Hypoxic Intrusions to Puget Sound from the Pacific Ocean

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Motivation

- Hypoxic water in Puget Sound can be harmful to marine organisms
- What is the role of the ocean in modulating dissolved oxygen (DO) levels?

**Goal:** Develop a method for predicting hypoxic intrusions to Puget Sound from the ocean that does not require in situ measurements
Admiralty Inlet, Puget Sound, WA, USA

- Strong tidal currents (>3 m/s)
- Long, shallow sill
- Important factors for intrusions
  - Tidal modulation (mixing)
  - Strait of Juan de Fuca dynamics (availability)
    - Coastal Upwelling
    - Fraser River Discharge
Past Studies of Intrusions to Puget Sound

- **Geyer & Cannon (1982)**
  - High salinity intrusions over the sill occur during conditions of Neap Tides and during the Maximum Diurnal Inequality (coincide during the equinox)
  - Increased river discharge may affect availability

- **Cannon, et al. (1990)**
  - Winter coastal storms with onshore winds may suppress inflow of dense water
Observation Locations

Key

- **Tripod mooring** (at Admiralty Inlet)
- **Victoria Clipper track** (section for analysis)
- **Cast stations**
- **Main Sound moorings**
  - MUK – Mukilteo
  - MCH – Manchester
  - SQX – Squaxin
- **Hood Canal moorings**
  - NB – North Buoy
  - DB – Dabob Bay
  - HP – Hoodport
  - TW – Twanoh
Data Collection: Tripod Mooring

- CTDO & ADCP on bottom tripod
  - Water depth: 55 m at MLLW
  - 0.5 m above seabed

- Data collection: 2009 – 2013

- Associated with tidal energy site characterization
Hypoxic Water $\rightarrow$ Oceanic Source
Observed Dissolved Oxygen Time Series
Intrusion: Autumn Equinox 2011

Neap Tide + Maximum Diurnal Inequality = Minimal Mixing

\[ TEI = \frac{\text{demean} (\text{Pressure})}{-\text{MLLW}} \]
Hypoxic Intrusion Prediction Method

If \( \text{DOAP} < 6.241 \),

\[ \text{DO Availability Prediction (DOAP)} \]

Regression Equation

Fraser River Discharge Index (FRDI)

Upwelling Persistence Index (UPI)

If \( \text{DII} > 0.72 \) & \( \text{NTI} > 0.8 \),

Neap Tide Index (NTI)

Diurnal Inequality Index (DII)

Hypoxic Intrusion Prediction Method

Flow

Availability
Intrusion Events obtaining an IEI of at least 0.5 and related signals

\[ IEI = \frac{\int udL}{L} \]
Regression used to predict seasonal dissolved oxygen availability

- **Upwelling Persistence Index**

  \[ UPI = \text{detrend} \left( \int \text{sign} \left( \mathcal{F}_{40} (UI - 7.25 \text{days}) \right) \, dt \right) \]
Success of Predictions

- Intrusion Event Predictions

  If \( NTI > 0.8 \) \& \( DII > 0.72 \), Intrusion = 1

  - Identified **100%** of events with IEI of at least 0.5
  - False positive prediction 1.52% for non-intrusions
Observations and Predictions of Intrusions
Operational Test

Observed Intrusion Event Index and Predictions

Observed DO Concentration and Hypoxic Intrusion Event Favorable Periods
Operational Test Success

- Agrees with in situ method
- Intrusion events correctly identified
  - 100 % for IEI>0.5
  - False positives only 1.68 %
- Hypoxic Favorable Periods identified successfully
  - Covers 98% of DO<4.0 mg/L and 84% <4.5 mg/L
- Able to make predictions during in situ data gaps

Operational Inputs
- Tidal elevation: NOAA (for DII)
- Moon Phase: USNO (for NTI)
- Upwelling Index: PFEL (for DOAP)
- Fraser River discharge: Water Survey of Canada (for DOAP)
Intrusions Over Admiralty Sill

1. Low DO water over sill is oceanic in origin

1. Exchange flows can be predicted using tidal elevation data using thresholds for NTI & DII

1. Hypoxic water availability controlled by coastal upwelling and Fraser River discharge

1. Method developed able to predict periods of high risk for major hypoxic intrusion events using publicly available data (no in situ observations)
Exchange Flow Observations

- Victoria Clipper
  - Surface observations
    - Salinity & Temperature
  - Analysis limited to data between 48.1 - 48.2 N and 122.6 – 122.8 W

- Monthly CTDO Casts from float plane surveys
  - Vertical Profiles
  - Salinity, Temperature, DO with depth
Victoria Clipper: Surface Observations

Residual Current

Surface Salinity in Admiralty Inlet, Victoria Clipper

Surface Temperature in Admiralty Inlet, Victoria Clipper
Admiralty Inlet: Bottom vs. Surface

- Two-layer exchange flow conditions
  - Fresh water outflow at surface
  - Dense, high-salinity water inflow at bottom

- Importance of intrusion events vs. overall signal
Admiralty Inlet: Exchange Flow

Salinity at Bottom and Surface

Temperature at Bottom and Surface

Residual Current

IEI x 45
Bottom vs. Surface: Hourly and Sub-tidal

- Individual intrusion events highlighted in overall signal
- Intrusion events observed on sub-tidal scale
- Unique trends from overall seasonal relationship
Sub-tidal Intrusion Event Signals

**Salinity**

**Temperature**
Sub-tidal Dissolved Oxygen Prediction

\[ STDO_{P} = 32.6253 - [0.6094 \times F_{40} (Sal_{Surf})] - [0.8084 \times F_{40} (Temp_{Surf})] \]

Sub-tidal Dissolved Oxygen &
Empirical Prediction from Victoria Clipper Data

\[ R^2 = 0.92 \]
Admiralty CTDO Casts

*Salinity, Temperature, DO with depth*

- Conditions during cast
  - Neap or Spring?
  - Active sub-tidal intrusion?
  - Max. diurnal inequality?

- Data set under-sampled for this purpose

\[ TGI = F_{12.5} \left( \frac{d}{dt} TEI \right) \]
Local Conclusions: Admiralty Inlet

1. Hypoxic water oceanic in origin
2. Operational prediction method successfully identifies intrusion events and hypoxic intrusion favorable periods
   - Importance of minimal mixing and seasonal dissolved oxygen availability
3. Surface observations from Victoria Clipper compliment bottom observations
   - Exchange flow conditions
   - Prediction of sub-tidal dissolved oxygen signal at bottom
4. Float plane casts under-sampled
   - Profiles available agree with expected observations
   - Importance of small ebb/flood and neap tides
Regional Response

- Where does low DO water go after it makes it over the Admiralty Sill?

- When Low DO inflow occurs, do we see the signature in other locations?

- After inflow, gravity current into main basin
  - Geyer & Cannon (1982)

- Intrusion propagations at 7 – 14 cm/s

- Direct effects or cumulative effects?
  - Importance of internal sills (Lavelle, et al., 1991)
Regional Observations in Puget Sound

- **Main Sound Moorings**
  - Mukilteo
  - Manchester
  - Squaxin

- **Hood Canal Moorings**
  - North Buoy
  - Dabob Bay
  - Hoodsport
  - Twanoh
Main Sound
> bottom observations

Admiralty ➔
Main Sound: DO Signals

- Lag in seasonal DO signal from Admiralty to other stations further South
- No clear direct response to hypoxic intrusion events
Main Sound: Signal Lags

- Cumulative Response
  - Cross-correlation between hourly DO signals
  - Diffuse signal, **Tacoma Narrows** sill mixing important

- Direct Response
  - Cross-correlation between Dissolved Oxygen Deficit
  - Not traceable

### Table 3.1: Main Sound, Lags and Correlation to Admiralty Signal.

<table>
<thead>
<tr>
<th>Mooring Station</th>
<th>DO Signal Lag</th>
<th>Correlation&lt;sup&gt;a&lt;/sup&gt;</th>
<th>DO Deficit Lag</th>
<th>Correlation&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mukilteo</td>
<td>956 hr</td>
<td>0.619</td>
<td>135 hr</td>
<td>0.173</td>
</tr>
<tr>
<td>Manchester</td>
<td>1344 hr</td>
<td>0.647</td>
<td>166 hr</td>
<td>0.144</td>
</tr>
<tr>
<td>Squaxin</td>
<td>1840 hr</td>
<td>0.450</td>
<td>499 hr</td>
<td>0.104</td>
</tr>
</tbody>
</table>
Main Sound: Intrusion Propagations

Main Sound DOD Propagation Correlations

- Mukilteo
- Manchester
- Squaxin

- 14 cm/s propagation speed
- 7 cm/s propagation speed

Distance (km)
0 50 100 150 200 250 300
Lag (hours)
0 500 1000 1500
Correlation Coefficient
0 0.05 0.1 0.15

Key
- Tripod mooring (at Admiralty Inlet)
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  - HP – Hoodsport
  - TW – Twanoh
Hood Canal
> near-bottom observations

Admiralty ➔

North Buoy

Dabob Bay

Hoodsport

Twanoh
Hood Canal: DO Signals

- Much lower DO observations South of North Buoy
- Bathymetry important
  - Dabob and Hoodsport past deeper sections
  - Twano much shallower
- Similar seasonal signal but different temp/salinity association
Hood Canal: Signal Lags

- **Cumulative Response**
  - Diffuse signal at North Buoy
  - In most of Hood Canal, DO has distinct temperature & salinity signature from Admiralty

- **Direct Response**
  - Not traceable

### Table 3.3: Hood Canal, Lags and Correlation to Admiralty Signal.

<table>
<thead>
<tr>
<th>Mooring Station</th>
<th>DO Signal Lag</th>
<th>Correlation $^a$</th>
<th>DO Deficit Lag</th>
<th>Correlation $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Buoy</td>
<td>175 hr</td>
<td>0.767</td>
<td>351 hr</td>
<td>0.156</td>
</tr>
<tr>
<td>Dabob Bay</td>
<td>467 hr</td>
<td>0.296</td>
<td>276 hr</td>
<td>0.201</td>
</tr>
<tr>
<td>Hoodsport</td>
<td>0 hr</td>
<td>0.135</td>
<td>362 hr</td>
<td>0.358</td>
</tr>
<tr>
<td>Twanoh</td>
<td>175 hr</td>
<td>0.691</td>
<td>476 hr</td>
<td>0.097</td>
</tr>
</tbody>
</table>
Regional Conclusions

- Hypoxic water sources
  - Main basin
    - Tied to Admiralty
  - South Sound & Hood Canal
    - Not directly tied to Admiralty water mass
    - Signal mixed over sills?

- Diffuse cumulative response to external DO modulation in main Sound and mouth of Hood Canal

- Mixing at internal sills important

- Direct response to intrusions untraceable
  - 7-14 cm/s average propagation speed seems reasonable
Overall Conclusions

1. Successful hypoxic intrusion prediction method using real-time data products (from government agencies)
   - Not able to assess severity/duration or oxygen flux

2. Minimal mixing important for intrusions
   - Neap tides and maximum diurnal inequality

3. Seasonal availability of hypoxic water
   - Exchange flow in Strait of Juan de Fuca

4. Surface temperature & salinity from Victoria Clipper could predict sub-tidal dissolved oxygen signal at bottom

1. DO modulation at Admiralty contributes to a diffuse, lagged seasonal modulation in the main basin

1. DO modulation in Hood Canal & South Sound not directly linked
Acknowledgements

- Jim Thomson, Brian Polagye, Christopher Krembs
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Questions?
Extra Slides
Coincident Observations

Admiralty

Mukilteo

Salinity (psu)

Temperature (deg C)

DO (mg/L)

Salinity (psu)

Temperature (deg C)
Coincident Observations

Admiralty

Salinity (psu) vs. Temperature (deg C)

Manchester

Salinity (psu) vs. Temperature (deg C)
Coincident Observations

Admiralty

Salinity (psu)

32
30
28
26
24
22
20

Temperature (deg C)

5
10
15

DO (mg/L)

9
8
7
6
5
4

Squaxin

Salinity (psu)

32
30
28
26
24
22
20

Temperature (deg C)

5
10
15

DO (mg/L)

9
8
7
6
5
4
Coincident Observations

Admiralty

Salinity (psu)

DO (mg/L)

North Buoy

Salinity (psu)

DO (mg/L)
Coincident Observations
Coincident Observations

Admiralty

Salinity (psu)

Temperatupe (deg C)

33
32
31
30
29
28
5
10
15

DO (mg/L)

4
5
6
7
8
9

Hoodsport

Salinity (psu)

Temperature (deg C)

33
32
31
30
29
28
5
10
15

DO (mg/L)

4
5
6
7
8
9