**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 bathymetry in energetic 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 salt wedge and its variations on tidal 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, based on *in situ* time series measurements from moored sensors maintained by the Center for Coastal Margin Observation and Prediction (CMOP). This is required in order to convert temperature to salinity from seal and waterbird sensor packages that only measure temperature.
3. Use deepest pinniped and waterbird dives to grid a bathymetric map of the region and compare to 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. For example, the pinnipeds and waterbirds may target frontal features.

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 (OSUDFW). 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 (OSUDFW) led the waterbird tagging operations. Lerczak is responsible for processing the data and interpreting it in a physical context.

In addition, the PIs are collaborating with Dr. Merrick Haller (OSU, Civil and Construction Engineering) to identify surface features measured with his X-band radar imaging system at the MCR that may be targeted and sampled by tagged cormorants.

**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 (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 (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. All five CTD instrument packages have been recovered.

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. Three tags were recovered (Fig. 1; two with CTDs and GPS/TDRs and one with just GPS/TDR).

In 2014, a total of 32 tag deployments on cormorants took place between late May to early August (15 Brandt’s cormorants and 17 double-crested cormorants). All deployments collected georeferenced temperature profile data, while 13 also collected CTD data.
We report on the processing and analysis of the data in the results section below.

RESULTS

1) Harbor Seal Tagging:

   a) GPS-phone Tag lifetime. Tag lifetime was dependent on configuration (Fig. 2). 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. Lifetime 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 Willipa Bay or Grays Harbor, WA. Four seals spent <1 day in the Columbia before heading north to Willipa 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. These numbers declined gradually in July and August as the number of working tags decreased (Fig 2).

   The total number of GPS fixes, temperature profiles and dive profiles varied significantly with seal tag. The number of GPS fixes is not correlated with number of T/D profiles or the number of dive profiles. The number of T/D profiles is correlated with the number of depth profiles. There were 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, \( \Delta t \), 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 \( \Delta t \). The fraction of acceptable profiles is dependent both on tag and on \( \Delta t \). We are currently assessing what \( \Delta t \) 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 sampling of the estuaries by seals and cormorants was heterogeneous. For example, many seals remained near Desdemona Sands, and the channel south of Desdemona Sands (Fig. 1).

2) Cormorant Tagging:

   Two of the three recovered tags reported both GPS fixes and T/D profiles (Fig. 2). Very accurate and frequent GPS fixes were obtained, allowing for accurate georeferencing of dive profiles. A total of 724 T/D profiles were recorded (91 dives/bird/day).

   In 2014, locations of cormorant profiles spanned the MCR and offshore waters near the river mouth (not shown). Duration of a tag deployment ranged from 3-7 days and 3-6 animals were tagged at any given time. Approximately 14,000 dive profiles were recorded over the three month tagging period.
3) 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 (three observatory sites at the MCR). 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:

\[ S - \langle S \rangle = a \left( T - \langle T \rangle \right)^2 + b \left( T - \langle T \rangle \right) + c \]

where the angle brackets indicate the mean of \( S \) or \( T \) over the daily period for which the fit is being calculated. The parameter \( b \) is negative for the duration of the tagging period, indicating that river water was always warmer than ocean water. RMS deviations between modeled and observed \( S \) were always less than 3 psu, and for much of the tagging period, deviations were \( \leq 1 \) psu, indicating the T-S relationship should work well in converting \( T \) to \( S \) for the T/D profiles.

4) Bathymetry Map from Dive Profiles. Dive profiles to a maximum depth within a gridded region were used to construct a bathymetric map of the MCR (only 2013 data used so far). For cormorant profiles, bottom dives were distinguished from dives to mid-water column based on profile shape (Fig. 3a). Depths from cormorant bottom dives generally agreed with depths from bathymetric data collected by the USGS as part of the RIVET-II study. Large differences occurred in regions of large bathymetric gradients (Figs. 3c and 4a) and may be due to errors in dive georeferencing or animal behavior.

Bathymetry derived from tagged animal data clearly resolved the north and south channels of the MCR as well as intertidal flats of Desdemona Sands and Clatsop Spit to the north of the South Jetty (Fig. 4b).

5) Resolving the Salt Wedge. Due to the spatial and temporal intermittency of profiles, the ability to map out tidal variations in the salinity intrusion were limited. To resolve the salt wedge variability we combine profile data from a particular phase of the diurnal tide and over comparable river discharge conditions. For example, profile data was combined over seven diurnal cycles during spring tide conditions between June 5-12, 2013 (Figs. 2 and 5). With this diurnal phase averaging, variations in the salt wedge along the south channel of the estuary could be resolved (Fig. 6).

IMPACT/APPLICATIONS

Sampling coastal regions from marine animal platforms may allow the characterization of hydrography and bathymetry in estuaries and the coastal ocean at higher spatial and temporal resolution and temporal duration than is feasible by moored instrument, 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 collaborating with Dr. Merrick Haller (OSU, Civil and Construction Engineering) to determine whether diving animals (particularly cormorants) are resolving and measuring hydrographic variability of small scale features (e.g., fronts) that are apparent at the surface in his X-band radar measurements at the MCR.

REFERENCES


Figure 1. Map of the mouth of the Columbia River estuary. Colored symbols (without black border) indicate GPS fixes from fifteen harbor seals tagged in 2013. Diamonds with black borders indicate dive locations of the two cormorants tagged in 2013. Different symbol colors and shapes distinguish individual tagged animals. The origin of the map is at the harbor seal haul-out location (Desdemona Sands). The location of the cormorant breeding colony (East Sand Island) is indicated. Also indicated is the site of the Saturn Observatory site 3 (SAT03; Center for Coastal Margin Observation and Prediction) from which time series of surface and bottom salinity were obtained.
Figure 2. a) Columbia River discharge during the 2013 tagging period (USGS Gage 14246900). b) Tidal sea level fluctuations. c) Surface and bottom salinity at the Saturn Observatory site 03 (SAT03; see Fig. 1 for location). d) Endurance of GPS-phone tags attached to harbor seals indicated by times of uploaded GPS fixes. Also indicated are cormorant dives during the pilot study in July 2013. Shaded region indicates the time period of the diurnal phase analysis.
Figure 3. Dive profiles of a tagged cormorant in 2013. a) Dives to the sea floor (last four dives) were determined as those for which the animal spent a significant time (>15 s in this analysis) at the maximum depth. If the first dive would not be considered a bottom dive in this analysis. b-c) Depths of bottom dives by tagged cormorants. b) Comparing bottom depths from cormorants (red symbols; squares and triangles distinguish the two birds) to depths from a bathymetric data set collected by the USGS as part of the RIVET-II DRI. c) Difference between USGS and cormorant bottom depths (magenta: difference > 5 m; blue difference > 20 m).
Figure 4. Bathymetric maps. a) Constructed from USGS data set (smoothed to 200 m horizontal resolution). Triangles indicate locations of cormorant bottom dives in Fig. 3b. b) Constructed from bottom dives of tagged animals (200 m resolution). c) Difference between USGS and tagged animal bathymetric maps.

North and South Channels, Deep Holes and Intertidal regions resolved by diving animals (mostly seal data)
Figure 5. Variability over seven diurnal cycles between 5-12 June 2013. a) Tidal sea level fluctuations. b) Surface salinity at SAT03. c) Bottom salinity at SAT03. d) Maximum depth of T/D profiles by all tagged seals during this period, color coded by seal number (see Fig. 2d).
Figure 6  a) Map showing transect along the south channel along which diurnal variations in the salt wedge are mapped.  
b-d) Diurnal variations in the salinity wedge based on 2013 tagged seal profile data. Temperatures were converted to salinities based on the T/S relationship constructed from Saturn Observatory time series during the period of the diurnal phase averaging (5-12 June 2013). Along channel sections are constructed by sorting data by diurnal phase and distance along the south channel transect shown in a).