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Short communication

Observations of oceanic-forced subtidal elevations in a convergent estuary

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A R T I C L E I N F O

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A B S T R A C T

Remotely-forced downwelling events are found to generate oceanic subtidal elevations along the Pacific Northwest that are transmitted upstream in a large, river-tide, convergent Columbia River estuary (CRE). The oceanic subtidal generation mechanism was evaluated using NOAA tidal and USGS river gage station data along the northern California, Oregon, and Washington estuaries and throughout the Columbia River and the NOAA Coastal Upwelling Index. Oceanic downwelling-induced subtidal motions propagate upstream with a slight decrease in amplitude. River discharge pulses also generate subtidal motions that propagate downstream with decreasing amplitude. The relative oceanic subtidal motions represent 90% of the total subtidal contribution near the entrance that decrease to 40% at 169 km upstream.

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1. Introduction

Subtidal ($f < 1/2\ d^{-1}$) motions are important in estuaries as they are able to transport water masses more effectively than diurnal and semi-diurnal tides owing to their longer wave periods (lengths) (Buijsman and Ridderinkhof, 2007; MacMahan et al., 2014; amongst others). Subtidal motions, owing to their longer and aperiodic behavior, are often observed relatively far upstream with amplification (LeBlond, 1979; Godin and Martinez, 1994; Kukulka and Jay, 2003; Buschman et al., 2009; amongst others).

There are three primary mechanisms for the generation of subtidal motions in an estuarine system that includes large freshwater river discharge. First, a forced subtidal elevation can develop due to the temporal variability of the bottom friction by spring-neap tidal modulations (LeBlond, 1978, 1979; Jay and Flinchem, 1997; Godin and Martinez, 1994; Godin, 1999; Buschman et al., 2009). With constant river discharge with a modulated ocean tide, the river-tide interactions owing to non-linear bottom friction generate fortnightly river oscillations that amplify upstream (LeBlond, 1979). This has been shown in one-dimensional analytical models (LeBlond, 1979; Jay and Flinchem, 1997; amongst others). Much of the focus on subtidal motions in strong river-tide estuaries has been on the generation of the fortnightly subtidal response by the modulated spring-neap tides interacting with the river flow.

Second, subtidal generation is associated with variations in the river discharge. Subtidal motions can develop upstream as a function of subtidal river discharge pulses and propagate downstream increasing the local sea level elevations (Jay et al., 2015). These river subtidal elevations decrease in amplitude with increasing distance downstream owing to increasing cross-sectional area downstream associated with the convergent estuary. The river subtidal pulses interact with the incoming ocean-forced subtidal elevations and tides.

Third, subtidal motions have been shown to develop from oceanic remote forcing owing to coastal set-up from wind-induced downwelling events (Garvine, 1985; Wong, 2002; Wong and Garvine, 1984; Jay et al., 2015). During downwelling favorable wind stress, the onshore component of the Ekman transport (Ekman, 1905) induces a coastal set-up along the coastline (Lentz and Fewings, 2012). The elevation set-up at the mouth of the estuary is then transmitted into the estuary (Garvine, 1985). Downwelling favorable wind stresses are typically associated with synoptic weather systems, and the temporal duration of sea surface elevation set-up is O (days) that repeats with each passing storm system. These elevations are referred to as remote oceanic-forced subtidal motions. Oceanic subtidal motions have been observed in estuaries along the east coast of the US (Janzen and Wong, 1998, 2002; MacMahan et al., 2014), the North Sea (Buijsman and Ridderinkhof, 2007), and other locations throughout the world.

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Most of these estuaries are associated with low-river discharge. Jay et al. (2015) noted that the relative influence of the coastal upwelling and downwelling was most important in the lower part of the CRE, Columbia River Estuary. There are few studies that have explored the oceanic subtidal motions in convergent estuaries with high river discharge.

Here, observations are used specifically for describing the generation of remote oceanic-forced subtidal elevations along the coast via downwelling events and their propagation into the strong river-tide CRE. NOAA-NOS has a network of tidal stations located in PNW (Pacific Northwest) estuaries and throughout the CRE. NOAA also computes Coastal Upwelling Indices (CUI) at latitudes for the west coast of North America (Fig. 1). Jay et al. (2015) described the origin and attenuation of the elevations at various temporal scales, including overtides, semi-diurnal, diurnal, fortnightly, monthly, and seasonal variations in the CRE. In general, the signals that originated from the ocean were found to decrease with increasing distance upstream due to strong river flow friction (Jay, 1991). River signals were found to decrease with increasing distance downstream owing to increasing cross-sectional area associated with channel divergence. The monthly tidal signal was found to increase with increasing distance upstream caused by river-tide interactions of the spring-neap tidal modulation (LeBlond, 1979; Godin and Martinez, 1994; Buschman et al., 2009). There are seasonal and event-scale upwelling and downwelling along the PNW composed of Washington, Oregon, and Northern California (Lentz, 1992; Allen et al., 1995; Allen and Newberger, 1996; Hickey and Banas, 2003; amongst others). The PNW includes the CRE. The winds are typically to the southward during fair weather conditions and northward during storm systems that are favorable to downwelling events (Hickey and Banas, 2003). The interest here is in whether oceanic subtidal elevations propagate upstream in a convergent river-estuary and whether there is any decay in their amplitude.

2. Observations

Hourly water level elevations were obtained from the NOAA-NOS tidal stations located in estuaries along the west coast from northern California to northern Washington and throughout the CRE (http://tidesandcurrents.noaa.gov). The along-coast NOAA-NOS stations used herein are Arena Cove, CA (AC), Crescent City, CA (CC), Port Orford, OR (PO), South Beach, OR (SB), Toke Point, WA

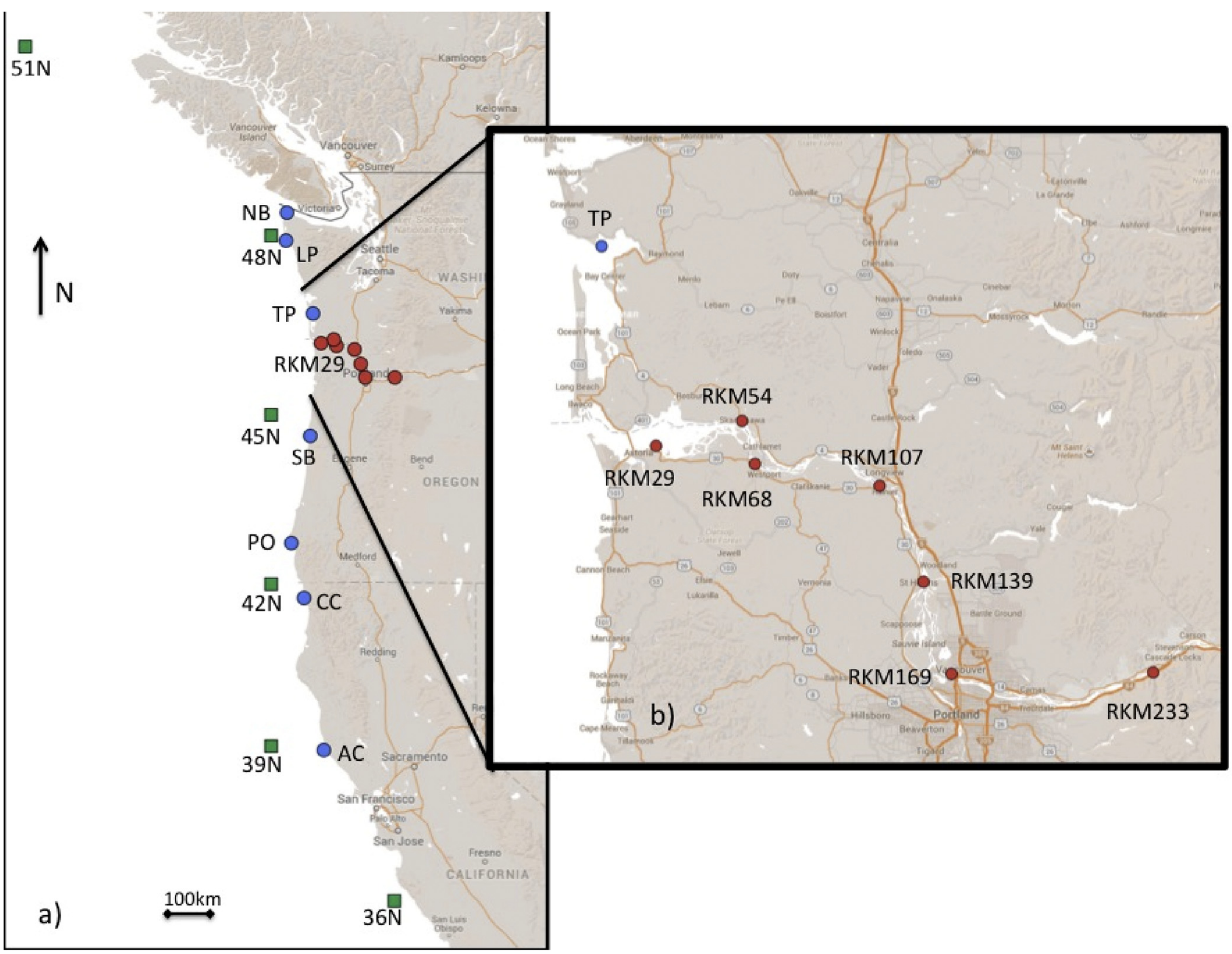

Fig. 1. a) Location map for NOAA tidal stations and USGS gage stations along the coast (blue circles) and in the Columbia River Estuary (CRE) (red circles). Locations for Coastal Upwelling Indices for 36N, 39N, 42N, 45N, 48N, and 51N are provided as green squares. Coastal stations include Arena Cove, CA (AC); Crescent City, CA (CC); Port Orford, OR (PO); South Beach, OR (SB); Astoria, OR (RKM29); Toke Point, WA (TP); La Push, WA (LP); and Neah Bay, WA (NB). b) Focused maps of CRE stations include Toke Point, WA (TP); Astoria, OR (RKM29); Skamokawa, WA (RKM54); Wauna, OR (RKM68); Longville, OR (RKM107), St. Helens, OR (RKM139), Vancouver, WA (RKM169), and Bonneville Dam (RKM233).