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8.1 SPATIAL VARIABILITY OF TIDAL CURRENTS IN PUGET SOUND, WASHINGTON

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1. INTRODUCTION

Tidal currents are an important factor in estuarine circulation, stratification and exchange, while also critically important to predict for safe and efficient marine navigation. In many nearshore regions the vast majority of current energy is dictated by the tides, and since tidal currents are predictable, it is possible to generate indefinite predictions of tidal currents at specific locations after collecting at least a month of observations. The National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) provides tidal current predictions at over 5000 coastal and estuarine locations throughout the U.S. These predictions are provided by completing short duration current profiler deployments at select regions each year. For three years beginning in 2015 CO-OPS is deploying 138 Acoustic Doppler Current Profilers (ADCPs) covering the regions of Puget Sound, the Strait of Juan de Fuca and the San Juan Islands in Washington State. This paper details initial results from the first 48 ADCP deployments in southern Puget Sound, along with deployments of six co-located Conductivity, Temperature and Depth (CTD) sensors. These observations will improve tidal current predictions for Puget Sound, aid in the development of an operational hydrodynamic model and support a variety of research and academic partners.

2. BACKGROUND

Puget Sound is a hydrodynamically complex, fjord-like estuarine system with significant tidal forcing (range > 3 m) and strong tidal currents. Although the dynamics of Puget Sound have been well researched (Ebbesmeyer and Barnes, 1980; Khangaonkar et al., 2011; Sutherland et al., 2011; Thomson, 1994; etc.), there has not been a large scale effort at observing the currents since the last NOAA current survey completed in the 1970s (Ebbesmeyer et al., 1984). Much of the data used to generate the NOAA tidal current predictions presently available are from short-duration observations (< 10 days) collected in the 1940s - ‘60s by radio current meters and captive drift poles (Cox et al., 1984). The accuracy of these predictions is limited due to the now antiquated instrumentation, as well as the short duration of observations, which preclude a full harmonic realization of the tides. The short duration of observation requires historic predictions at most locations in Puget Sound to be referenced to a few stations which had longer data records and full harmonic predictions.

3. METHODS

A total of 48 ADCPs were deployed in the summer of 2015, with 42 short-term stations deployed for about 45 days and six long-term stations deployed for at least 90 days (Figure 1). In addition, six CTDs were co-deployed with the ADCPs at select locations (Table 1). All ADCPs were Teledyne RDI Workhorse Sentinel (300 kHz, 600 kHz, 1200 kHz) or Long Ranger (75 kHz) models, with instrument frequency dependent on deployment depth. ADCPs collected 6-minute current velocity averages throughout the water column with bin depths ranging from 1 to 4 meters long, depending on deployment depth. SeaBird SBE 37 CTDs collected 30 second samples, which were then averaged to 6 minutes to correspond to ADCP measurements.

Instruments were deployed either on the sea floor using a variety of bottom mounted platforms or suspended with a taut-line mooring from 5 m to 35 m above the bottom using

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Corresponding author address: Gregory Dusek, NOAA/NOS/CO-OPS, 1305 East West Highway, Silver Spring, MD 20910; email: gregory.dusek@noaa.gov subsurface buoys (Figure 2). CTDs were deployed in-line with the subsurface buoys, about 1 m below the buoy.

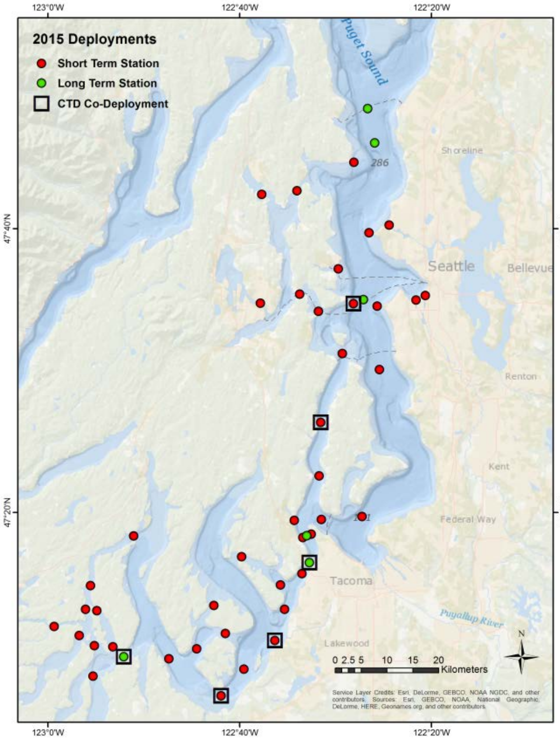

Figure 1. Map of 2015 deployment locations. Short-term (~45 days; red dots), long-term (~90 days; green dots), and CTD (black squares) locations are shown.

Current, salinity and temperature observations were quality controlled to remove spikes or bad data points. A least-squares harmonic analysis was performed on all currents data solving 25 to 29 tidal constituents and providing the tidal component of current, as well as tidal current predictions (as in Parker, 2007). A low pass Chebyshev Type 2 digital filter with a pass band period of 40 hours and stop band of 30 hours was used to analyze low-frequency or sub-tidal variability in the currents, salinity and temperature.

4. RESULTS

4.1 *Spatial variability in tidal currents*

Currents in Puget Sound are highly rectilinear, with a majority of current energy observed along the major axis, and generally aligned with the channel. Of the 48 stations deployed, 30 had at least 90% of the current energy along the major axis for the near-surface bin, with a minimum of 69%. This indicates that for all locations, limiting our analysis and tidal current predictions to only the major axis direction is a reasonable first-order approach.

Table 1. The station deployment locations and deployment and recovery dates in 2015. CTD locations are noted by a *, and long-term stations are bold.

Station	Lat (°N)	Lon (°W)	Deploy	Recover
PUG1501	47.71102	122.56715	7/27	9/9
PUG1502	**47.58368**	**122.45175**	**5/29**	**9/14**
PUG1503	**47.80712**	**122.44413**	**5/28**	**9/11**
PUG1504	47.67098	122.40700	7/28	9/10
PUG1505	47.61957	122.49530	7/28	9/10
PUG1506	47.58845	122.34397	7/25	9/10
PUG1507	47.58313	122.36022	7/25	9/10
PUG1508	47.70682	122.62825	7/27	9/12
PUG1509	47.74447	122.46802	7/27	9/11
PUG1510	47.57957	122.63065	7/26	9/9
PUG1511	**47.76712**	**122.43190**	**5/29**	**8/29**
PUG1512*	47.57885	122.46872	7/26	9/10
PUG1513	47.57002	122.52980	7/26	9/9
PUG1514	47.58993	122.56233	7/26	9/9
PUG1515	47.66207	122.44168	7/27	9/10
PUG1516	47.57607	122.42783	7/25	9/14
PUG1517	47.52028	122.48792	7/26	9/10
PUG1518*	47.43943	122.52578	7/23	9/12
PUG1519	47.37662	122.52867	7/23	9/12
PUG1520	47.50155	122.42358	7/24	9/14
PUG1521	47.32870	122.45405	5/29	7/23
PUG1522	47.32512	122.52468	7/23	9/13
PUG1523	47.32415	122.57187	7/24	9/14
PUG1524	**47.30600**	**122.55003**	**5/29**	**9/12**
PUG1525	47.30778	122.54213	7/24	9/12
PUG1526	47.30400	122.55675	7/24	9/14
PUG1527*	**47.27432**	**122.54532**	**5/29**	**9/13**
PUG1528	47.26130	122.55828	7/20	9/13
PUG1529	47.24790	122.59560	7/20	9/12
PUG1530	47.28138	122.66312	7/20	9/12
PUG1531	47.21913	122.58867	5/29	7/17
PUG1532*	47.18238	122.60560	5/29	7/17
PUG1533	47.14860	122.65940	5/30	7/17
PUG1534*	47.11693	122.69885	5/30	7/17
PUG1535	47.19062	122.69155	5/30	7/19
PUG1536	47.22383	122.71137	6/3	7/17
PUG1537	47.17258	122.74148	5/30	7/17
PUG1538	47.16067	122.78937	5/30	7/17
PUG1539*	**47.16310**	**122.86810**	**5/31**	**9/13**
PUG1540	47.14016	122.92145	5/31	7/16
PUG1541	47.17495	122.88697	6/1	7/16
PUG1542	47.21752	122.91465	6/1	7/15
PUG1543	47.17627	122.91900	6/1	7/15
PUG1544	47.18825	122.94537	6/2	7/15
PUG1545	47.19892	122.98900	6/2	7/21
PUG1546	47.21928	122.93452	6/2	7/18
PUG1547	47.24725	122.92592	5/31	7/16
PUG1548	47.30572	122.85092	5/30	7/16

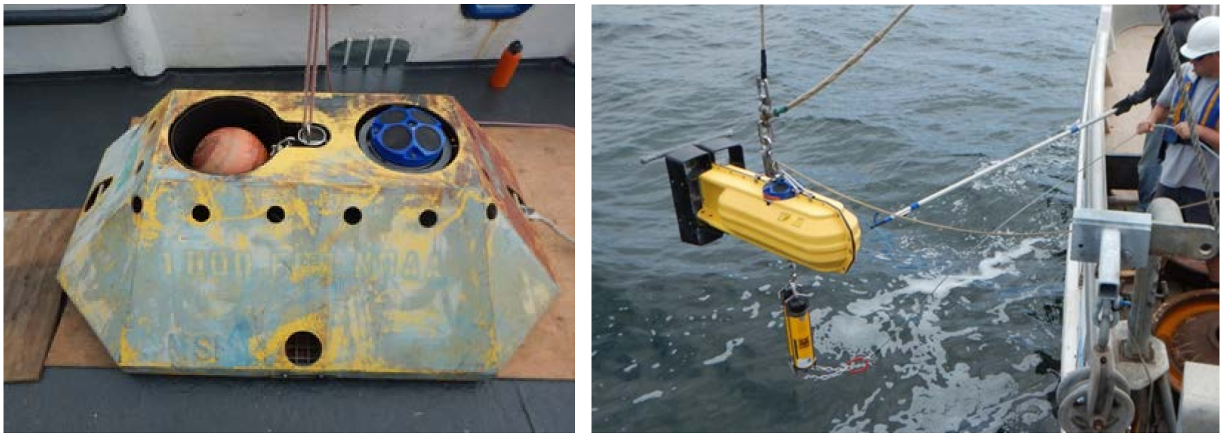

Figure 2. An example of one type of bottom mounted platform (left) and subsurface buoy mount (right) used for deployments.

The currents at a vast majority of the stations sampled are tidally dominated (Figure 3). The harmonic analysis results indicate that the tidal current captures over 66% of the total current energy for the near-surface bin at all 48 stations sampled, and 25 of the stations are over 90% tidal.

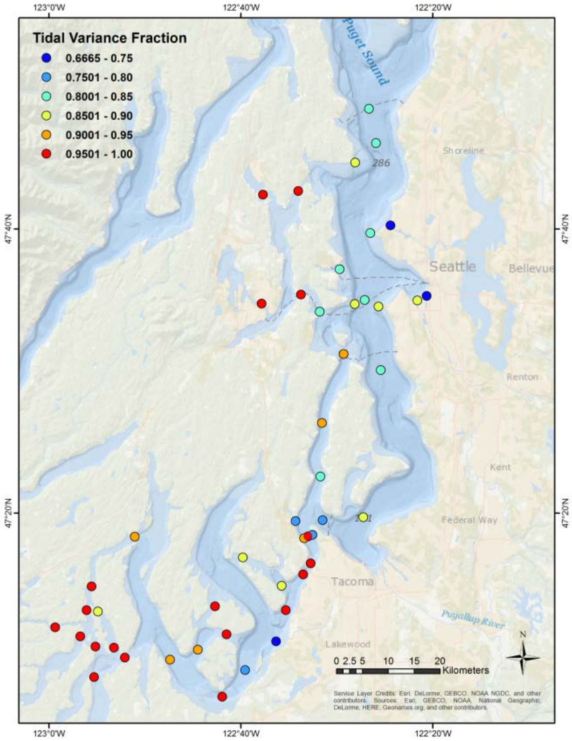

Figure 3. Fraction of current variance captured by the tidal component of the current for the near-surface bin.

The relatively large tidal amplitudes in the Sound coupled with large cross-sectional bathymetry gradients leads to strong tidal currents, especially in locations with topographic constrictions (Figure 4). Tidal currents in excess of 100 cm/s are common throughout the study region. The mean of the maximum flood and ebb tidal currents at the surface reach nearly 200 cm/s in the Tacoma Narrows sill region, which exhibit the fastest currents in the southern part of Puget Sound. Maximum tidal currents tend to decrease with depth, though the shallower, faster areas like the Narrows typically display very uniform flow as observed over the study period. Puget Sound exhibits traditional estuarine mean circulation (fresher outflow at the surface, saltier inflow at depth), and thus for some locations flood currents are actually faster at depth than at the surface.

The two most significant tidal constituents at nearly all 48 deployment locations are the M_2 and K_1 constituents, which are the predominant semi-diurnal and diurnal constituents, respectively. The M_2 constituent dominates the tidal signal at all locations with an amplitude exceeding 100 cm/s for the near-surface at eight locations, and exceeding 160 cm/s at two locations in the Tacoma Narrows (Figure 5). The K_1 amplitude mirrors the M_2 amplitude at most locations, though markedly smaller, with maximum amplitudes of about 40 cm/s (Figure 6). Calculation of the Detrich ratio (Detrich, 1967):

$$\frac{K_1+O_1}{M_2},$$

ranges from 0.17 to 1.28 for all locations, not surprisingly indicating tidal currents that are mixed, mostly semidiurnal. Tidal ellipses for

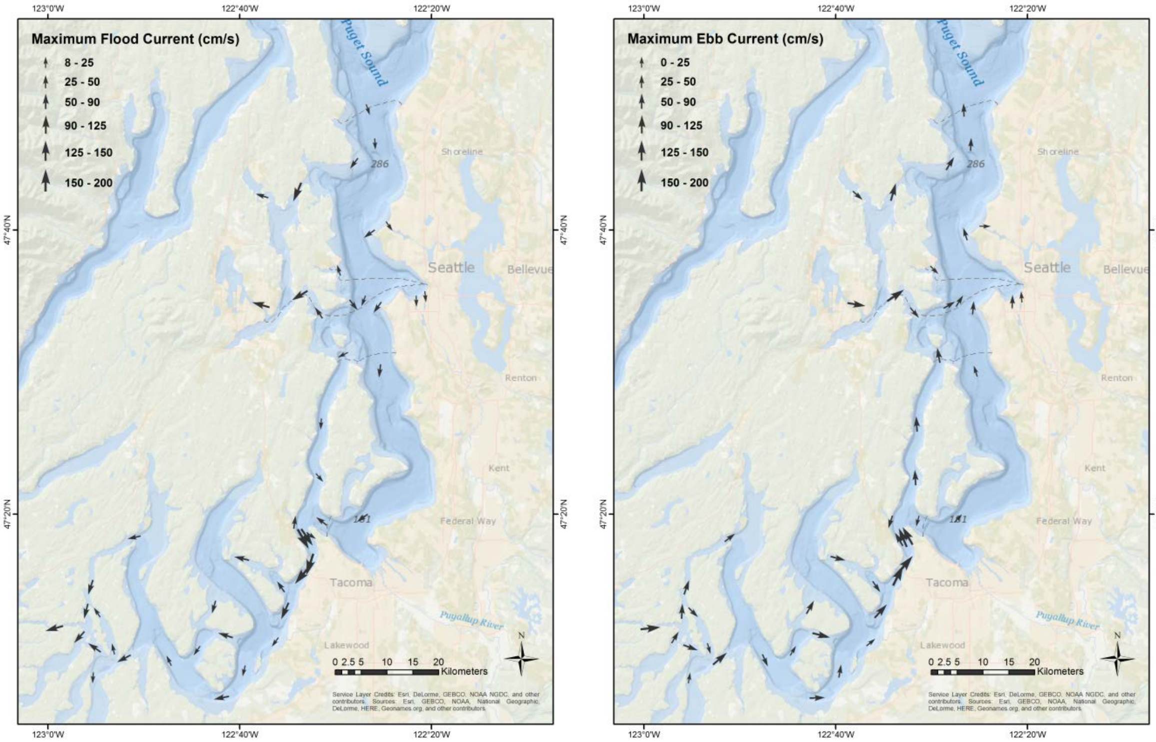

Figure 4. The near-surface mean maximum flood (left) and ebb (right) tidal currents over the observation period

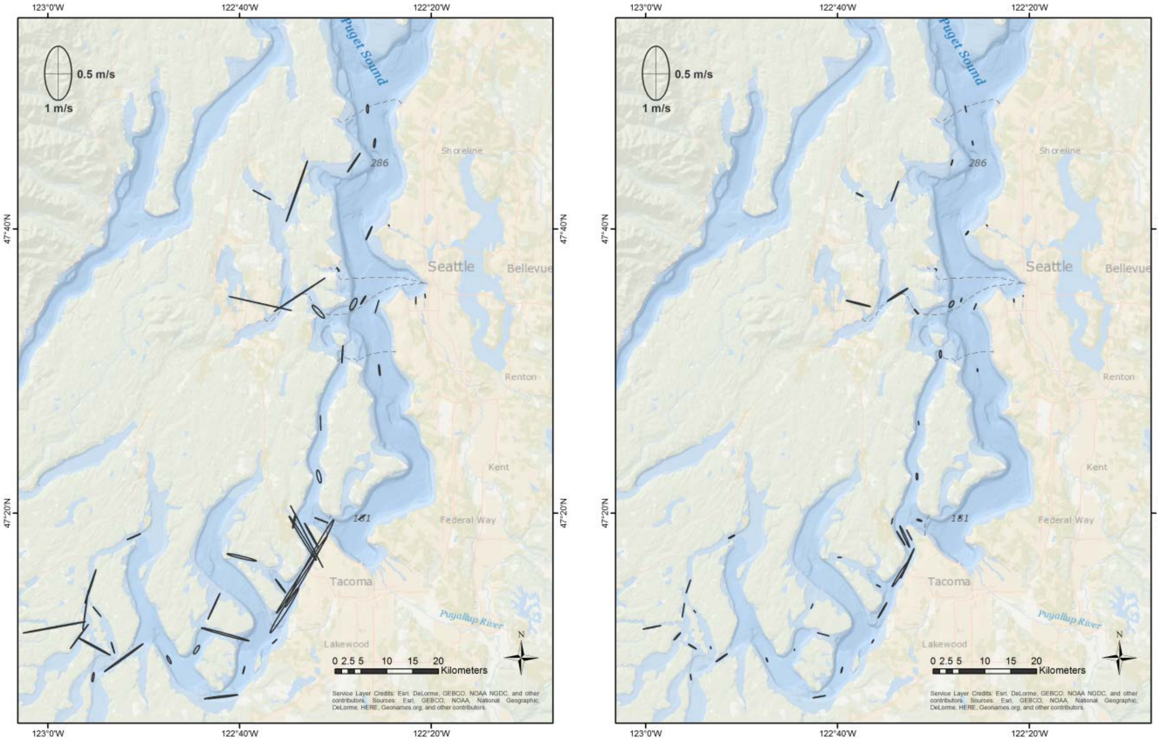

Figure 5. The M_2 (left) and K_1 (right) tidal ellipses for the near-surface bin at each location. Note the ellipse scale in the upper left corner of the plot.

both M_2 and K_1 are narrow for all locations, again indicating the predominantly rectilinear flow along the major axis (Figure 5).

One example of the variability of the four major tidal constituents with depth is shown by the tidal ellipse plot for station PUG1527 in the Tacoma Narrows (Figure 6). Of note is that there is relatively little depth variability evident in any of the major constituents at this location, with the exception of slight changes in the orientation and eccentricity of the ellipses.

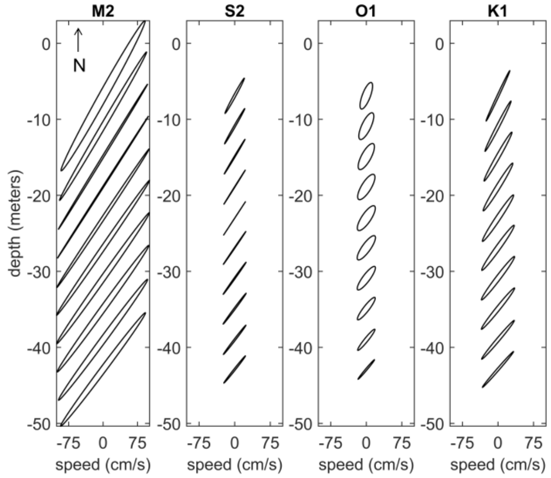

Figure 6. Tidal ellipses with depth for the Tacoma Narrows station PUG1527. Orientation of the ellipse indicates the direction relative to True North.

4.2 *Salinity and temperature variability*

The co-deployed SeaBird CTDs indicate saline water at depth, with a linear trend of increasing salinity and water temperature throughout the summer (Figure 7). This seasonal trend is not surprising given the warm and dry summer months typical of the region. Also evident is the high frequency tidal forcing for both salinity and temperature, where flood tides result in a slight increase in salinity and decrease in temperature and the inverse occurring during ebb tides. This tidal variability is the dominant signal for five of the CTD locations where it accounts for at least 60% of the variance in the salinity and temperature over the study period. The exception is PUG1518 where only 48% of the salinity variance and 23% of the temperature variance is within tidal frequencies.

An examination of the low-pass filtered currents, salinity and temperature was performed to look for correlations over sub-tidal frequencies, an example of which is shown in Figure 8. Very little evidence of any strong correlations between either salinity or temperature with currents was found over sub-tidal scales. During periods of strong tidal currents (spring tides) there is evidence of a deepening of the depth of no-motion and an increased uniform circulation throughout the water column, potentially due to increased mixing during these periods.

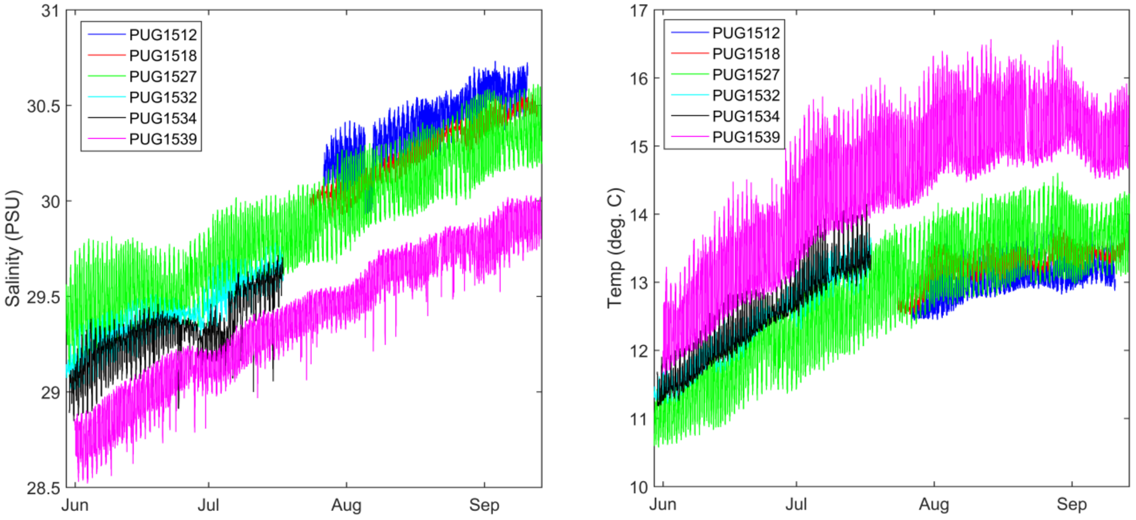

Figure 7. Salinity (left) and water temperature (right) as observed near-bottom at six locations with co-located SeaBird CTDs.

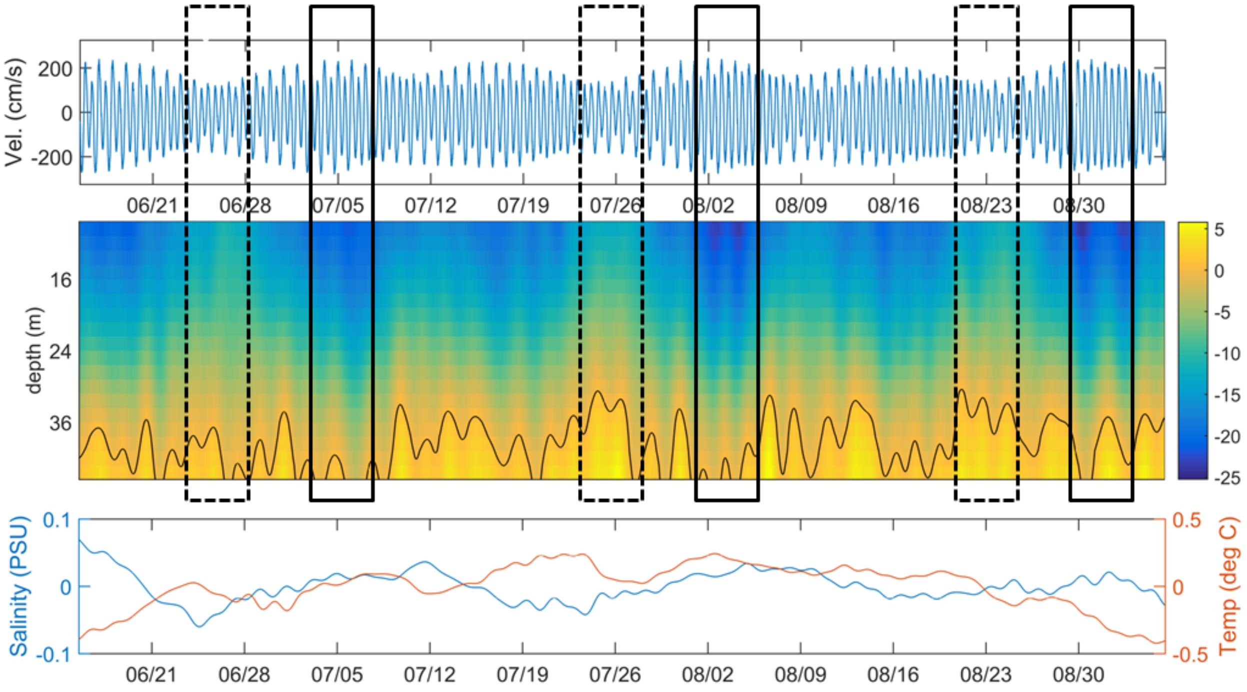

Figure 8. Each plot is for the Tacoma Narrows station PUG1527. Shown is the near-surface observed major axis current (Top), the low-pass filtered major axis current with depth (Middle) and the low-pass filtered and detrended Salinity and Water Temperature from the near-bottom co-located CTD (Bottom). The solid black line in the middle plot indicates the depth of no-motion (0 mean current) and positive values indicate flood and negative ebb. The solid black boxes indicate some periods of increased uniform ebb flow, and dashed boxes indicate some periods of increased two layer flow.

Conversely, periods of relatively weak tidal currents (neap tides) exhibit a shallower depth of no-motion indicating more substantial two layer circulation and potentially increased stratification.

4.3 *Improvements in tidal current predictions*

One of the primary purposes of performing current surveys is to improve upon historical tidal current predictions, and not surprisingly the new predictions are more accurate when compared to observations. The only deployment location for which predictions can be compared directly with historic harmonic predictions is PUG1524, another location within the Tacoma Narrows in the center of the channel about 3 km to the north of PUG1527. Through a comparison with observations over the deployment period, new predictions at PUG1524 capture an additional 4.1% of the major axis current variance and demonstrate a reduction in RMSE from 32.5 cm/s to 20.4 cm/s. The new predictions also show significant improvement during spring tides, when the historic predictions over-estimate periods of maximum flood by nearly 100 cm/s (Figure 9).

For the remaining new deployment stations a direct comparison to historic predictions cannot be performed because there are no harmonic constituents for any other historic station in southern Puget Sound. These historic predictions are calculated by time and speed offsets of slack current (current near 0 cm/s) and periods of peak flood and ebb to a handful of historic harmonic stations (e.g. PUG1524). Times of slack current as well as times and speeds for peak flood and ebb currents were calculated for the observations and new predictions to enable a valid comparison to historic stations. The results for three of the stations with relatively fast tidal currents (> 100 cm/s) show a significant improvement for new predictions, especially for predicting the speed of peak flood and ebb (Table 2).

5. CONCLUSIONS AND FUTURE WORK

Tidal currents in Puget Sound are rectilinear, fast, spatially variable and predominantly

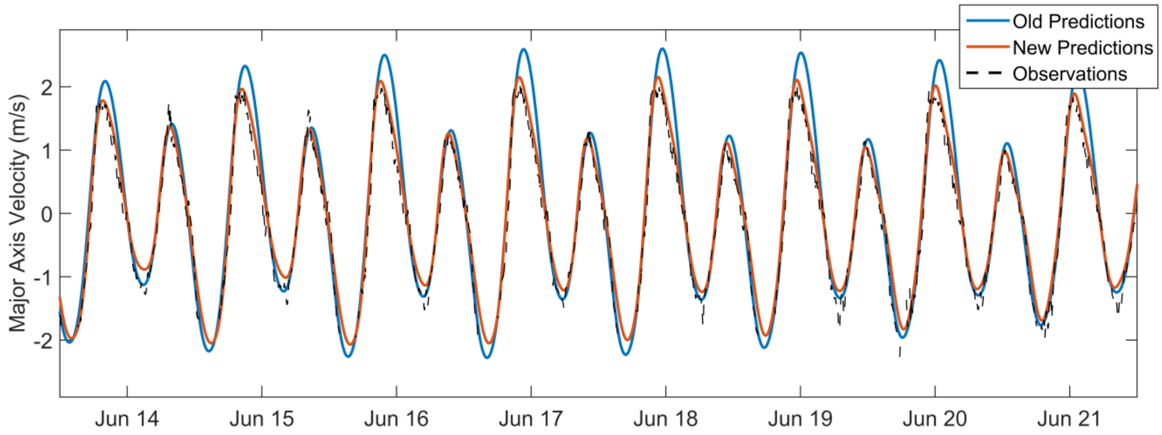

Figure 9. An example of the differences between the historic predictions, new predictions and observed data at the historic reference station in Tacoma Narrows, PUG1524.

Table 2. Mean absolute error between historical or new predictions and observed major axis current velocity. Time (minutes) and velocity (cm/s) differences are shown.

Station		Slack	Flood		Ebb	
		Time Diff.	Time Diff.	Vel. Diff.	Time Diff.	Vel. Diff.
PUG1514	Hist.	16	22	21.0	17	24.9
	New	**6**	**21**	**5.9**	**16**	**7.4**
PUG1534	Hist.	9	33	17.8	33	16.2
	New	**8**	**25**	**5.6**	**27**	**6.6**
PUG1546	Hist.	17	36	13.2	30	27.4
	New	**11**	**32**	**5.8**	**33**	**23.3**

characterized by a large M_2 tidal constituent. Over 66% of current energy at all 48 deployment locations is tidal and over 90% of the current energy is tidal at a majority of stations.

Locations with large cross-channel bathymetry gradients or topographic constrictions like the Tacoma Narrows, have the fastest tidal currents, in excess of 200 cm/s. Salinity and water temperature variability observed by CTDs deployed at depth is also predominantly observed in tidal frequencies, and relatively little correlation of salinity and temperature with sub-tidal flow was observed. Lastly, one of the primary goals of this deployment effort was met as the tidal current predictions generated from the new observations demonstrate significant improvement over historical predictions.

Future work includes completing ADCP and CTD deployments in the northern Puget Sound and Strait of Juan de Fuca in 2016 and in the San Juan Islands in 2017. Alternative deployment strategies for CTDs will be considered to determine if salinity and temperature data can be collected at multiple depths or closer to the surface. Over the long-term, the potential for coupling tidal current predictions with operational hydrodynamic forecast models of the currents will be investigated.

6. ACKNOWLEDGEMENTS

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