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Marine bird aggregations associated with the tidally-driven plume and plume fronts of the Columbia River

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ABSTRACT

Freshwater discharge from large rivers into the coastal ocean creates tidally-driven frontal systems known to enhance mixing, primary production, and secondary production. Many authors suggest that tidal plume fronts increase energy flow to fish-eating predators by attracting planktivorous fishes to feed on plankton aggregated by the fronts. However, few studies of plume fronts directly examine piscivorous predator response to plume fronts. Our work examined densities of piscivorous seabirds relative to the plume region and plume fronts of the Columbia River, USA. Common murres (*Uria aalge*) and sooty shearwaters (*Puffinus griseus*) composed 83% of all birds detected on mesoscale surveys of the Washington and Oregon coasts (June 2003–2006), and 91.3% of all birds detected on fine scale surveys of the plume region less than 40 km from the river mouth (May 2003 and 2006). Mesoscale comparisons showed consistently more predators in the central plume area compared to the surrounding marine area (murres: 10.1–21.5 vs. 3.4–8.2 birds km^{-2}; shearwaters: 24.2–75.1 vs. 11.8–25.9 birds km^{-2}). Fine scale comparisons showed that murre density in 2003 and shearwater density in both 2003 and 2006 were significantly elevated in the tidal plume region composed of the most recently discharged river water. Murres tended to be more abundant on the north face of the plume. In May 2003, more murres and shearwaters were found within 3 km of the front on any given transect, although maximum bird density was not necessarily found in the same location as the front itself. Predator density on a given transect was not correlated with frontal strength in either year. The high bird densities we observed associated with the tidal plume demonstrate that the turbid Columbia River plume does not necessarily provide fish with refuge from visual predators. Bird predation in the plume region may therefore impact early marine survival of Pacific salmon (*Oncorhynchus* spp.), which must migrate through the tidal plume and plume front to enter the ocean. Because murres and shearwaters eat primarily planktivorous fish such as the northern anchovy (*Engraulis mordax*), aggregation of these birds in the plume supports the hypothesis that it is the plume region as a whole, and not just the plume fronts, which enhances trophic transfer to piscivorous predators via planktivorous fishes.

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1. Introduction

The tidal discharge of freshwater from large rivers into the sea creates convergent river plume fronts that structure physical and biological properties of the nearshore ocean. Convergent fronts at the leading edge of river plumes aggregate planktonic organisms in coastal ecosystems and therefore provide a predictable food source that may attract schools of planktivorous fishes to the frontal region (Govoni and Grimes, 1992; Grimes and Finucane, 1991; Le Fevre, 1986; Morgan et al., 2005). Increased concentrations of planktivorous fishes such as anchovy (*Engraulis* spp.) and herring (*Clupea* spp.) are then thought to create feeding "hot spots" that lead to elevated densities of piscivorous predators including fishes, birds, and mammals. Many authors suggest that these multi-trophic level responses to fronts, frontal mixing, and coastal water masses created by river discharge are important to energy flow and fish recruitment in coastal ecosystems (e.g. De Robertis et al., 2005; Grimes and Kingsford, 1996; Kudela et al., 2010; Morgan et al., 2005). Examples of systems where responses to river plume fronts are known in lower trophic levels and suspected for upper trophic levels include – but are not limited to – the Elbe and the Rhône rivers in Europe (Skov and Prins, 2001), the Amazon River in South America (Grimes and Kingsford, 1996), and the Mississippi (Govoni and Grimes, 1992), Columbia (De Robertis et al., 2005; Morgan et al., 2005), and Fraser

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(St. John et al., 1992) rivers in North America. However, only one of these studies specifically examined the spatial response of fish predators (loons) to river discharge and its associated frontal system (Skov and Prins, 2001). Skov and Prins (2001) found that the winter density of loons was consistently and significantly higher within 5 km of the estuarine front of the Jutland Coastal Current in the southwestern North Sea. These authors could find only two additional published studies which mention bird response to plume fronts (Briggs et al., 1987; Uspenskvi, 1956); neither of those studies presented quantitative analyses of predator distributions.

The Columbia River is the fourth largest river in North America by volume, with an average flow of 7300 $m^3 s^{-1}$ (Bottom et al., 2005). The river plume is a dominant feature along the coasts of Oregon and Washington throughout the year (Hickey et al., 2010). Recent multi-disciplinary studies examined the physical, chemical, and biological structure of the Columbia River plume and plume front (e.g. Hickey et al. (2010) and the references therein). Interdisciplinary studies of ocean salmon ecology have also independently examined biological responses to the plume front (De Robertis et al., 2005; Morgan et al., 2005). Investigators from both research efforts frequently infer that energy transfer to piscivorous predators is enhanced in the region of the Columbia River plume (De Robertis et al., 2005; Hickey et al., 2010; Morgan et al., 2005 and references therein), yet we could find no published data which test that specific hypothesis.

The purpose of our work was to examine the distribution and abundance of piscivorous seabirds compared to the Columbia River plume and the strength and position of tidal fronts associated with the plume region. Seabirds are some of the most abundant predators found in this area. The response of seabirds to the plume and plume front is of interest to fisheries oceanographers not only for understanding the plume's role in trophic transfer through the food web, but also because seaward-migrating juvenile salmon must pass through the plume front to enter the ocean, and ocean avian predation at the front may account for some of the as-yet unexplained variation in salmon marine survival (Pearcy, 1992; Scheuerell et al., 2009). Understanding the mechanisms behind variation in early marine survival of salmon is of concern to regional fisheries managers legally responsible for restoring threatened salmon populations (NMFS, 2008, 2010).

We investigated four basic aspects of predator response to the Columbia River plume and the strength and location of plume fronts. First, we determined whether fish-eating birds were more abundant in the central plume area compared with other areas of the Washington and Oregon shelf. Second, we examined whether birds near the river mouth were equally distributed among the three coastal water masses derived from frontal mixing of river discharge with coastal waters (c.f. Horner-Devine et al., 2009). Third, we examined the relationship between bird density and the strength of salinity gradients across the frontal zone of the plume. Finally, we investigated bird abundance relative to the position of the plume front to determine whether maximum bird densities were seen at or near the frontal zone itself. The answers to these questions will begin to address the hypothesis that plumes or plume fronts facilitate energy flow through planktivorous fishes to piscivorous predators.

2. Methods

2.1. Mesoscale surveys: June 2003–2006

We began collecting at-sea survey data for marine birds in 2003 as part of a long-term effort by NOAA Fisheries, Oregon State University, and the Bonneville Power Administration to understand biological and physical processes impacting marine survival of juvenile salmon in the Pacific Northwest. During late June of 2003–2006, we recorded counts of marine birds along each of nine cross-shelf transects from the northern border of Washington State to Newport, Oregon, USA (Fig. 1). Transect locations allowed general comparison of bird density between two coastal areas: the central plume area, including the three transects bracketing the river mouth (Willapa Bay-WB, Columbia River-CR, Cape Meares-CM); and the marine area, including all other shelf transects influenced primarily by ambient marine waters (from north to south: Father and Son-FS, La Push-LP, Queets River-QR, Grays Harbor-GH, Cascade Head-CH, and Newport Hydrographic-NH). We recorded bird counts continuously for approximately 2 hours while traveling due east from 33–43 km offshore and proceeding as far inshore as the survey vessel could safely navigate (typically between 2–9 km from the beach). We maintained a speed of 4.1–4.6 m/s (8–9 knots) during data collection.

2.2. Fine scale surveys: May 2003, May 2006

To examine relationships between bird density, the plume region itself, and tidally-driven plume fronts, we completed a series of fine scale radial transects during 24–27 May 2003 and 02–04 May 2006 (Fig. 2). Transects originated ~10 km north of the river mouth and varied in length from 18–31 km long. The radial design was necessary to maximize the probability of encountering and crossing a visible surface tidal front (Morgan et al., 2005). The radial design also allowed us to sample water in the three major water masses found in the plume: the tidal plume (surface salinities < 21), containing the most recent river discharge released onto the coast; the recirculating plume (surface salinities 21–26), created by 3–4 days of mixing at tidal fronts; and the far-field plume (surface salinities 26–32.5), where ultimate mixing of river water and ambient ocean water occurs (c.f. Horner-Devine et al., 2009). Surveys began at dawn and continued until dusk. We recorded bird and salinity data continuously along each transect.

2.3. Bird observations

For both meso- and fine scale surveys, we used standard, 300-m wide strip-transect methods to collect continuous observations of marine bird abundance and distribution (Tasker et al., 1984). A primary observer used 8 × binoculars to identify and count all flying or sitting birds within a strip extending 300-m out from the bow to the beam of the ship in a 90-degree arc on the side of the vessel with the best viewing conditions. Every bird sighting was recorded by a secondary observer who immediately entered the data into a laptop computer running either WinFlock (2003–2004, G.L. Hunt, Jr., University of California, Irvine, CA) or SeeBird (2005–2006, L. Ballance, Southwest Fisheries Science Center, La Jolla, CA) data acquisition programs. The computer automatically stamped each observation in WinFlock with the date and time to the nearest second. These time stamps were subsequently converted to latitude and longitude based on interpolation from latitude and longitude positions entered manually on a regular basis throughout the survey. Observations in SeeBird were automatically stamped with date, time, latitude, and longitude via a direct NMEA data stream from a global positioning satellite (GPS) antenna to the computer. The secondary observer also assisted with sightings or identifications (Spear et al., 2004). During the fine-scale surveys, observer and recorder duties rotated every 2 h to minimize fatigue. Observers were 7.1-m above sea level on the bridge of the F/V *Frosti* (May 2003, June 2003, 2004, and 2006); 12.6-m above sea level on the flying bridge of the NOAA R/V *McArthur II* (May 2006); and 3.0-m above sea level on