

Time-Dependent Salinity and Temperature Structure of the Columbia River Salt Wedge and River Plume: Analysis of Conductivity/Temperature/Depth Profiles from Sensors Attached to Pinnipeds and Diving Waterbirds

James Lerczak

College of Earth, Ocean, and Atmospheric Sciences

Oregon State University

104 CEOAS Admin Bldg

Corvallis, OR 97331

phone: (541) 737-6128 fax: (541) 737-2064 email: jlerczak@coas.oregonstate.edu

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LONG-TERM GOALS

The overall objective of this study is to assess the efficiency and effectiveness of using sensors attached to pinnipeds and waterbirds to make water-column measurements to quantify variability in hydrographic properties and to map variations in bathymetry in environments such as estuaries and the coastal ocean. Marine mammals and waterbirds have been used in the past to document water column properties in the ocean (Boehlert et al., 2001; Lydersen et al., 2002; Daunt et al., 2003; McMahon et al., 2005; Charassin et al., 2008; Costa et al., 2008; Simmons et al., 2009; Boehme et al., 2009; Costa et al., 2010; Padman et al., 2010). In this study, we utilize tagged marine animals in regions where water properties exhibit a high degree of variability, both in space and time, such as estuaries and the inner continental shelf.

OBJECTIVES

The scientific objectives of this study are to quantify the temporal and spatial variability of the salinity wedge within the Columbia River estuary using vertical profiles of temperature and salinity from sensors attached to pinnipeds and waterbirds that spend a significant amount of time within the estuary near the mouth of the Columbia River (MCR), and to construct a bathymetric map of the estuary using deepest dives by animals in different regions of the MCR. Our specific scientific objectives in this study are to:

1. Determine how well the pinniped- and waterbird-derived profiles resolve the estuary salinity wedge and its variations on tidal time scales and longer time scales, such as the spring-neap cycle and time scales over which river discharge varies.
2. Determine a time dependent temperature-salinity relationship to convert temperature to salinity along profiles, based on *in situ* time series measurements from moored sensors maintained by the Center for Coastal Margin Observation and Prediction (CMOP). This will be required to convert temperature to salinity for seal and waterbird sensor packages that only measure temperature profiles.
3. Use deepest pinniped and waterbird dives to grid a bathymetric map of the region and compare to

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existing bathymetry in order to assess the accuracy and identify potential biases in pinniped/waterbird-derived bathymetric maps.

4. Identify surface features in the pinniped- and waterbird-derived data that may be relevant to interpreting remotely sensed data of the region. Specifically, the pinnipeds and waterbirds may target frontal features and sample them at high spatial resolution.
5. Collaborate with RIVET-II and DARLA team members in understanding and predicting the dynamics driving variability in salinity and currents in the region.

APPROACH

This work is being undertaken in collaboration with researchers with expertise in marine animal tagging at the Oregon Department of Fisheries and Wildlife (ODFW) and Oregon State University, Department of Fisheries and Wildlife (OSUODFW). Drs. Bryan Wright and Robin Brown (ODFW) led the harbor seal tagging operations. Drs. Don Lyons and Dan Roby and graduate student Adam Peck-Richardson (OSUODFW) are leading the waterbird tagging operations. Lerczak is responsible for processing the data and interpreting it in a physical context.

WORK COMPLETED

Fifteen harbor seals were tagged during low-tide, on Desdemona Sands (Fig. 1) on May 29-30, 2013. All animals were tagged with a GPS-phone tag (Fig. 2; Sea Mammal Research Unit, SMRU, St. Andrews Scotland), which record GPS fixes, dive profiles, and temperature/depth profiles. Data is stored internally and uploaded periodically through cellular phone network. Additionally, five animals were tagged with an internally recording CTD (Fig. 2; DST-CTD, Star-Oddi, Iceland). These CTDs were attached to the animal with a syntactic foam housing, and this instrument package was also equipped with a VHF radio transmitter (Advanced Telemetry Systems, Minnesota, USA) to track and recover the package once it fell off the animal. To date, two of the five CTD instrument packages have been recovered.

Tagging of waterbirds was delayed due to delays in tag fabrication and shipment. Trial tagging of waterbirds (cormorants) took place in July 2013. This is late in the bird nesting season, and risks of losing tags were high due to the likelihood of disturbed birds not returning to their nest. Data recovery relies on re-capturing birds in order to download data from internally-recording tags. Four Brandt's cormorants were tagged with GPS and temperature-depth-recorder (GPS/TDR; Earth and Ocean Technologies, Kiel, Germany) sensors to obtain GPS fixes and temperature/depth profiles. Two of these birds were also equipped with Star-Oddi CTDs. The tags were programmed to record for about four days. To date, three tags have been recovered (the two with CTDs and GPS/TDRs and one with just GPS/TDR). We plan to conduct a second, large scale, tagging study next spring (early May to late June), early in the nesting season for both Brandt's and Double-Crested cormorants.

Processing and analysis of the data is underway, and is summarized in the results section below.

RESULTS

1) Harbor Seal Tagging Results:

a) GPS-phone Tag lifetime. The tag lifetime was dependent on configuration. Five tags were configured to attempt to get a gps fix every five minutes, and the expected battery lifetime was 1-2 months. The other ten tags were configured to attempt a GPS fix every 8-10 minutes, and their expected battery lifetime was 3-4 months. Duration is also limited by seal molting, which typically happens in August. Duration is defined as time from first and last GPS fix reported by the tag and ranged from 21 to 86 days. Nine seals spent the entire duration of their tagged period within the Columbia River estuary. Two seals spent >10 days in the estuary before heading to Willapa Bay or Grays Harbor, WA. Four seals spent <1 day in the Columbia before heading north to Willapa Bay or Grays Harbor.

b) GPS-phone tag statistics. A total of 23,912 gps fixes, 100,356 temperature/depth (T/D) profiles and 179,271 depth profiles were recorded from GPS-phone tags. During June, about 1600 T/D profiles and 3200 depth profiles were recorded daily (Fig. 4). These numbers declined gradually in July and August as the number of working tags decrease.

The total number of GPS fixes, temperature profiles and dive profiles varied significantly with seal tag (Fig. 5). For example, tag 1 had just 11% the number of GPS fixes that tag 6 had (324 compared to 2994). The number of GPS fixes is not correlated with number of T/D profiles or the number of dive profiles (Figs. 5 and 6). For example, for tag 1, the total number of GPS fixes (and number of fixes per day) is low while the number of temperature profiles is high. Whereas, for tags 6 and 9, the number of GPS fixes is high, while the number of T/D profiles is low. The number of temperature profiles is correlated with the number of depth profiles. There are about 79% more dive profiles than T/D profiles (179,271 compared to 100,356).

c) Locations of profiles. In order to get locations for profiles, we linearly interpolate GPS fixes in time to the time of a particular profile. The accuracy of the profile location is dependent on the time difference, Δt , of the GPS fixes that the profile location is interpolated between. An ‘acceptable’ profile is defined as one for which location is interpolated using GPS fixes with a time difference less than or equal to Δt . The fraction of acceptable profiles is dependent both on tag and on Δt (Fig. 6). We are currently assessing what Δt to use so that accuracy of profile locations is balanced by the need for a large number of profiles to resolve salt wedge variability.

The locations of profiles within the estuary is not homogenous (Fig. 1, $\Delta t=1\text{hr}$), with many animals remaining near Desdemona Sands, and the channel south of Desdemona Sands.

d) Bathymetry from dive profiles. Using seal profiles (maximum dive depth) to map out bathymetry within the estuary looks promising at the locations where seals spend a significant amount of time (Fig. 7). The sand flats of Desdemona Sands and the channels to the south and north of the flats are clearly captured by the seal dives, for both $\Delta t=1\text{hr}$ and $\Delta t=0.25\text{hr}$.

2) CMOP Saturn Observatory Analysis:

We have processed the CMOP moored time series data of temperature and salinity at locations Saturn-03, Saturn-01, and Saturn-04 (see Fig. 1 for locations). A summary of this data is shown in Fig. 8 for the period of time when seal tags were collecting data. Salinity structure is dependent both on river

discharge and tidal amplitude. The number of seal profiles is sparse for an individual tidal cycle. We are therefore analyzing profile data that is phase averaged over a diurnal tidal cycle. For example, the green shaded area in Fig. 8, indicates four consecutive diurnal tidal periods for which conditions in the estuary, as measured by the Saturn time series, are similar. Figure 9 shows how each of these diurnal tides compare at the Saturn locations. Averaging by diurnal tidal phase will allow us to increase dive density over a tidal cycle.

We used all the processed Saturn time series data to calculate daily T-S relationships during the seal tag period so that temperature profiles from the tags can be converted to salinity profiles. Temperature and salinity were fit to the following function:

$$S - \langle S \rangle = a(T - \langle T \rangle)^2 + b(T - \langle T \rangle) + c$$

where the angle brackets indicate the mean of S or T over the daily period for which the fit is being calculated. The linear fit parameter, b , and the RMS deviation between the data and the fit are shown in Fig. 10. The parameter b is negative for the duration of the tagging period, indicating that river water was always warmer than ocean water. RMS deviations were always less than 3 psu, and for much of the tagging period, deviations were ≤ 1 psu, indicating the T-S relationship should work well in converting T to S .

3) Cormorant data.

Processing of the cormorant data has just begun. As with the seal tag data, cormorant foraging dives are heterogeneous in space. Preliminary processing indicates that reliable GPS fixes were obtained immediately before and after each dive allowing for accurate positioning of dive locations. The rapid response (< 2 s) of the thermistor of the T/D sensors will allow for resolution of sharp density gradients associated with the salinity intrusion. We have begun the georeferencing of all dives made by cormorants as well as referencing dives to tidal stage (and thus position of the salinity wedge).

IMPACT/APPLICATIONS

Sampling coastal regions from marine animal platforms may allow the characterization of hydrography and bathymetry in the coastal ocean at higher spatial and temporal resolution and temporal duration than is feasible by shipboard and autonomous vehicle methods. This study is quantifying the effectiveness of marine animal sensor platforms and developing the methodologies for processing and interpreting the data collected from these platforms.

RELATED PROJECTS

This study has strong collaborations with the tagging projects of Drs. Bryan Wright and Robin Brown (seal tagging; ODFW) and Drs. Don Lyons and Dan Roby (cormorant tagging; OSU-DFW), both funded under the ONR RIVET-II DRI. We are also planning to collaborate with DARLA and other RIVET-II investigators who can make use of this data and analyses in understanding the evolution and dynamics of the salinity wedge of the Columbia River estuary.

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HONORS/AWARDS/PRIZES

Jim Lerczak, '2013 Editor's Award, *Journal of Physical Oceanography*,' American Meteorological Society.

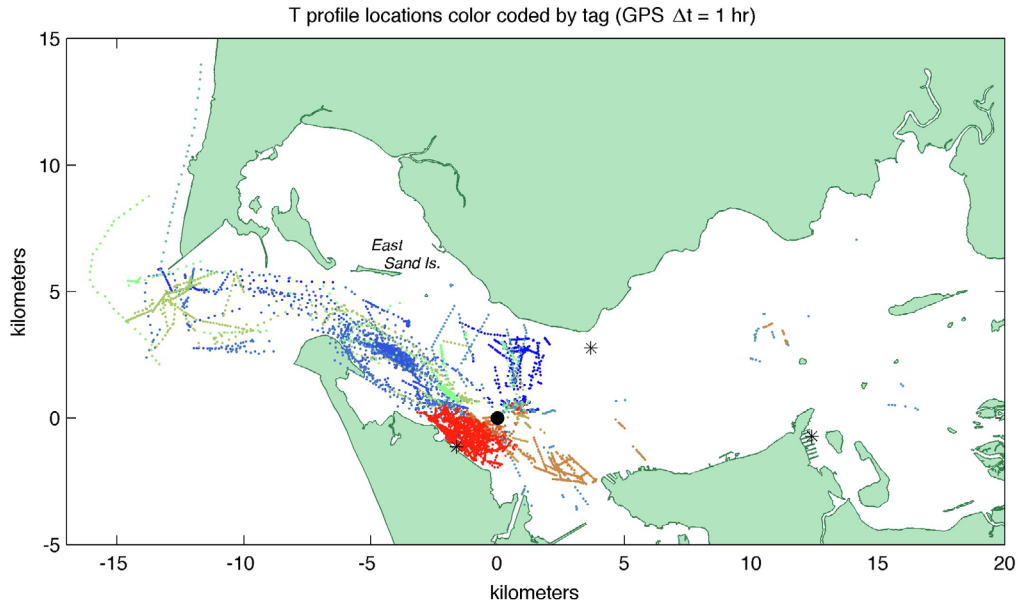


Figure 1. Map of the mouth of the Columbia River. Colored dots indicate locations of Temperature/Depth profiles from GPS-phone tags attached to harbor seals. Profiles are color-coded by seal. Only profiles are only shown for which a location could be interpolated between GPS fixes separated in time by no more than one hour. Black asterisks indicate the locations of Saturn-Observatory time series utilized in this study (Saturn-03, -01, 04, from west to east. The black circle indicates the location of Desdemona Sands, where seal tagging took place. East Sand Island, where cormorant capture and tagging took place, is also indicated.



Figure 2. a) Oregon State University oceanographer Jim Lerczak (left) and Oregon Department of Fish and Wildlife staff Craig Good (center) and Bryan Wright (right) attach a GPS-phone tag to a harbor seal captured near the mouth of the Columbia River. (This activity was conducted under NMFS Permit No. 13430-01; photo credit Julie Tennis). b) Instrument packages with internally-recording CTD and VHF transmitter, potted in syntactic foam (left) were deployed on five of the captured harbor seals. GPS-phone tags (right) were attached to 15 seals.

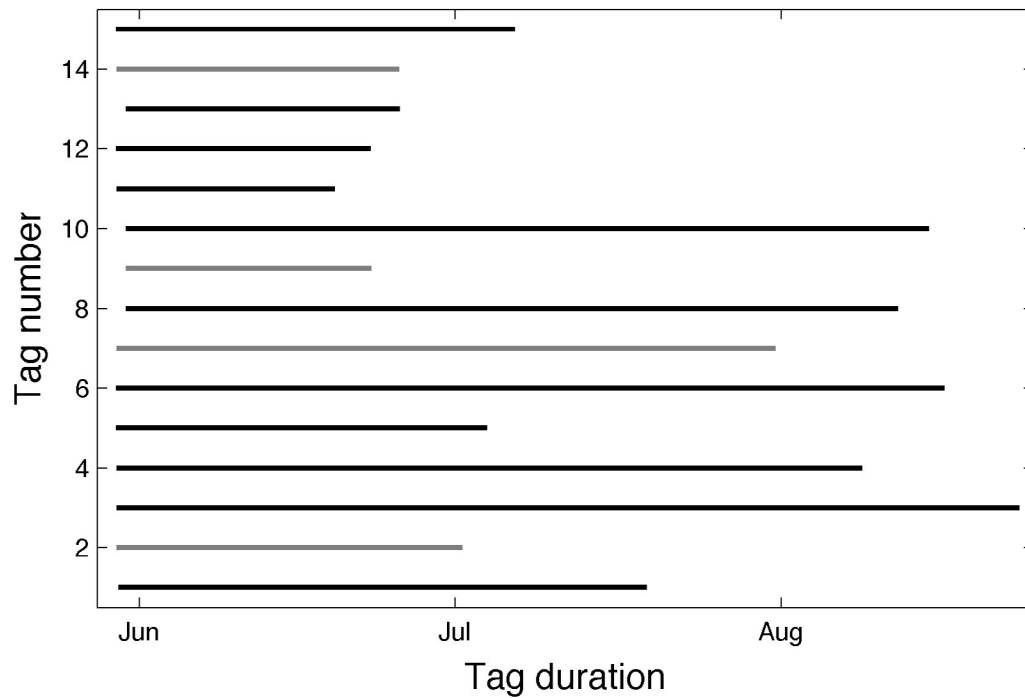


Figure 3. Duration of the 15 GPS-phone tags deployed on harbor seals in 2013. The same tag numbering is used consistently throughout this report. Gray-shaded lines indicate seals that <1 day in the Columbia River, before transiting to Willapa Bay or Grays Harbor, WA. Most of the other seals spent the entire tag duration within the Columbia.

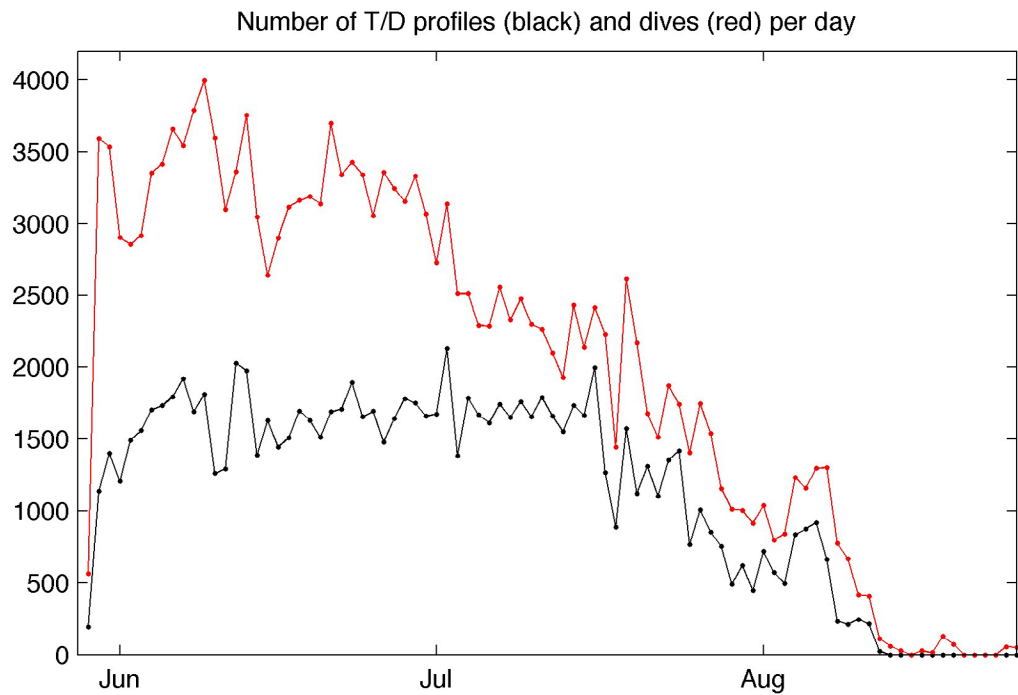


Figure 4. Total number of Temperature/Depth profiles (black) and dive profiles per day from GPS-phone tags attached to harbor seals. Not all T/D and dive profiles could be use in hydrodynamic and bathymetry analyses, because all profiles did not have reliable GPS fixes.

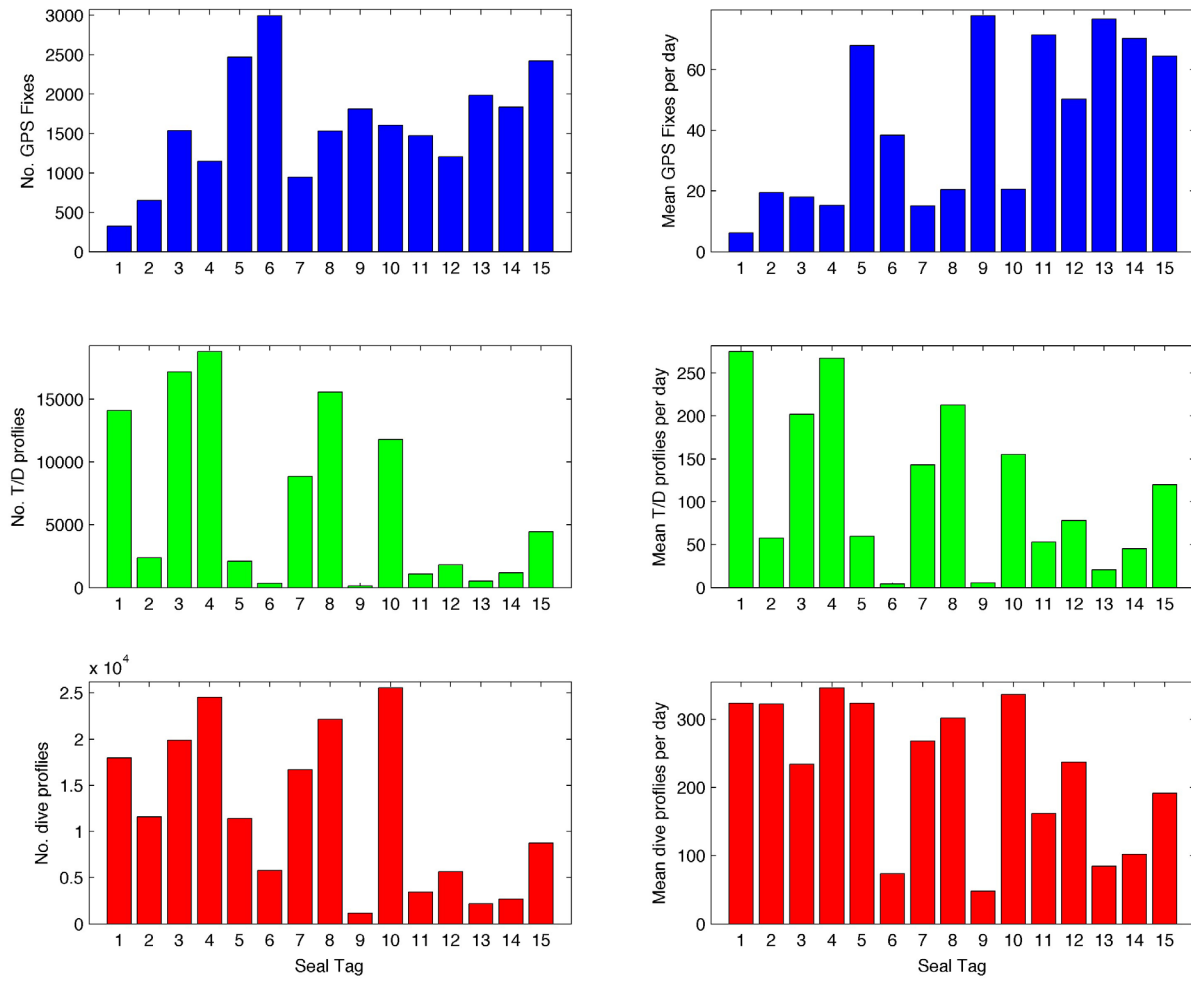


Figure 5. Left panels: total number of GPS fixes, T/D profiles and dive profiles vs. seal tag for the GPS-phone tags deployed on harbor seals. Right panels: average number of GPS fixes, T/D profiles, and dive profiles per day vs. tag number.

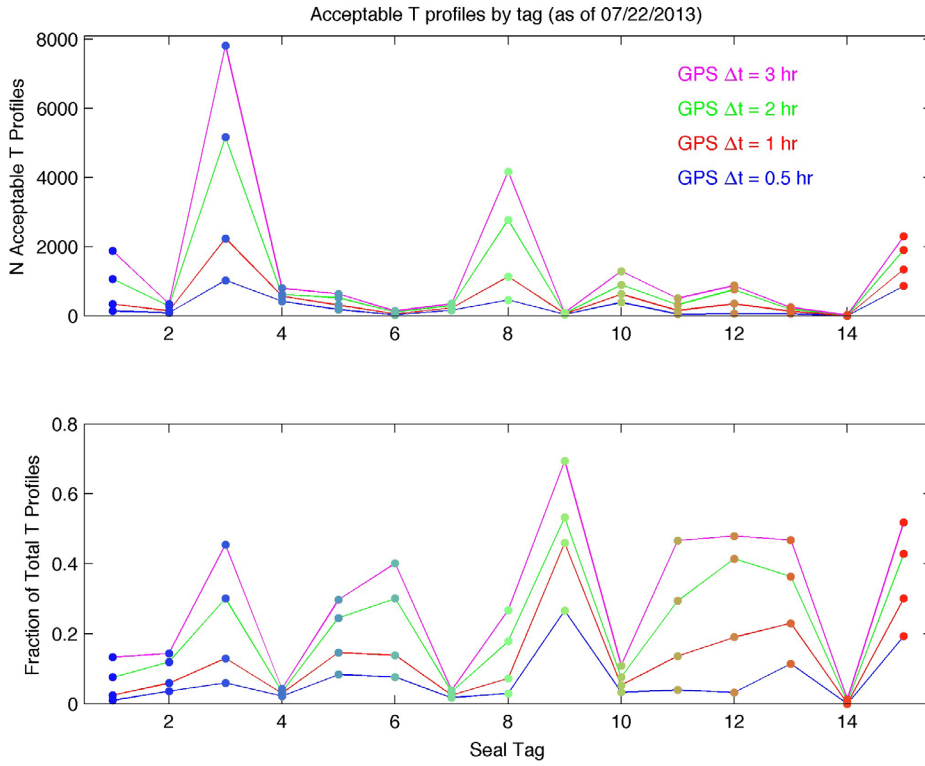


Figure 6. a) Number of acceptable temperature/depth profiles vs. seal tag for GPS-phone tags deployed on harbor seals. A profile is considered acceptable if its location can be determined by interpolating in time between GPS fixes that are separated in time by less than Δt . Fraction of acceptable temperature/depth profiles to total depth profiles vs seal tag.

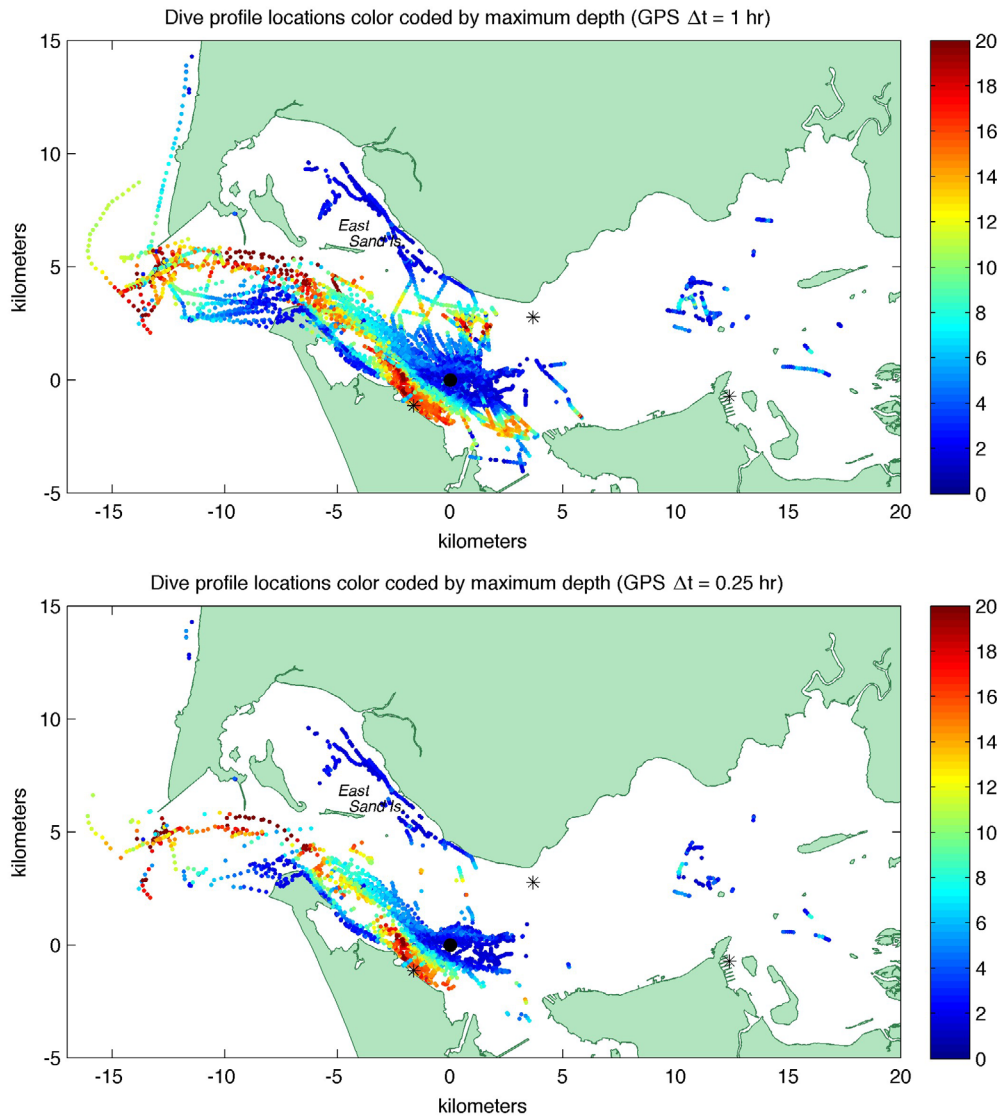


Figure 7. Locations of harbor seal dive profiles from GPS-phone tags, color coded by maximum dive depth. a) All seal dives for which a location could be determined by interpolation of GPS fixes separated in time by no more than 1 hour ($\Delta t = 1$ hr). b) $\Delta t = 0.25$ hr.

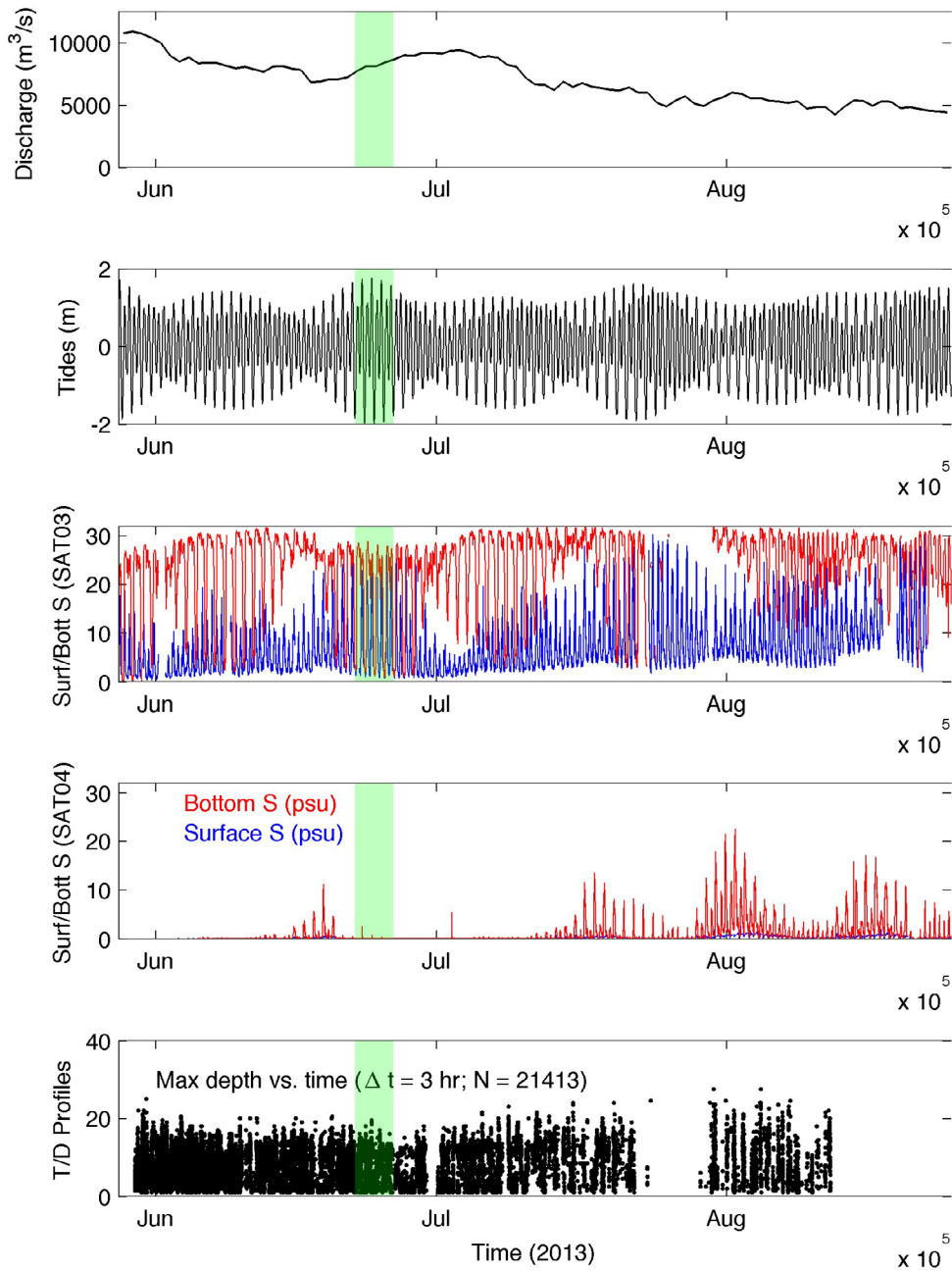


Figure 8. a) Columbia River daily discharge during the period of the harbor seal tag deployment (USGS Gage #14246900, Beaver Army Terminal). b) Tidal sea level fluctuations measured at the Saturn 03 observatory location (see Fig. 1). c) Surface and bottom salinity at the Saturn 03 observatory. d) Surface and bottom salinity at the Saturn 01 observatory location (see Fig. 1). e) Maximum depth of T/D profiles ($\Delta t=3\text{hr}$) vs time for GPS-phone tags on harbor seals. The light-green shaded area indicates the period over which a diurnal phase analysis is underway.

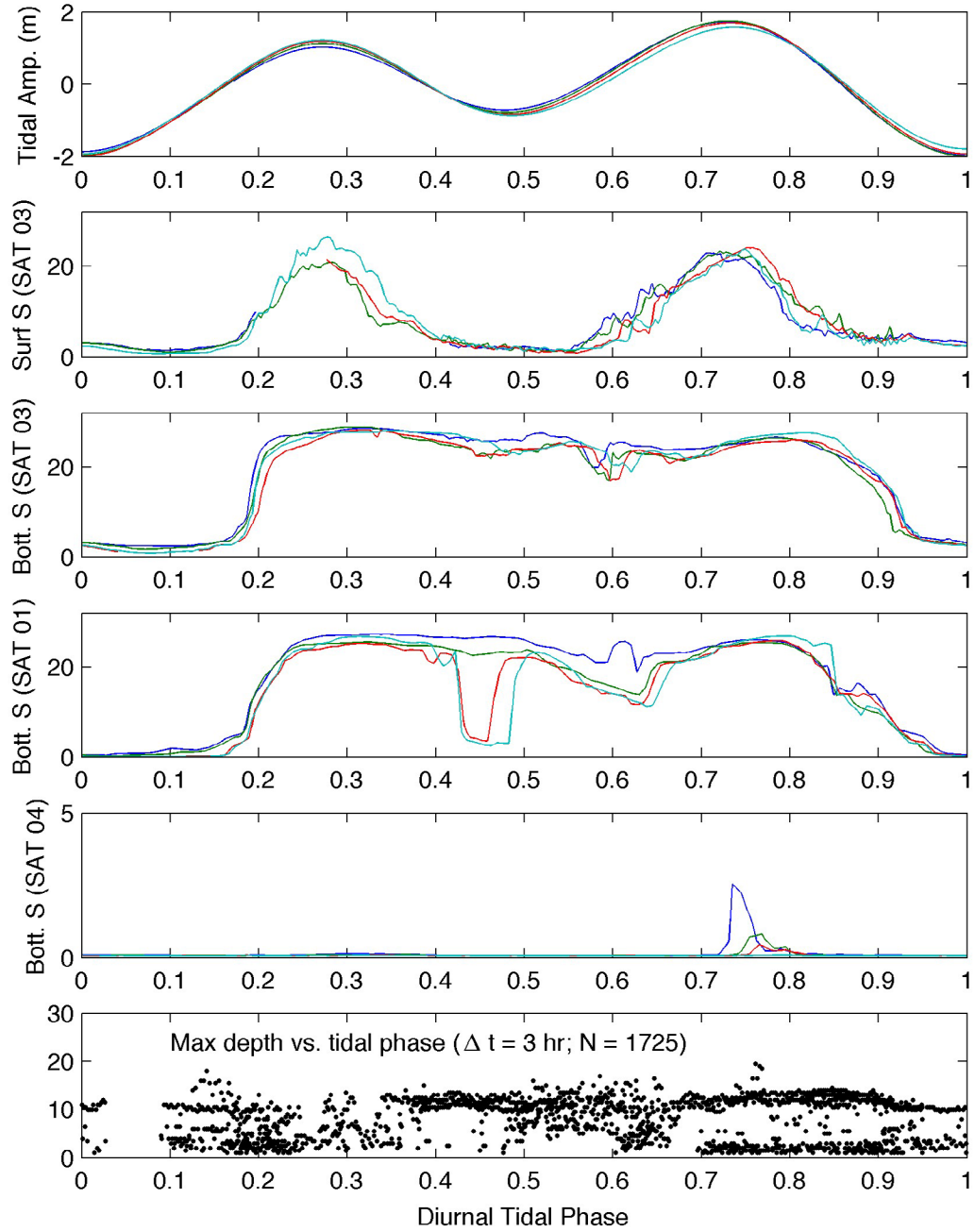


Figure 9. *Diurnal phase variability for four consecutive diurnal tides in July 2013 (spring tides; see green shaded region in Fig. 8). a) Tidal sea level fluctuations at the Saturn 03 observatory location. b) Surface salinity at Saturn 03. c) Bottom salinity at Saturn 03. d) Bottom salinity at Saturn 01. e) Bottom salinity at Saturn 04. f) Maximum depth of T/D profiles ($\Delta t=3\text{hr}$) vs diurnal phase for GPS-phone tags on harbor seals.*

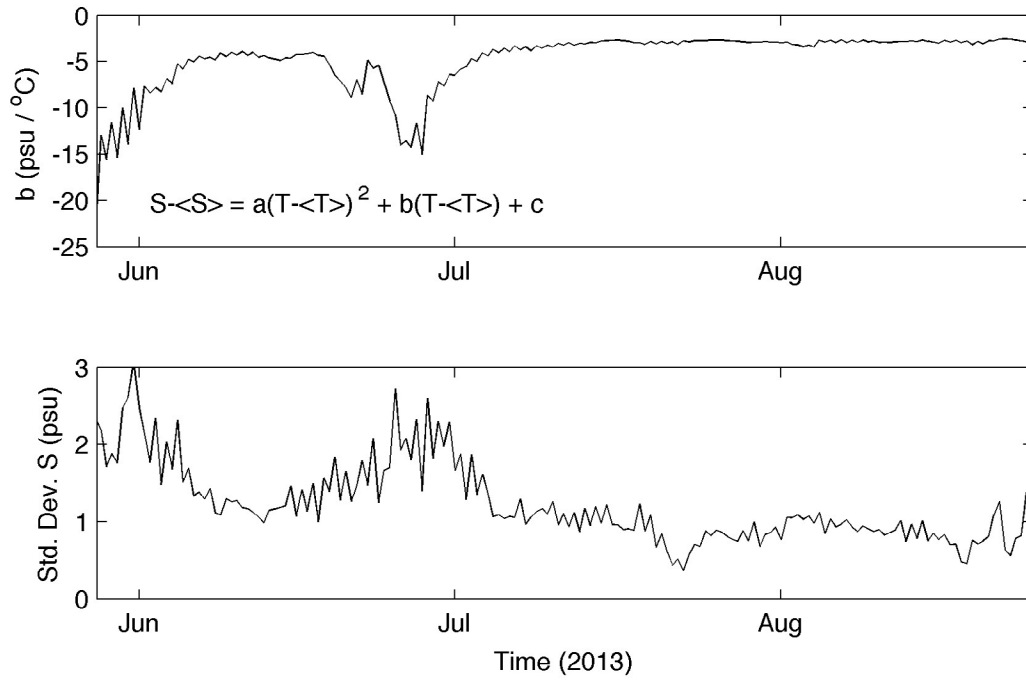


Figure 10. Daily quadratic fits of the T-S relationship in the Columbia River estuary using time-series data from the CMOP observatory network at locations Saturn-03, Saturn-01, and Saturn-04. a) The linear term in the quadratic T-S fit. b) RMS difference between observed salinity and salinity based on the T-S fit.