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Dynamics of wind-driven estuarine-shelf exchange in the Narragansett Bay estuary

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ABSTRACT

Physical exchange between estuarine and continental shelf waters impacts flushing dynamics of the estuary and determines rates of ocean inputs of nutrients and plankton. To investigate the occurrence and propagation of shelf water intrusions into the Narragansett Bay estuary, we collected velocity data near the estuarine–shelf interface during three summer periods. These data were compared to environmental forcing factors, including wind velocity, tidal mixing and river discharge. Results suggest a background cyclonic flow within the two passages of the estuary based on mean inflow in the channel on the eastern side of the estuary and mean outflow on the western shoals. Within the lower estuary this background circulation was perturbed by channel-parallel winds. On the shelf outside of the estuary, winds parallel to the coast were associated with cross-shelf flow of deep water. Strong pulses in estuarine–shelf exchange flow fell into two wind-driven modes: responses to direct forcing by down-estuary wind or rebounds following relaxation or reversal of up-estuary wind. Rebound events were common, providing the most dramatic perturbations to the mean background estuarine circulation. A reduction in exchange between Narragansett Bay and shelf waters during prevailing up-estuary winds in the summertime and short-lived pulses in exchange flow under wind reversal events are expected to affect nutrient fluxes and dynamics of hypoxia in the estuary.

1. Introduction

The exchange between an estuary and continental shelf waters is a complex dynamical problem that influences ecosystem processes such as biogeochemical balances (Nixon et al., 1996; Jickells, 1998; Boehlert and Mundy, 1988) and larval transport (Boehlert and Mundy, 1988; Hare and Govoni, 2005; Tilburg et al., 2005). Wind influences circulation at the estuary–shelf interface on time scales of a few to several days (Weisberg and Sturges, 1976; Wang and Elliott, 1978; Klinck et al., 1982; Janzen et al., 2005). In this study, we examined the effects of wind forcing on exchange between estuary and shelf waters.

Wind is a dominant driver of flows on the continental shelf on synoptic time scales (Brink, 1998). In general, along-shelf wind stress drives cross-shelf surface Ekman transport on the shelf and development of a cross-shelf pressure gradient (Ekman, 1905; Allen, 1980; Brink, 1983). Interior geostrophic flow driven by the cross-shelf pressure gradient subsequently causes bottom Ekman transport opposing the surface layer transport (Allen, 1980; Weisberg et al., 2000). This balance evolves in response to the onset of wind over the course of a few inertial periods in numerical models (Li and Weisberg, 1999a; Austin and Lentz, 2002). In the inner shelf, defined alternatively as water depths where surface and bottom Ekman layers overlap (Lentz, 1995) or where bottom stress balances the bottom pressure torque due to cross-isobath flow (Weisberg et al., 2001), cross-shelf wind stress also becomes an important driver of cross-shelf transport (Li and Weisberg, 1999b; Fewings et al., 2008). Density stratification alters the cross-shelf structure and magnitude of the wind response by reducing boundary layer thicknesses, which both shifts the location of surface divergence into shallower water and strengthens the cross-shelf transports (Weisberg et al., 2000; Lentz, 2001; Austin and Lentz, 2002). The wind response may also be modified by bathymetric features that cause spatial heterogeneity in the strength of upwelling and downwelling along the coast (Brink, 1983; Weisberg et al., 2001; Castelao and Barth, 2005) and other along-shelf variability (Brink, 1991).

Estuarine circulation was traditionally viewed as a balance of the along-channel baroclinic pressure gradient and vertical mixing (Pritchard, 1956; Hansen and Rattray, 1965), but these flows are also modified by wind forcing (Weisberg, 1976; Weisberg and

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Sturges, 1976). In the simple case of a narrow, laterally-uniform channel, the component of wind blowing along the axis of the channel drives near-surface water in a down-wind direction and the resulting sea surface gradient drives deeper waters up-wind (Bowden, 1953; Csanady, 1973). Observations support this basic pattern of wind-driven circulation (Pape and Garvine, 1982; Geyer, 1997; Janzen et al., 2005). Because the background gravitational circulation results in surface outflow and bottom inflow, a down-estuary wind enhances estuarine circulation and up-estuary wind stalls or reverses this background flow (Weisberg, 1976; Weisberg and Sturges, 1976).

Many estuaries are not narrow, rectangular channels, so it is important to consider how topography and rotation modify currents across an estuary. Wong (1994) developed an analytical model that extended Pritchard's (1956) momentum balances to a simple case of a channel with a triangular cross-section. Even without the influence of rotation, the model predicts that the saltier inflow from the shelf extends throughout the water column in the deepest part of the channel and the fresher outflow shifts to the shallower sides (Wong, 1994). A similar distribution of currents and salinity is observed in estuaries with approximately triangular cross sections such as Delaware Bay (Wong and Munchow, 1995) and Chesapeake Bay (Valle-Levinson and Lwiza, 1995). In estuaries with a deep channel flanked by shoals, observations and numerical models show that the wind-driven component of flow is down-wind on the shoals and up-wind in the channel (Wong, 1994; Valle-Levinson et al., 1998; Weisberg and Zheng, 2006; Narvaez and Valle-Levinson, 2008). Numerical modeling studies also demonstrate an influence of cross-channel circulation on along-channel momentum by an interaction of tides, stratification and rotation (Lerczak and Geyer, 2004; Scully et al., 2009; Li and Li, 2011, 2012). The net effect of tidal rectification and rotation is to tilt the deep inflow to the right (looking up-estuary in the Northern Hemisphere) and the outflow to the left (Huijts et al., 2009; MacCready and Geyer, 2010).

Wind also remotely influences estuary–shelf exchange by setting up sea surface elevation gradients. Through Ekman transport, an along-shelf wind that is upwelling-favorable will lower the sea level on the shelf and a downwelling-favorable wind will raise the shelf sea level relative to the estuary. The sea level gradient may then drive a barotropic response through the estuary mouth, such that upwelling conditions increase outflow and downwelling conditions increase inflow into the estuary (Wang and Elliott, 1978; Wang, 1979; Klinck et al., 1982; Wong and Valle-Levinson, 2002). There are conflicting observational and modeling results regarding the relative importance of direct and remote effects of wind on estuarine exchange. Two hydrodynamic models of estuary–shelf exchange suggest a dominant influence of remote effects by along-shelf wind forcing (Klinck et al., 1982; Garvine, 1985). Field data and an analytical model of Delaware Bay showed that currents driven by local wind forcing are up to an order of magnitude stronger than remotely-forced currents (Janzen and Wong, 2002). Observations in Chesapeake Bay, however, revealed a similar forcing magnitude between remote and local wind during strong density stratification, but remote winds dominated over local winds during periods of weak stratification (Wong and Valle-Levinson, 2002).

Here, observations of currents on the shelf and inside the lower portion of the partially-mixed Narragansett Bay estuary were used to assess the influence of wind on subtidal estuary–shelf exchange. Observations were analyzed to address three questions. First, what are the mean circulation patterns near the estuary–shelf interface of a partially-mixed estuary with complex geometry? Second, does wind forcing explain large, short-lived estuary–shelf exchange events observed in the data? Third, what are the potential impacts of the estuary–shelf exchange events on circulation and ecological processes in the estuary?

2. Study site

Narragansett Bay is a partially-to well-mixed estuary on the southern New England coastline (Fig. 1). The mid-to-lower portion of the estuary is divided into two channels with distinct topography, known as the West and East Passages. The West Passage is 4–14 km wide and 6–16 m deep, while the East Passage is slightly narrower (3–10 km) and deeper (16–48 m). Both passages have north–south trending channels flanked by a shoal on the western side. A third passage east of the East Passage, Sakonnet River, is connected by a narrow constriction that limits exchange with the rest of the bay (DeLeo, 2001) and was not included in this study. The internal Rossby radius of both the West and East passages are nearly equal to the width of each channel during the summer (Kincaid et al., 2003), making the Kelvin number ≥ 1 and indicating an importance of rotational effects.

Narragansett Bay receives water from several rivers that pass through industrialized areas. Surface freshwater input to the estuary typically ranges from 150–300 $m^3\,s^{-1}$ in the late spring to 40–65 $m^3\,s^{-1}$ in the late summer (Pilson, 1985). The estuary has fairly weak vertical stratification, with surface-to-bottom salinity differences typically less than 2 psu (Pilson, 1985) and thermal stratification appearing only in May through July (Hicks, 1959). Horizontally, the East Passage has higher salinity that the West Passage in both surface and bottom waters (Hicks, 1959). A strong influence of wind forcing on current velocities within Narragansett Bay has been reported by observational (Weisberg, 1976; Weisberg and Sturges, 1976; Kincaid et al., 2008) and modeling (Gordon and Spaulding, 1987; Bergondo, 2004; Rogers, 2008) studies. Previous shipboard surveys identified a persistent inflow on the eastern side of the East Passage and a persistent outflow on the western side of the West Passage (Kincaid et al., 2003).

Rhode Island Sound is the inner continental shelf adjacent to Narragansett Bay and bordered on the seaward side by Block Island, Rhode Island and Martha's Vineyard, Massachusetts. The depth of Rhode Island Sound has a range of 30–40 m. The inner portion of the sound has open boundaries to the south and east, but the coastline bends nearly 90° toward the south on the western side of the entrance to Narragansett Bay (Fig. 1). Rhode Island Sound is typically stratified in June through mid-September, with most of the density stratification due to a strong thermal gradient (Shonting and Cook, 1970; Rosenberger, 2001). Prior investigations suggest that summertime near-surface flow in inner Rhode Island Sound is typically west to southwestward and bottom flow is weaker and more variable (Shonting, 1969; Rosenberger, 2001; Kincaid et al., 2003).

3. Materials and methods

3.1. Data collection and processing

Time series of velocity and bottom temperature were collected by upward-looking RD Instruments Acoustic Doppler Current Profilers (ADCPs) in the late spring to summer of 2000, 2007 and 2008 (Table 1). ADCP moorings spanned the area from the inner shelf south of the estuary mouth to the mid-estuary (Fig. 1). The velocity records collected at three of the stations (SHN, EPL, WPL) in 2000 have been previously described by Rosenberger (2001) and Kincaid et al. (2008). We included these data in our analysis to extend the spatial coverage of time series information. Data collected in May–July 2000 covered the inner shelf and both passages of the lower estuary simultaneously (Table 1). The shelf mooring