstices), tidal currents can advect dense water into Puget Sound, but that these instances are rare due to the sill length. Thus, the tidally modulated two-layer estuarine exchange flow of Geyer and Cannon (1982) is considered the dominant process governing water exchange at Admiralty Inlet. Eddies may also contribute to exchange, as shown in Yang and Wang (2013), and these can provide significant cross-channel and temporal variations in the exchange signal.

Geyer and Cannon (1982) note that the presence of dense water seaward of the Admiralty sill is controlled by the larger-scale circulation in the Strait of Juan de Fuca. Fresh water input from rivers and wind-driven coastal upwelling are key factors that influence the vertical and horizontal salinity gradients and, thus, the gravitational circulation, in the Strait of Juan de Fuca (Thomson 1994). An increase in this density difference would increase the strength a twolayer exchange flow in the Strait of Juan de Fuca (Helfrich 1995). Cannon et al. (1990) note that coastal upwelling and downwelling, in particular, may be important factors for the availability of near-bed dense water on the seaward side of Admiralty Inlet as well. Cannon et al. (1990) observe that coastal storms in the winter, which cause downwelling along the coast, may suppress high-salinity water intrusions by causing flow reversals along the length of the Strait of Juan de Fuca, reducing the density of the bottom water seaward of Admiralty Sill. They calculate a strong inverse correlation between bottom salinity near Admiralty Sill and coastal sea level height. They also found increases in bottom salinity near Admiralty Sill following the cessation of coastal storms with downwelling conditions. The bottom salinity at Admiralty Inlet is found to lag strong southerly

¹In this paper, we use "neap tides" as a short-hand for the fortnightly minimum in currents in Admiralty Inlet (which are related to basin-wide tides that are relatively muted at the sill).

Table 1 Glossary of indices

Index	Full name	Data used	Use of index
UI	Upwelling Index	From Pacific Fisheries Environmental Laboratory	Upwelling Persistence Index
TEI	Tidal Elevation Index	Tidal elevation from NOAA (for operational method) OR pressure from CTDO at seabed (for in situ method)	Diurnal Inequality Index
IEI	Intrusion Event Index	ADCP velocity at admiralty inlet	To compare with intrusion predictions
LI	Lunar Index	Lunar phase from United States Naval Observatory	For intrusion prediction
DII	Diurnal Inequality Index	Tidal Elevation Index	For intrusion prediction
UPI	Upwelling Persistence Index	Upwelling Index	Dissolved Oxygen Availability Prediction
FRDI	Fraser River Discharge Index	Fraser river discharge from the Water Survey of Canada	Dissolved Oxygen Availability Prediction
DOD	Dissolved Oxygen Deficit	Dissolved oxygen from CTDO at seabed on admiralty sill	To compare with Intrusion Event Index
DOAP	Dissolved Oxygen Availability Prediction	Upwelling Persistence Index and Fraser River Discharge Index	For low-DO intrusion prediction

wind measurements at N 48, W 125 (located in the Pacific Ocean, Southwest of the mouth of the Straight of Juan de Fuca, offshore from the Olympic Peninsula) by about 7.25 days (Cannon et al. 1990).

The existing literature for the site is thus summarized as a two-part system. First, the bottom water properties near the entrance to Puget Sound are set by seasonal signals of exchange and upwelling in the Strait of Juan de Fuca. Second, the actual intrusion of bottom water is controlled by neap tides with maximum diurnal inequality. For application to low DO signals, it is the combination of the availability of the low-DO water in the Strait and the tidal intrusion dynamics that determine whether low-DO water enters Puget Sound.

Intrusion Analysis and Prediction Indices for Admiralty Inlet

This section presents observations of intrusions and indices to quantify the combined tidal and regional conditions necessary for intrusions, with a focus on low-DO events. "Field Observations" describes seabed observations. "Intrusion Event Index (IEI)" to "Dissolved Oxygen Deficit (DOD)" describe and apply indices that determine whether conditions are favorable for bottom intrusions and whether the intrusion is likely to have low-DO water. Table 1 is a reference for indices used in this paper, their abbreviations, data used to create them, and their usage.

Field Observations

From August 2009 to October 2013, a Seabird 16plusv2 CTDO (Conductivity, Temperature, Depth, Oxygen) sensor was 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 (Fig. 1b). This location is referred to as TS1 (Tripod Site 1). The water depth at TS1 is approximately 55 m (ref. MLLW). Since TS1 is on the eastern side of the sill, it is slightly shallower than the saddle point of this sill (60 m). The CTDO was mounted on the tripod 0.5 m above the seabed and sampled every 30 min. The tripod was recovered and redeployed every 3 months, and each time the CTDO was replaced with a newly calibrated unit. The tripod location was shifted slightly (less than 100 m) to TS1 in May 2010 and did not change through the final deployment.

A Nortek Continental ADCP (Acoustic Doppler Current Profiler) was mounted to the tripod. The tripod deployments were motivated originally by a tidal energy site characterization, as detailed by Polagye and Thomson (2013) and Thomson et al. (2012). The ADCP sampled currents in 1 m bins from 1.7 to 50.7 m above the seabed² and recorded ensemble averages every 1 min. Prior to analysis, all CTDO and ADCP data were 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 salt or dissolved oxygen through the Inlet. Rather, we focus on diagnosing intrusion events and in particular those events with low dissolved oxygen. First, the salinity and temperature measurements are used to identify the water mass associated with low dissolved oxygen. As shown in Fig. 3, the low dissolved oxygen levels correspond with high salinity water and a narrow temperature range, indicating an oceanic source (water from Puget Sound is expected to be fresher as result of the large river outflows from rivers, including the Skagit, Snohomish, and Stillaguamish).

 $^{^{2}}$ For the final deployment, July to October 2013, the ADCP range only reaches up to 20 m above the seabed.



Fig. 3 Salinity versus temperature at Admiralty Inlet from August 2009 to October 2013, with density contour lines. Data (30534 data points) colored according to corresponding dissolved oxygen concentration

Dissolved oxygen observations below an arbitrary threshold of 4.5 mg/L are concentrated between 31.3 and 32.5 psu and between 8.2 and 10.2 °C, with sigma-t values greater than 24 (Fig. 3). This suggests that occurrences of low dissolved oxygen water in Admiralty Inlet can be paired with the tidal dynamics of dense water intrusions (i.e., Geyer and Cannon 1982). In this paper, we consider two subjectively chosen low dissolved oxygen thresholds, 4.5 and 4.0 mg/L, representing the lowest 4.0 percent and 0.2 percent of the data respectively (for hourly data May 2010 to April 2013). We consider these to be the thresholds for the notably low values observed in our data but there is no absolute or objective biogeochemical reason for their selection.

The full time series of dissolved oxygen concentration from the CTDO sensor, shown in Fig. 4, covers a span of over four years. Missing sections of data are due to instrument failure or corrupted data. There is a clear seasonality in the time series, in which the lowest dissolved oxygen levels occur in the late summer and early autumn and higher levels occur in the spring. There is also clear variability on shorter time scales. Figure 5a shows a particular 4-week period in detail, wherein dissolved oxygen levels are low and the tidal conditions are theoretically favorable for an intrusion. In Fig. 5b, a Tidal Elevation Index (TEI) is shown in conjunction with the neap tides, which are shaded blue. The TEI derived via de-meaning (by deployment) and normalizing the pressure signal (so that Mean Low-Low Water is non-dimensional -1) from the CTDO.

As expected, the neap tides and the maximum diurnal inequality occur simultaneously during the equinox. These are protracted periods of weak tidal currents and weak tidal mixing (Geyer and Cannon 1982). Thus, exchange flow is

strong during each equinox, including in detailed example shown in Fig. 5. The residual currents, calculated using a low-pass filter³ \mathscr{F}_{40} (low-pass filter notation) on the ADCP current velocity data with a half-amplitude period of 40 h (Beardsley et al. 1985; Polagye and Thomson 2013), show pronounced exchange flow occurring coincident with reduced tidal amplitude and the minima in observed dissolved oxygen (Fig. 5c). In contrast, periods with large tidal amplitudes do not show exchange flow or low dissolved oxygen, because tidal mixing is strong.

Related to the tidal modulation of exchange flow, there is a negative correlation between observed dissolved oxygen and tidal elevation from August to November of 2011, which is an example subset of data with a relatively stable background dissolved oxygen signal. This can be seen in the seasonally filtered DO in Fig. 6c (seasonal lowpass filter \mathscr{F}_{610} explained in "Dissolved Oxygen Deficit (DOD)"). This correlation suggests that on short time scales with constant seasonal-scale trends, tidal elevation may be a useful predictor of exchange flow conditions. However, whether low dissolved oxygen water is available to enter Puget Sound during these conditions likely depends on other regional factors such as coastal upwelling and river discharge. Revisiting Fig. 4 during the same time period, it appears that consistent coastal downwelling begins at the end of September 2011, stopping the transport of the most dense, low-DO ocean water toward Puget Sound via the Strait of Juan de Fuca.

To examine the influence of upwelling, an Upwelling Index (UI) available from the Pacific Fisheries Environmental Laboratory for the same longitude and latitude as the wind data used by Cannon et al. (1990) is used. This index is lagged by 7.25 days (consistent with the temporal relationship they determined between offshore wind observations and subsequent effects at Admiralty Inlet) and then compared with the dissolved oxygen time series from Admiralty Inlet in Fig. 4). Positive Upwelling Index values indicate winds from the North that favor upwelling and negative values indicate winds from the South that favor downwelling. On a seasonal time scale, downwelling conditions in winter reduce the availability of low DO water that can be transported over the Admiralty sill, while upwelling conditions in summer increase the availability of this low DO bottom water.

In addition to the seasonal cycle of upwelling/downwelling conditions, there are changes in dissolved oxygen availability in the Strait on shorter time scales. These are anomalies in seasonal trends in DO concentrations (i.e., the temporary decrease in average DO concentrations on the order

³A low-pass filter was chosen for this study instead of harmonic analysis because of unique tidal dynamics and headland influences at Admiralty Inlet.



Fig. 4 Time series of dissolved oxygen concentration (mg/L) at Admiralty Inlet from August 2009 to October 2013. Data points colored according to an Upwelling Index obtained from the Pacific Fisheries Environmental Laboratory, linearly interpolated to an hourly

time scale, and lagged 7.25 days, based on Cannon et al. (1990). The Upwelling Index color axis is limited to -20 to 20 in order to simply show the sign of the index in relation to DO. The *aqua-shaded* section is the period examined in Fig. 5

of weeks during December 2011 in Fig. 4). Sustained periods with upwelling-favorable winds at the coast are related to decreases in DO concentrations on subtidal time scales, while downwelling-favorable winds have the opposite relationship (see DO trend relative to upwelling colormap in Fig. 4).

There is also variability in DO concentration on the timescales of individual tidal cycles, and this too can be associated with upwelling/downwelling conditions. Figure 4 and the detailed DO data in Fig. 5a show that during sustained upwelling time periods, tidal variability in DO concentrations is larger than during sustained downwelling time



Fig. 5 A four-week subset of data surrounding the 2011 autumnal equinox, showing: **a** dissolved oxygen concentration (mg/L), **b** Tidal Elevation Index (from demeaned pressure measurements), and

c 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



Fig. 6 a Upwelling Persistence Index time series from May 2010 to October 2013. **b** Fraser River Discharge Index time series from May 2010 to October 2013; **c** Time Series of observed seasonally filtered \mathscr{F}_{610} DO from May 2010 to October 2013 and the Dissolved Oxygen Availability Prediction constructed though regression

periods. This may be because the background stratification is reduced during downwelling periods, and that reduces the variations that can be advected (or mixed) past the measurement site. Alternatively, it could be that increased DO variability during upwelling conditions appears because of larger horizontal DO gradients in Admiralty Inlet. Such horizontal gradients would increase the observed variability in DO as eddies pass and tidal currents flow back and forth across Admiralty Sill.

Intrusion Event Index (IEI)

An Intrusion Event Index (IEI) is developed based on the filtered ADCP data, and this index is used to quantify the duration and magnitude of a bottom water intrusion event at the tripod location in Admiralty Inlet. This index is independent of dissolved oxygen levels and simply identifies active exchange flow intrusions into Puget Sound. Thus, the index is determined by the spring-neap tidal cycle and diurnal inequality of the tidal currents. Due to a new primary tripod location (TS1) starting May 2010, only the time series from May 2010 to October 2013 was considered in the intrusion analysis to preserve consistency in the index related to site-specific residual current patterns. Residual current

data was first interpolated to create consistent bin sizes and depths between different ADCP deployments. Then, residual current velocities were vertically averaged for all bins with positive (into Puget Sound) current velocities from the seabed up to the height of the zero-velocity crossing (i.e., where residual current velocity switches to negative, out of Puget Sound) to create an intrusion velocity. This depth-averaged intrusion velocity is intended to quantify the strength of the intrusion; it has a value of zero for all net negative bottom residual current velocities.

Next, the intrusion velocities are integrated in time to produce a length scale of advection for each intrusion. The integral is reset to zero each time the intrusion velocity is zero, such that intrusion events are isolated. This length scale represents the distance that a water parcel would travel under an assumption of homogenous flow through Admiralty Inlet. Comparing this length scale to the approximate L = 30 km length of Admiralty Sill (Geyer and Cannon 1982), it can be approximated that if the time-integrated intrusion length is greater than 30 km, then dense-water could travel all the way into the basins of Puget Sound during that intrusion. A non-dimensional Intrusion Event Index is defined

$$IEI = \frac{\int \mathscr{F}_{40}(u)dt}{L},\tag{1}$$

in which any intrusion that exceeds unity before resetting to zero is considered an input of new bottom water into Puget Sound. The magnitude of the IEI is thus a normalized product of the intrusion velocity and the duration of the event.

Lunar Index (LI)

A Lunar Index (LI), based on lunar phase, is used to quantify the lunar spring tide to neap tide cycle. As noted by Mojfeld and Larsen (1984), the apparent fortnightly tidal range variation in Admiralty Inlet is actually a consequence of the tropic-equatorial modulations of the primary diurnal constituents (K1, O1), which produce a periodic beating at 13.7 days. This tropic-equatorial modulation is treated separately as part of the diurnal inequality quantification in the next section. In the present section, we isolate the more typical fortnightly variation, which is the beating of the primary semidiurnal constituents (M2, S2), with a periodic beating at 14.8 days (Mojfeld and Larsen 1984; Hicks et al. 2000). In Admiralty Inlet, the primary semidiurnal amplitudes are smaller than the diurnal constituents and the dominance of M2 over S2 yields only a weak fortnightly range variation. However, this is not the case for the tidal currents driving low-DO intrusions, where the semidiurnal forcing dominates over the diurnal and the fortnightly variation is primarily associated with the semidiurnal beat period. This mismatch between tide and current behavior in Admiralty Inlet is associated with the nearby amphidromic point for M2 tides.

Daily lunar phase data downloaded from the Astronomical Applications Department of the US Naval Observatory are used to quantify the lunar neap-spring cycle. These daily products are formatted on a scale where a full moon has a lunar phase value of 1 (spring tide), a quarter moon has a lunar phase value of 0.5 (neap tide), and a new moon has a lunar phase value of 0 (spring tide). The Lunar Index, where a lunar phase value of 1 represents peak lunar neap period and a lunar phase value of 0 represents peak lunar spring period is given by

$$LI = (-2 \times |Lunar Phase - 0.5|) + 1.$$
(2)

Since the *LI* has a period of approximately 14.8 days, it does not need to be filtered to remove a tidal signal to be compared with residual current data or the Intrusion Event Index.

Tidal Elevation Index (TEI) and Diurnal Inequality Index (DII)

A Diurnal Inequality Index (DII) is determined based on the time derivative of tidal elevations, which are first quantified using the Tidal Elevation Index (TEI). The TEI is a normalized tide stage given by

$$TEI = \frac{\text{demean}\left(TideLevel\right)}{-MLLW},\tag{3}$$

where *MLLW* is the mean lower low water tide level datum. The maximum diurnal inequality occurs when the difference between successive low and high tidal heights is largest. This means that there is about a half-day period of gradual change in tidal elevation followed by about a half-day period of rapid change in tidal elevation, as can be seen in Fig. 5b. During the gradual portion of the period, tidal currents are weak, mixing is minimum, and intrusions are likely. The absolute value of the time derivative of the Tidal Elevation Index (TEI) is low-pass filtered to create the Diurnal Inequality Index (DII)

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

where sign of the derivative is reversed so that maximum values indicate periods of maximum diurnal inequality. Finally, the index is renormalized to a scale from 0 to 1 for a given time series. Values closer to 1 indicate periods of maximum diurnal inequality (with minima in mixing), and values closer to 0 indicate periods near equality (with maxima in mixing). Temporary exchanges can occur during spring currents, but only during the lesser flood tide of a diurnal cycle. Mixing is too strong during the greater flood and a subsequent greater ebb will cause mixing. The

exchanges are not sustained unless the maximum diurnal inequality and the neap tide are coincident (i.e., DII and LI are both high).

Upwelling Persistence Index (UPI)

An Upwelling Persistence Index (UPI) based on the PMEL's Upwelling Index is used to quantify the coastal conditions near the mouth of the Strait of Juan de Fuca, which influence the seasonal trend in dissolved oxygen concentration on the seaward side of Admiralty Inlet (Fig. 4). The UPI is filtered and integrated to describe 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 southerly winds in the winter, compared with lighter northerly winds in summer), a conditional time integral is used to capture the signal of the temporal persistence of the signals. First, the 7.25 day lagged Upwelling Index 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 de-trended by subtracting the mean of the time-integrated value for the year prior to each data point. This de-trended result (removing interannual variability) is termed the Upwelling Persistence Index:

$$UPI = \int \operatorname{sign} \left[\mathscr{F}_{40} \left(UI_{(t-7.25 \, days)} \right) \right] dt$$
$$-mean \left[\int \operatorname{sign} \left[\mathscr{F}_{40} (UI_{(t-7.25 \, days)}) \right] dt \right]_{t-365.25 \, days}^{t}$$
(5)

The Upwelling Persistence Index is shown in Fig. 6a.

Fraser River Discharge Index (FRDI)

A Fraser River Discharge Index (*FRDI*) is used to quantify the input of fresh water to the Strait of Juan de Fuca, which influences the regional exchange flow and thus the seasonal trend in dissolved oxygen concentration on the seaward side of Admiralty Inlet. Discharge data (*D*) for the Fraser River measured at Hope, British Columbia, Canada, are obtained from the Water Survey of Canada website. This station is the nearest main-channel station that has complete discharge data for the appropriate time period. The data obtained are linearly interpolated to an hourly time scale, then low-pass filtered with \mathscr{F}_{40} , and finally normalized to a scale of 0 to 1 based on the maximum and minimum observed discharges from May 2010 to April 2013. The index is

$$FRDI = \frac{\mathscr{F}_{40}(D) - 691.56 \ m^3/s}{11748 \ m^3/s - 691.56 \ m^3/s},\tag{6}$$

and is shown in Fig. 6b for the time period examined in this study.

Dissolved Oxygen Deficit (DOD)

A final index is the Dissolved Oxygen Deficit (*DOD*), which quantifies subtidal anomalies, relative to the background seasonal modulation, of DO concentration. First, the measured dissolved oxygen is low-pass filtered by \mathscr{F}_{40} . Then, the result is filtered again with a 610-h (~25.4-day) half-amplitude period filter \mathscr{F}_{610} that is chosen as 1.6 times the period associated with the maximum observed intrusion event duration (the distinct time period in which the IEI is positive, from initiation to termination of an event).⁴ The Dissolved Oxygen Deficit (*DOD*) is determined by the difference in these filtered signals:

$$DOD = \mathscr{F}_{610} \left(DO \right) - \mathscr{F}_{40} \left(DO \right) \tag{7}$$

The *DOD* value are positive during an intrusion event and indicate an intrusion with low-DO if the observed seasonal dissolved oxygen signal \mathscr{F}_{610} indicates the availability of low-DO water seaward of Admiralty Sill. The progress of the *DOD* index during major intrusion events, along with the progress of the *DII* and the *LI* indices, are shown in Fig. 7. The *DOD* index is used only as a diagnostic metric to identify actual intrusions and to benchmark method performance. The *DOD* index was not used in either part of the combined intrusion and low-DO prediction method described in the next section.

Combined Intrusion and Low Dissolved Oxygen Prediction Method

This section presents a two-part prediction method, shown schematically in Fig. 2, to determine whether a bottom water intrusion carrying low-DO into Puget Sound is expected to occur at a given time. The prediction methods are based solely on indices that can be determined in absence of any in situ data collection in Admiralty Inlet. The first part of the method uses the tidal conditions (Lunar Index, *LI*, 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 low-DO water availability conditions (Upwelling Persistence Index, *UPI*, and Fraser River



Fig. 7 Composite in time of intrusion events that obtain an IEI value of at least 0.5, showing the signals of **a** Intrusion Event Index with threshold line of 0.5, **b** Diurnal Inequality Index with threshold line of 0.72, **c** Lunar Index with threshold line of 0.8, and **d** Dissolved Oxygen Deficit with zero-crossing line. Time axis shows number of hours since initiation of intrusion event. The *different line colors* are only to show different independent events (no other significance to color)

Discharge Index, FRDI) to empirically predict whether a given intrusion is likely to carry low dissolved oxygen water. When both the tidal and availability conditions are met, low-DO intrusions are likely. The Intrusion Event Index (*IEI*), independent of *DO*, is developed from in situ current measurements and used to assess the skill of the intrusion event predictions based on tidal conditions.

We also compare the use of tide level data from NOAA tide tables to tide level using in situ pressure data for TEI determination. This is important for an operational version of the intrusion prediction method that uses inputs solely from publicly available from realtime databases. The operational version of the intrusion prediction method relies on tidal elevation data from NOAA at the Port Townsend, WA, station 9444900. This water level data is downloaded

⁴The maximum observed intrusion event with coincident DO observations is about 191 h (~8 days), likely related to the fortnightly cycle. Therefore, the maximum period of the intrusion cycle is about 382 h (~15.9 days). The ratio of the 40-h half-amplitude period for residual currents to the 25-h tidal period was 1.6:1. This ratio was used to choose a 610-h half-amplitude period for the low-pass filter to remove fluctuations associated with the intrusion cycle.

in meters, relative to MLLW, as an hourly time series in GMT. This time series serves as the "Tide Level" metric in Eq. 3 for *TE1*, and no additional de-meaning or normalization is necessary. After making this adjustment, the methods outlined in the following subsections are used as presented earlier. The corresponding codes are available online (http://faculty.washington.edu/jmt3rd/DeppeCodes/) and can be used to run the intrusion prediction methods with only time series inputs of:

- Hourly time-step vector constructed based on chosen analysis time period,
- Tidal elevation from National Oceanic and Atmospheric Administration (http://tidesandcurrents.noaa.gov/waterlevels.html?id= 9444090)
- Lunar phase from United States Naval Observatory (http://aa.usno.navy.mil/data/docs/MoonFraction.php)
- Upwelling Index at N 48, W 125, from Pacific Fisheries Environmental Laboratory (https://www.pfeg.noaa.gov/products/PFEL/modeled/ indices/upwelling/NA/data_download.html), and
- Fraser River discharge at Hope, BC, Canada, from the Water Survey of Canada.
 (http://www.wateroffice.ec.gc.ca/index_e.html)

Intrusion Event Predictions

Observations show that both the LI and the DII must be elevated at the same time for a large intrusion event to develop and be sustained.⁵ Events evolve according to the LI and DII, such that intrusions terminate as soon as tidal conditions are no longer favorable (i.e., when tidal currents become stronger and mixing intensifies over the sill). Thus, intrusion events are predicted solely based on choosing thresholds in LI and DII, as follows

If
$$LI > 0.8$$
 & $DII > 0.72$, (8)

These are the strictest coincident values for *LI* and *DII* that successfully predict intrusion events at least one time step during their development.

As is shown in Table 2, using these two conditional thresholds achieves a high success rate for correctly identifying observed intrusion events. In fact, these threshold conditions can correctly identify all events that reach an

Table 2	Operational	test,	intrusion	event	prediction	results
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	Operationa test	ıl	Using in situ tidal elevation data	
Intrusion events with IEI	Number of events	Percent identified	Number of events	Percent identified
≥1.0	9	100	Same	Same
≥0.9	10	100	Same	Same
≥0.8	15	100	Same	Same
≥0.5	26	100	25	100
≥0.4	29	93.1	28	92.9
≥0.3	35	85.7	33	84.8
≥0.2	39	79.5	37	78.4
≥0.1	52	69.2	49	69.4
>0.0	102	41.18	88	43.2

Intrusion Event Index of at least 0.5. As shown in Table 2, the operational method (using NOAA tidal elevation tables) is shown to correctly identify intrusion events just as well as when using in situ observed tide levels. The operational method also suggests additional intrusion events during times in which there were data gaps from the in situ data due to instrument failure. The operational method produces a false positive prediction 1.68% of the times that the true Intrusion Event Index is zero, as compared to 1.52% for the prediction based on in situ pressure. Figure 8a, shows the observed Intrusion Event Index over the time series and marks when the tidal condition indices are both above the chosen threshold, demonstrating when intrusion predictions are made using both methods (blue), using only the operational method (gold), and using only the in situ data method (magenta). This demonstrates the strong agreement between the two versions.

Empirical Prediction of Seasonal Dissolved Oxygen Availability

The second portion of the method uses an empirical prediction of the background (seasonal) dissolved oxygen signal to asses low-DO water availability. The *DOD* index (Fig. 7) suggests that intrusion events cause a temporary deficit in dissolved oxygen levels (*DOD* > 0) compared with the seasonal signal of dissolved oxygen in Puget Sound. The deficit associated with an intrusion event only produces low-DO levels (less than 4.0 mg/L) if the seasonal background levels are already seasonally low, and thus a prediction of background levels is necessary to predict which intrusions will have low-DO.

The Upwelling Persistence Index and the Fraser River Discharge Index are regressed against observed dissolved

⁵Only the LI and DII were determined to be useful in the Intrusion Event prediction. Other variables, such as local winds, and discharge from the major rivers into Puget Sound (Skagit, Snohomish, Stillaguamish), and lagged Upwelling Index were all considered but had no patterns noticeably associated with Intrusion Events that could improve prediction skill.

oxygen levels to determine an empirical equation for predicting seasonal dissolved oxygen trends in Admiralty Inlet. Figure 6 shows that the Upwelling Persistence Index follows the reverse seasonal signal of the seasonally filtered (\mathscr{F}_{610}) dissolved oxygen data, consistent with the mechanism of upwelling bringing oceanic water with low dissolved oxygen from the Juan de Fuca Canyon or the continental shelf into the Strait of Juan de Fuca. The Fraser River Discharge Index (also shown in Fig. 6) must be considered as it modulates the signal further and is important for tracking the initial seasonal decrease in DO. The mid-year peak in river discharge increases the exchange flow in the Strait of Juan de Fuca, and thereby increases the availability of low-DO waters just seaward of Admiralty Sill.

Performing a multi-linear regression for the data from May 2010 to April 2013, the Upwelling Persistence Index and the Fraser River Discharge Index fit the observed seasonal dissolved oxygen data as

$$DOAP = 7.14 - [0.00127 \times UPI] - [2.77 \times FRDI],$$
(9)

where the R-squared correlation value is 0.72. The resultant empirical Dissolved Oxygen Availability Prediction (DOAP) is shown in Fig. 6c, where it is compared with the observed seasonal dissolved oxygen pattern at the bottommounted mooring site. While the DOAP does not precisely predict the observed seasonally filtered DO data, it does reproduce a similar pattern. The availability prediction for DO was not designed to strictly follow the observed hourly DO time series because of the degree of local variability. Rather, the prediction addresses the regional availability of low-DO water to be carried by a given intrusion.

Intrusion Event Predictions and Dissolved Oxygen Availability

Finally, a combined set of thresholds is established empirically with the data from May 2010 to April 2013 to predict intrusion events with low-DO. We chose the strictest possible threshold values that successfully predict whether an intrusion event includes low-DO water. If an Intrusion Event Prediction from the first part of the method coincides with an empirical DOAP less than or equal to 6.2 mg/L,

If
$$LI > 0.8$$
 & $DII > 0.72$ & $DOAP < 6.2$,
(10)

an intrusion event with low-DO water (less than 4.0 mg/L) is predicted.

Conditions are regarded as favorable for dissolved oxygen to drop to low-DO levels in any time period of 5 days⁶ before or after an Intrusion Event Prediction. Therefore, an independent low-DO intrusion event favorable period is designated as the 10-day period centered on a positivelyidentified low-DO intrusion event (based on the index thresholds). Consecutive positive event identifications less than 10 days apart can overlap and result in low-DO intrusion event favorable periods that last longer than 10 days.

Figure 8b shows the combined result for predicted low-DO intrusion favorable periods. Observed dissolved oxygen data less than or equal to 4.5 mg/L are marked red to highlight lower-DO dissolved oxygen measurements at the mooring site. We focus on these values because points below 4.5 mg/L appear to only occur when both seasonal DO levels are low and intrusion events are active. DO observations of 4.0 mg/L and below represent the most extreme of these low-DO observations.

The operationally predicted low-DO intrusion event favorable periods (*LDOIFP*'s) encompass 97.9% of observed DO concentrations below 4.0 mg/L and 66.7% of observed DO concentrations below 4.5 mg/L (Table 3). These low-DO intrusion favorable periods also include many DO observations above 4.5 mg/L. Predictions are based on a subtidal time-scale whereas DO data are examined on an hourly time-scale, and thus false positives are inevitable. A low-DO intrusion favorable period is only meant to indicate when there is a reasonable expectation that an low-DO oceanic intrusion could occur.

Discussion of Prediction Outcomes

The first part of the method predicts major bottom water intrusion events, which may carry nutrients or other water properties of interest beyond low DO, such as acidified water (Johannessen et al. 2014; Feely et al. 2010). This intrusion prediction works solely with routine predictions of tidal elevation and lunar phase. In situ data are preferred to determine for the duration and magnitude of events, but there are no real-time, continuous velocity measurements available in the main channel of Admiralty Sill. However, Shipboard ADCPs were recently installed on the ferries that traverse Admiralty Inlet multiple times each day (http://apl. uw.edu/ferriesforscience) and those data are now available on the Northwest Association of Networked Ocean Observing Systems (NANOOS) website. During future studies, the data collected from these transits could be useful in estimating the flux of water through Admiralty Inlet and may provide insight into the potential intensity of individual intrusion events.

The secondary part of the method specifically addresses dissolved oxygen modulation over Admiralty Sill and may help to better understand oceanic influences on dissolved oxygen levels in Puget Sound. Although the method

⁶Eight days is the maximum observed low-DO intrusion event duration. Five days was chosen as the window for low-DO intrusion favorable periods, because it was shown to have the same success rate as 8 days while reducing window size.



Fig. 8 Presentation of results from operational test of low-DO intrusion event predictions. *Yellow* indicates that a prediction was made only by the operational method using tidal elevation data from NOAA. *Magenta* indicates that a prediction was made only by the method using in situ pressure data from the CTDO. *Blue* indicates that a prediction was made using both methods. **a** The observed Intrusion Event

identifies events, it does not prescribe the severity of the low-DO intrusion or the overall impact to Puget Sound water quality. These details would require extensive in situ monitoring and calibrated circulation modeling. Timing of such efforts can be guided and optimized by the dominant variables identified herein. The DOAP is a simple model of seasonal DO modulation and could be refined further given a more intensive study. The low-DO intrusion prediction method is currently in use by the Washington State Department of Ecology and is incorporated into ongoing work by their Marine Water Quality Monitoring group. The low-DO intrusion favorable period metric is reported in their monthly analysis of coastal conditions influencing Puget Sound.

A close examination of Fig. 6 highlights the importance of the UPI and FRDI signals as inputs to the DOAP and how they help track to the seasonal DO signal that also varies inter-annually. Seasonal DO begins decreasing around local minimum UPI (at the end of persistent downwelling winds). Although the downward trend in DO does not track with the UPI immediately, it does begin decreasing about when discharge begins increasing rapidly. The FRDI helps drive the downward trend in DOAP (e.g., May 2013, post-training period for regression equation). Once discharge eases, the peak in UPI extends low-DO seasonality (e.g., 2011).

Index time series from May 2010 to October 2013 with marks indicating when the tidal condition indices are both above the proposed threshold for prediction (LI > 0.8, DII > 0.72). **b** Hourly dissolved oxygen observations (points less than or equal to 4.5 mg/L marked *red*) from May 2010 to October 2013, with background shaded for Low-DO Intrusion Event Favorable Periods (LDOIFP)

It is also important to note that the thresholds are empirically-derived and customized based on the observations from May 2010 to April 2013 (but were tested for data collected through October 2013). The prediction method is dependent on the quality and consistency of the publicly available data inputs it uses. The thresholds were chosen by

 Table 3 Operational test, low-DO intrusion event prediction results

	Operational test	Using in situ tidal data	
Observed DO (mg/L) below	Percent of points identified	Percent of points identified	
4.0	97.9	Same	
4.25	77.7	Same	
4.50	66.7	66.5	
4.75	60.6	59.2	
5.0	55.3	52.9	
5.25	52.4	48.7	
5.5	50.7	45.7	
5.75	47.8	42.3	
6.0	45.9	40.5	
6.25	43.9	38.3	
6.5	41.4	37.0	

maximizing the success of the prediction agreement with observations at this particular mooring site (TS1) during this approximately three-year time period.

Some additional regional exploration was conducted to investigate the influence of low-DO intrusion events on dissolved oxygen levels within Puget Sound, but the results were inconclusive. Geyer and Cannon (1982) explained that intrusions propagate landward as gravity currents in Puget Sound basins after traversing the sill. Our investigation of DO observations at moorings throughout Puget Sound (maintained by the Washington State Department of Ecology), including one in Hood Canal, did indicate that the seasonal signal of DO in the basins of Puget Sound tends to follow similar general patterns as the seasonal DO signal at Admiralty Sill. This agrees with the dynamics described by Mickett et al. (2004) in which dense intrusions propagate southward in Puget Sound at mid-depth or near-bottom after passing over the sill region. The advection of dense, low-DO water during the late summer and early fall contributes to bottom water renewal by displacing and mixing resident water upward and is important to recirculation of deep water in the Main Sound. In locations like Hood Canal, bottom water has been observed to reach hypoxic levels in the late summer due to local forcing and residence time (Feely et al. 2010). Thus, low-DO, dense intrusions to Puget Sound, by displacing dense hypoxic water in deep basins like Hood Canal, can decrease DO levels in the upper water column and contribute to hypoxia at the surface.

Conclusions

Low dissolved oxygen water measured at Admiralty Inlet, the entrance of Puget Sound, is associated with deep ocean water masses, as identified by temperature and salinity. This ocean water can intrude across the sill into Puget Sound near the seabed as an exchange flow during conditions of minimal mixing, coincident with maximum diurnal inequality and neap currents. Tidal elevation data and the lunar cycle can be used as indicators for such exchange flow conditions. Residual current analysis from ADCP measurements validate that thresholding indices based on these data is a very successful method for identifying occurrences of bottom intrusions.

The intrusions can carry low dissolved oxygen concentrations into Puget Sound. Coastal upwelling and river discharge influence the availability of dense, low dissolved oxygen water in the Strait of Juan de Fuca at the entrance to Puget Sound. A regression to dissolved oxygen background (seasonal) levels using these inputs results in an empirical Dissolved Oxygen Availability Prediction that correlates well with the observed seasonal dissolved oxygen signal. Ultimately, the intrusion event prediction combines with a simple model of seasonal dissolved oxygen availability to successfully identify low-DO intrusion favorable periods that cover 98% of observed extreme intrusion events with DO < 4.0 mg/L.

The prediction method developed in this paper successfully identifies intrusion events and the conditions necessary for low-DO dense-water intrusions for the time period from May 2010 to October 2013. Climate shifts and inter-annual variability might affect these relationships in the future. Shifts in the Pacific Ocean, including ocean acidification, are intrinsically tied to Puget Sound by the dynamics at Admiralty Inlet.

This general prediction scheme could be applied to intrusion events at other tidal estuaries assuming there is knowledge of how exchange flow (or other type of circulation) is controlled by tidal conditions at the mouth (or other critical location) and what external forcing mechanisms influence the regional bottom water properties outside of that estuary. For instance, unique intrusions events of hypoxic, saline water into parts of Chesapeake Bay are observed due to wind and tidal forcing of circulation dynamics (Sanford et al. 1990). Additional estuaries for which subtidal circulation structures have been observed to be significantly influenced by tidal conditions, river flow, and other local and regional mechanisms include San Francisco Bay (Monismith et al. 2002) and the Hudson River estuary (Ralston et al. 2008). An intrusion prediction at another estuary would not need to be specific to dissolved oxygen levels. A variety of additional parameters tied to dense water masses could be studied (pH, nitrogen, etc.). With sufficient multi-year near-bottom observations, unique indices could be developed and thresholds could be chosen to develop a skillful two-part predictive method like the one we developed for low-DO intrusions to Puget Sound.

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