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ScienceDirect
Continental Shelf Research 27 (2007) 103–116
CONTINENTAL SHELF RESEARCH
www.elsevier.com/locate/csr

Residual circulation in eastern Long Island Sound: Observed transverse-vertical structure and exchange transport

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Received 8 April 2005; received in revised form 3 June 2006; accepted 8 September 2006
Available online 31 October 2006

Abstract

Residual currents in eastern Long Island Sound (LIS) are investigated using direct velocity measurements from an acoustic Doppler current profiler mounted on a ferry. Circulation at the site has major influence on exchange of water and water-borne materials between LIS and the coastal ocean. Ferry sampling enables sufficient averaging to isolate the residual motion from stronger tidal currents, and captures its spatial structure. Mean along-estuary currents based on about 2 years of sampling reveal a vigorous estuarine exchange circulation (peak 25–30 $cm\,s^{-1}$ at depth), with flow eastward out of the estuary in the upper water column of the southern half and inward westward movement strengthening with depth over the central and north section. Application of volume conservation implies there is a strong eastward current out of the estuary in the shallowest 7 m where no measurements were made, as expected for estuarine exchange flow. Water from the Connecticut River, entering LIS on the north shore nearby to the west, does not appear to exit the estuary directly eastward along the north shore unless this occurs wholly in the shallow layer not sampled. Transverse currents have complex structure with generally northward (southward) flow where shallow outward (deep inward) motion occurs. An idealized semi-analytic solution for transverse-vertical structure of along- and across-estuary flow has limited success accounting for observed currents, despite inclusion of bathymetric, frictional, and rotational influences; this suggests the importance in LIS of dynamics it omits, in particular stratification, or does not represent with sufficient realism, such as complex bathymetry. Estimated annual-mean exchange volume transport, based on the better-sampled deep inward component, is $22{,}700 \pm 5000\,m^3\,s^{-1}$. This is comparable to previous estimates from some salt budget and hydrographic analyses, and implies advection contributes substantially to the total salt transport, contrary to results of a recent box-model analysis of hydrographic measurements. At seasonal timescales, changes to the transverse-vertical velocity structure are modest, but amplitude variations cause exchange volume transport increases (decreases) to $30{,}000\,m^3\,s^{-1}$ ($18{,}000\,m^3\,s^{-1}$) in the summer (winter) months; a power-law dependence of exchange on river flow, as seen in other estuaries, is not supported. Strengthened summer transport is associated with enhanced stratification, suggesting that mixing effects modulate the exchange. To the extent that advection by residual flow contributes to total exchange between LIS and coastal waters, the flushing of materials from LIS should occur substantially faster in summer than in winter.

Keywords: Estuarine dynamics; Residual flow; Current profiles; Transport processes

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0278-4343/$ - see front matter
doi:10.1016/j.csr.2006.09.001

1. Introduction

Exchanges with the coastal ocean strongly shape estuary attributes such as salinity distributions and water quality. Exchange is generally divided into (1) advective transport tied to the residual circulation (mean currents and flow variations at sub-tidal frequencies), and (2) dispersive transport, due mainly to mixing by tidal motions. While residual currents are often weaker than tidal flow, their persistent advection can dominate total transport. Yet residual flow is typically poorly known, for lack of observations: sampling requirements to overcome aliasing by strong tidal currents are demanding.

The focus here is observed residual circulation and volume transport in a major urban estuary, the Long Island Sound (LIS; Fig. 1), near its eastern end where exchange with the coastal ocean is strongest. As in many estuaries impacted by anthropogenic activities, a motivation is to improve understanding of circulation impacts on water quality, including hypoxia. Sampling demands for residual flow are met through use of a commercial passenger ferry transiting the estuary laterally, nominally eight times daily year-round. (More information on the FOSTER-LIS (Ferry-based Observations for Science Targeting Estuarine Research in Long Island Sound) project, and downloadable data, is provided at www.gso.uri.edu/foster.) Similar methods are being applied at a number of other locations worldwide (e.g., Rossby and Gottlieb, 1998; Ridderinkhof et al., 2002). Here, almost 2 years of acoustic Doppler current profiler (ADCP) velocity transects are analyzed. Variability at timescales shorter than 2 months, such as tidal and weather-band currents, will be taken up separately and is not addressed.

Baseline understanding of the LIS salt budget, hydrography, and circulation is established (e.g., Riley, 1952, 1967; Wilson, 1976; Koppelman et al., 1976; Kaputa and Olsen, 2000; Signell et al., 2000; Viera, 2000). LIS is ~160 km long and ~15–30 km wide, with average depth 21 m and depth range ~10–90 m. It communicates with the ocean at its western end via the East River, a tidal strait to New York Harbor, and at its eastern end via Block Island Sound. The salt budget is dominated by transports at these two sites and fresh water delivered by rivers to the north shore, with evaporation–precipitation imbalance and groundwater flow considered much more minor. Both salinity and temperature are important to vertical density differences, which are about 0.25–0.5 $kg\,m^{-3}$ (1.0–1.5 $kg\,m^{-3}$) in winter (summer) in eastern LIS. Residual flow of fresher near-surface water outward to the east, and saltier water inward to the west at depth, has been identified as gravitational circulation and generally strengthens eastward. Associated volume transport, though poorly known, far exceeds river inputs.

There remain major gaps in understanding of eastern LIS residual flow, for which field data are limited (Viera, 2000 discusses historical efforts and presents one of the most complete datasets). The width constricts to ~15 km and flow negotiates a complex geometry of islands and narrow deep channels. Typical amplitudes of tidal currents, effectively an antinode of a nearly resonant basin-wide standing wave response, are 80–100 $cm\,s^{-1}$ or more. Residual flow dynamics are thus impacted by bathymetry and friction in addition to Coriolis. Basic questions persist, such as the extent to which outward flow concentrates on the north shore where the dominant freshwater input of the Connecticut River enters, as opposed to the south as expected from Coriolis influences.

Numerous estimates of exchange volume transport through eastern LIS appear in the literature. Nearly all are based on salt balances or hydrography, owing to a lack of velocity data. Results vary widely and are highly uncertain. A purely advective two-layer frictionless Knudsen balance approach (Riley, 1952) resulted in exchange of ~8000 $m^3\,s^{-1}$, and was revised, using limited data for currents with ad-hoc assumptions about their vertical structure, to ~18,000 $m^3\,s^{-1}$ (Riley, 1956). A diffusive salt balance implied volume exchange varied from 9000 to 60,000 $m^3\,s^{-1}$, was stronger (weaker) in summer (spring), and averaged ~25,000 $m^3\,s^{-1}$ (Riley, 1967). Analysis of gravitational circulation indicated ~30,000 $m^3\,s^{-1}$ (Wilson, 1976). A modified box model using several years of modern CTD data (Gay et al., 2004) yielded ~4000–8000 $m^3\,s^{-1}$, from which it was concluded that only a small fraction of total salt transport was advective.

In this paper, the transverse-vertical structure of both along-estuary and across-estuary residual currents in eastern LIS is described using the most comprehensive velocity observations collected to date. Then an idealized semi-analytical solution for transverse-vertical structure of estuarine exchange flow (Kasai et al., 2000; Valle-Levinson et al., 2003), chosen for its inclusion of bathymetric, frictional,