Circulation in Block Island Sound, Rhode Island Sound, and Adjacent Waters, with Emphasis on Subsurface Flows

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EXECUTIVE SUMMARY

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Abstract

Subsurface flows in sounds, such as Block Island Sound (BIS) and Rhode Island Sound (RIS), can be shaped by the three main coastal/estuarine circulation influences (buoyancy, tides, and winds) through several key processes. The extent to which subsurface circulation decouples (e.g., differs sharply in strength &/ direction) from the surface flow is largely determined by density stratification and thus strongly controlled by buoyancy inputs (river runoff, precipitation, and air/sea heat exchange). A second prominent influence of buoyancy is through river inputs to estuaries lying at the boundaries of a sound, which can drive bi-directional estuary-sound exchange flows (factors of 10+ stronger than the river flow) with a deeper up-estuary limb that can have substantial impact on subsurface circulation throughout the sound. Tidal currents across complex bathymetry drive local vertical turbulence, such that where the water depth is shallow enough &/ the tidal current strong enough, the potential strength and persistence of stratification becomes sharply limited. Tidal mixing fronts delineate shallower areas, which are more likely to be well-mixed, from deeper areas, where stronger stratification can persist and hence subsurface flow can be more independent from surface currents. Winds also drive vertical mixing, so winter storm activity can mean stratification is limited to summertime. Interaction of wind-driven flow with coastal boundaries generally yields oppositely-directed, coast-perpendicular, subsurface motion.

The BIS/RIS system is open to the shelf to the south and bounded at the west by the Long Island Sound (LIS) estuary, at the north by the Narragansett Bay estuary (NB), to the northeast by Buzzards Bay (BB), and to the east by the Vineyard Sound (VS) and Nantucket Sound (NS). Available observations suitable to address the long-term mean, non-tidal volume transport pathways have been reviewed to compile an overall budget for the system, with emphasis on the subsurface component. RIS is the most poorly sampled and understood, particularly its subsurface flow and its eastern portion. While deeper flow throughout RIS can apparently decouple from surface motions, particularly in summer when storm activity weakens, in VS/NS and in large portions of BIS the tidal currents make this less likely. The seasonal cycle of surface heating, and the river inputs to LIS (annual-mean ~0.8 units, using unit 1,000 m^3/s volume transport) and NB (~0.1 units), are the dominant buoyancy inputs. Available evidence suggests that (a) the deep inward limb of LIS exchange flow (annual-mean ~23 units; some ~10 times that of NB) plays a key role in driving deep flow throughout BIS/RIS; (b) deep transport in to BIS from the east (between Point Judith and Block Island) may be substantial (up to 20+ units in summer) and likely exceeds that from the south (between Montauk and Block Island); and (c) a coastal current likely flows nearly along isobaths northwestward in to Eastern RIS from the Nantucket Shoals area, serving as the source of most water throughout the region, with its deeper portion moving largely westward to BIS while its near-surface portion exits Western RIS southward and joins the LIS surface outflow in forming the coastal flow (~50 units) continuing toward the southwest. In this context, it can be argued that BIS and Western RIS should be viewed primarily as an extension of the LIS estuary.

Processes

The focus here is long-term (annual or seasonal) mean circulation, with emphasis on the subsurface component. Most generally, the likelihood that such currents will have strong vertical shear, and hence that subsurface flow can differ substantially in strength and direction from shallow circulation, increases with strong density stratification. Buoyancy forcing (inputs of fresher water by river discharge and/or precipitation; heating/cooling by air-sea exchanges) thus has a fundamental impact on subsurface flow through its influence on stratification. A second essential means by which buoyancy forcing can drive subsurface mean flow in a sound is through bi-directional estuarine exchange flow, which causes strong deep flow toward an adjacent estuary (Fig. 1); volume transport of such deep flow is commonly at least an order of magnitude larger than collective river inputs within the estuary. Tidal currents play an important role by driving turbulence which influences where stratification is unlikely to persist (Fig. 2). In shallow areas, tidal currents tend to be amplified and the associated turbulence can preclude sustained presence of a pycnocline; boundaries of such regions are commonly marked by a tidal mixing front. On the deeper stratified side of such boundaries the subsurface mean flow is more likely to be independent in strength and orientation from the shallower currents.

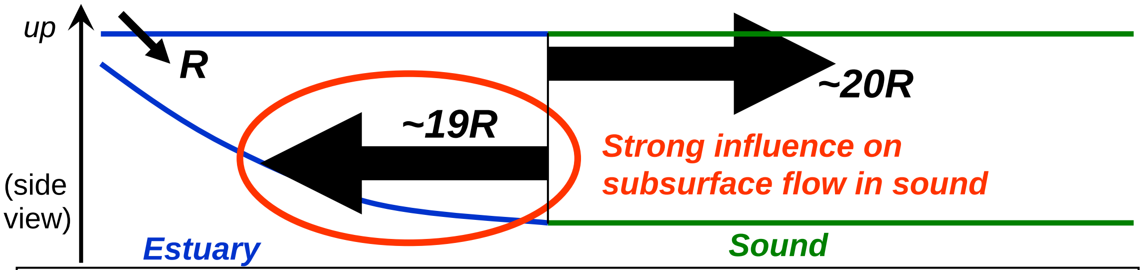

Fig. 1. The deep limb of bi-directional exchange flow with an adjacent estuary, driven by smaller river inputs R, can strongly control subsurface flow in a sound.

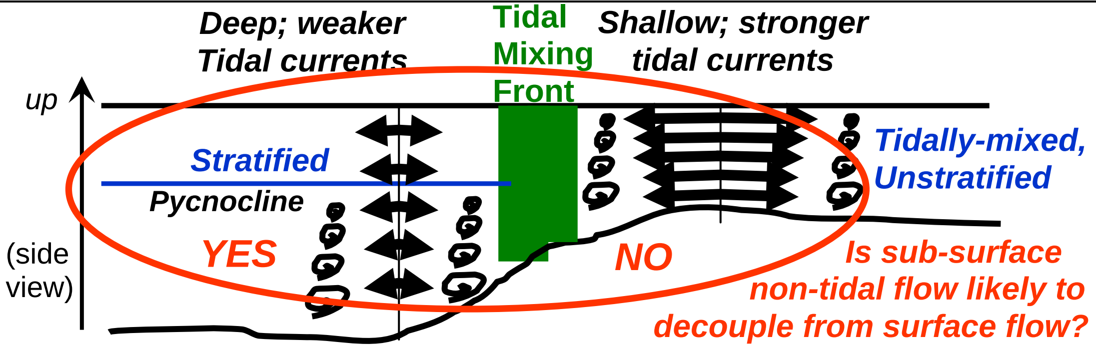

Fig. 2. Geographic variation in bathymetry and tidal flow (arrows) causes regions where (i) stratification can or cannot withstand tidally-driven turbulence, and (ii) non-tidal subsurface and shallow flows (neither shown) tend to decouple or not.

The BIS/RIS Region

Rivers flowing in to LIS dominate fresh water input to the BIS/RIS region. Collectively they amount to ~0.8 units (where throughout this discussion the unit is 1000 m^3/s) on an annual-mean basis (see, e.g, Codiga, 2005). The next most important source is the river inputs to NB, at ~0.1 units (see, e.g., Kincaid et al., 2003). River flow to BB and VS/NS is substantially smaller, and groundwater sources, though poorly known, are considered of relatively minor importance.

Based on observation-tested modeling studies (e.g., Edwards, 2004; He and Wilkin, 2006; Mau et al., 2006), tidal flow in the region is reasonably well-known. The regional bathymetry and near-resonant response of LIS to the M_2 constituent cause dramatic amplification of tidal currents, compared to those of RIS, in shallow regions of BIS and throughout VS/NS. The empirical "U^3/H" criterion (Simpson and Hunter, 1974) for the location of tidal mixing fronts is an imperfect but useful guide and has been applied in BIS and western RIS (Edwards, 2004a) as well as eastern RIS and VS/NS (He and Wilkin, 2006). Results suggest a strong pycnocline will be more likely to persist in RIS and northeastern portions of BIS than in other inshore areas.

There are few published direct current observations of sufficient duration to estimate the long-term mean circulation of the region; it is important to note that no such measurements exist for most of central and eastern RIS. All available data suitable to estimate volume transports, crudely broken in to shallow and deep components where possible, are summarized in Fig. 3.

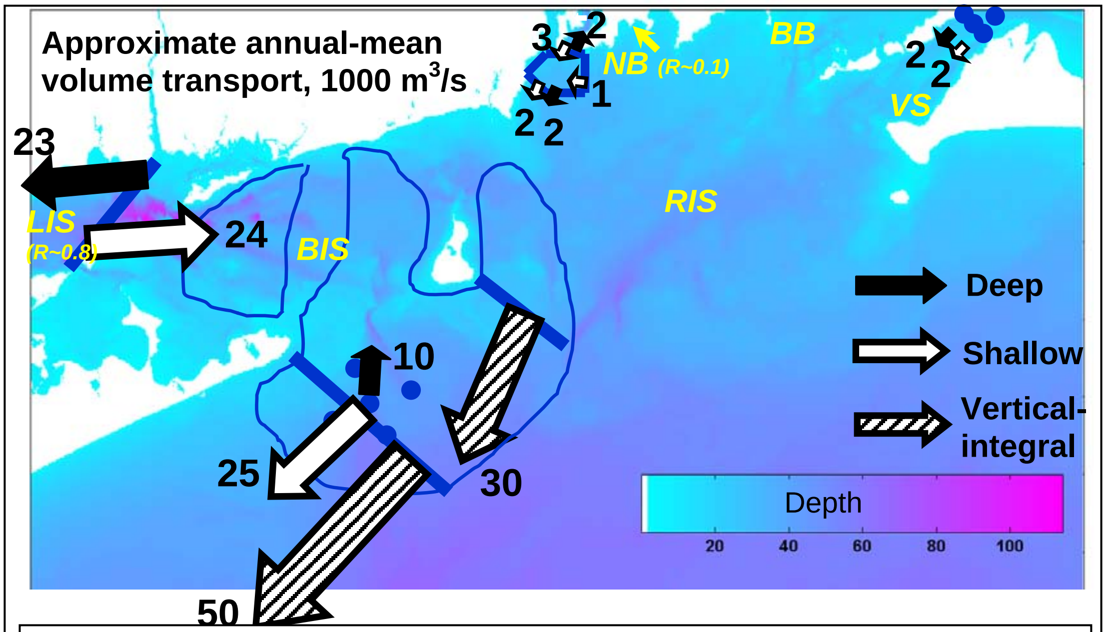

Fig. 3. Approximate annual-mean circulation based on all available observations having adequate temporal coverage to estimate multi-season long-term mean flow. Divided among deep and shallow components where possible. See text.

The exchange circulation in eastern LIS, based on Acoustic Doppler current profiler (ADCP) measurements from about two years of ~8-times daily ferry crossings (Codiga and Aurin, 2007), includes a strong deep inward flow limb (~23 units) that emerges as a primary influence on the subsurface circulation in RIS. The flow on the inner shelf to the south of BIS, examined using ~2.5 years of ADCP records from a bottom-mount array spanning an area 10-15 km across (Codiga, 2005), includes a shallow coastal current southwestward (~25 units) and a weaker deep flow eastward and inshore (~10 units). Multiple years of surface current measurements covering BIS and eastern RIS (areas outlined in blue on Fig. 3), collected by HF radar (Ullman and Codiga, 2004), have been combined with the moored ADCP records to estimate vertically-integrated transport across two transects (blue lines, Fig. 3). The result suggests the vertically-integrated transport through the ~25-30 km transect spanning the narrower moored array site carries ~50 units. The origin of this flow appears to be a combination of the ~30 units vertically-integrated transport south and east of Block Island, estimated similarly using the HF radar data, and the shallow flow out of eastern LIS. In the northwest corner of RIS, vessel-based ADCP data was collected during a series of research cruises along a survey pattern designed to capture exchange between NB and RIS (Kincaid et al., 2003). Based on their Fig. 7, which divides shallow and deep flow unlike their Fig. 6, it appears that annual mean flows in this vicinity carry 1-3 units. Exchange between BB and RIS has been omitted from Fig. 3 because it is thought to be weak, based on early analysis and modeling (Signell, 1987), and I am not aware of more recent observation-oriented analyses. Finally, a series of multi-month moored current meter deployments have been completed recently in VS (Beardsley et al., 2007). Transports estimated from them are highly uncertain but are approximated at 4 units westward from VS toward RIS, which is shown on Fig. 3 as 2 units in each layer.

There are marked seasonal shifts in the flow. Fig. 4 depicts late spring and summer conditions, along with recent vessel-based ADCP data collected along a transect spanning RIS from the RV Endeavor during a several-day cruise in summer 2006 (C. Kincaid, Pers. Comm.). Summer is when peak strength is taken by the estuarine exchange flow in eastern LIS (Codiga and Aurin, 2007) as well as the coastal jet off of Block Island (Ullman and Codiga, 2004).

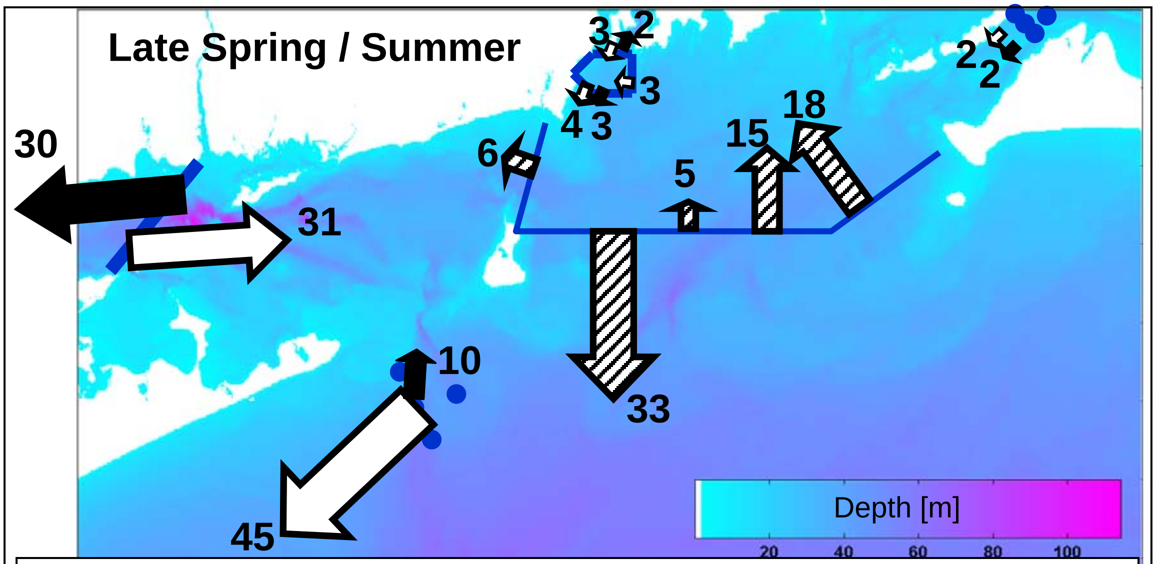

Fig. 4. As Fig. 3, except (i) values are adjusted (where possible) to reflect conditions in late Spring / Summer (as opposed to the annual mean), and (ii) recent summer R/V Endeavor research cruise results from RIS have been included.

A hypothesized schematic for the annual-mean circulation throughout the region (Fig. 5) has been constructed based on Figs. 3 and 4. The subsurface flow is shaped more strongly by the deep westward motion into eastern LIS than any other factor. The first main hypothesis that emerges from the schematic is that there exists a substantial deep flow moving westward from RIS to BIS between Block Island and Point Judith. In the summer, the combined transport through this eastern-BIS gap, with that through the southern-BIS gap between Montauk Point and Block Island, must reach ~30 units. It can be expected that this deep flow will occur predominantly via the eastern-BIS gap (for example, ~20+ units in summer) because it has a broader and deeper bathymetric cross-section, and has weaker tidal currents so is more likely to be stratified, as compared to the southern-BIS gap. It is difficult to know the extent to which the RV Endeavor cruise results (Fig. 4) support the presence of such a strong deep westward motion, since they are vertically-integrated, and are also not necessarily from a long enough period of time to give confidence they are representative of the long-term mean. In historical bottom drifter studies, there is strong evidence for a persistent deep westward flow north of Block Island (Cook, 1966), particularly in spring and summer. There is some support for the view that BIS and eastern RIS are mainly functioning as extensions of the LIS estuarine system: their shallow flow is dominantly outward from LIS, concentrated toward the south, and veering southward to feed the southwestward coastal current; their deep flow is dominated by an opposing westward flow apparently concentrated to the north. The second main hypothesis that emerges from Fig. 5 is that waters throughout the BIS/RIS region and its adjacent estuaries and sounds—both deep and

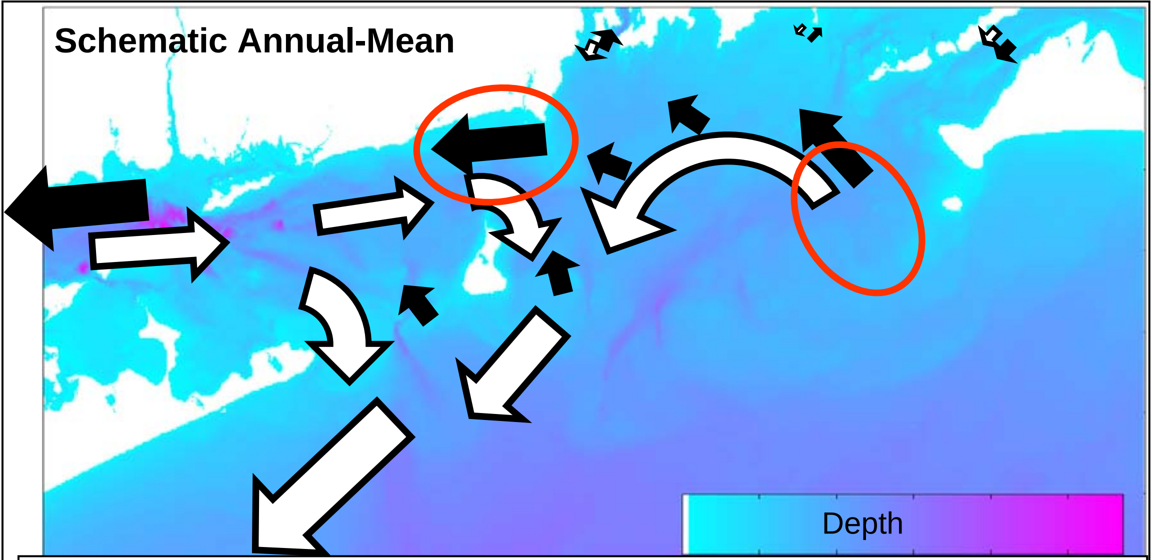

Fig. 5. Schematic based on Figs. 3 & 4. Key hypotheses (red ovals): (a) a sizable deep transport westward north of Block Island, and (b) primary origin of both deep and shallow waters throughout system is northwestward flow in to eastern RIS.

shallow—originate predominantly from a northwestward coastal current flowing in to the eastern portion of RIS from the Nantucket Shoals area.

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