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On the salt balance of Tampa Bay

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ABSTRACT

A three-dimensional, numerical circulation model, with resolution as high as 20 m at important mass conveyances (inlets, channels, bridge causeways, and rivers), is used to diagnose the point by point salt balances for Tampa Bay, FL. While the details of the salt flux divergences and the salt fluxes vary throughout the bay, each is fully three dimensional. On experimental duration (three month) average, the total (horizontal plus vertical) advective salt flux divergence is mainly balanced by the vertical diffusive salt flux divergence, except near the bottom of the deep shipping channel, where horizontal diffusive salt flux divergence is also important. Instantaneously, the local rate of change of salinity is primarily controlled by the advective salt flux divergence, with a secondary contribution by the vertical diffusive salt flux divergence everywhere and the horizontal diffusive salt flux divergence near the channel bottom. To examine the role of tidal pumping, the advective salt fluxes and divergences are further decomposed into the products of the mean salinity and velocity, and the correlation between the salinity and velocity fluctuations. The horizontal and vertical advective salt flux divergences by the mean quantities are equally large and counterbalancing (by continuity), with their sum being a small, but significant residual. The horizontal and vertical advective salt flux divergences due to tidal pumping are relatively small (when compared with the mean quantities) and counterbalancing; but, when summed their residual is comparable in magnitude to that by the mean quantities. So whereas the salt fluxes by tidal pumping are of secondary importance to the salt fluxes by the mean quantities, their total flux divergences are of comparable importance. The salt flux components in all three dimensions (axial, transverse and vertical) themselves vary along the Tampa Bay axis, and these findings may be typical of coastal plain estuaries given their geometrical complexities. Being that the distribution of salt flux bears upon the flux distributions of other scalars (e.g., nutrients, fish larvae, etc.) our findings for salt flux also have broader ecological implications.

1. Introduction

Tampa Bay is a partial to well-mixed estuary located on Florida's west coast. From the Gulf of Mexico at its mouth, the bay extends inland by about 56 km, and it consists of four major segments (Fig. 1): Old Tampa Bay, Hillsborough Bay and Middle and Lower Tampa Bay, each with widths ranging from 8 km to 16 km. The area weighed average depth of Tampa Bay is about 3–4 m, with deeper shipping channels maintained at about 12 m. Fresh water inflows are by four principal rivers, the Hillsborough, Alafia, Manatee, and Little Manatee rivers, with annually averaged discharge rates of about 15 $m^3 s^{-1}$, 13 $m^3 s^{-1}$, 10 $m^3 s^{-1}$, and 6 $m^3 s^{-1}$, respectively, plus numerous other fresh water sources of lesser magnitude (e.g., Lewis and Estevez, 1988). Thus the Tampa Bay circulation is driven by a combination of tides, winds and gravitational convection (e.g., Galperin et al., 1991a, 1991b; Weisberg and Williams, 1991; Weisberg and Zheng, 2006; Meyers et al., 2007), which controls the distribution of salinity and other ecologically important material properties. Given the large variations in water depth and the segmented geometry, the physics associated with the material property balances are not immediately apparent. Here we consider the salt balance as the simplest of these because it is conservative.

Estuarine salt balance studies may be traced back to the James River work of Pritchard (1954). Uncles and Jordan (1979) expanded on this by decomposing the variables of velocity, salinity and water depth into their tidal averages and their variations about the tidal averages. They found that the tidal averaged residual flow, characterized by a seaward flow in the upper layer and a landward flow in the lower layer, dominated the salt transport, with the tidal pumping of salt due to the non-zero correlations between the tidal

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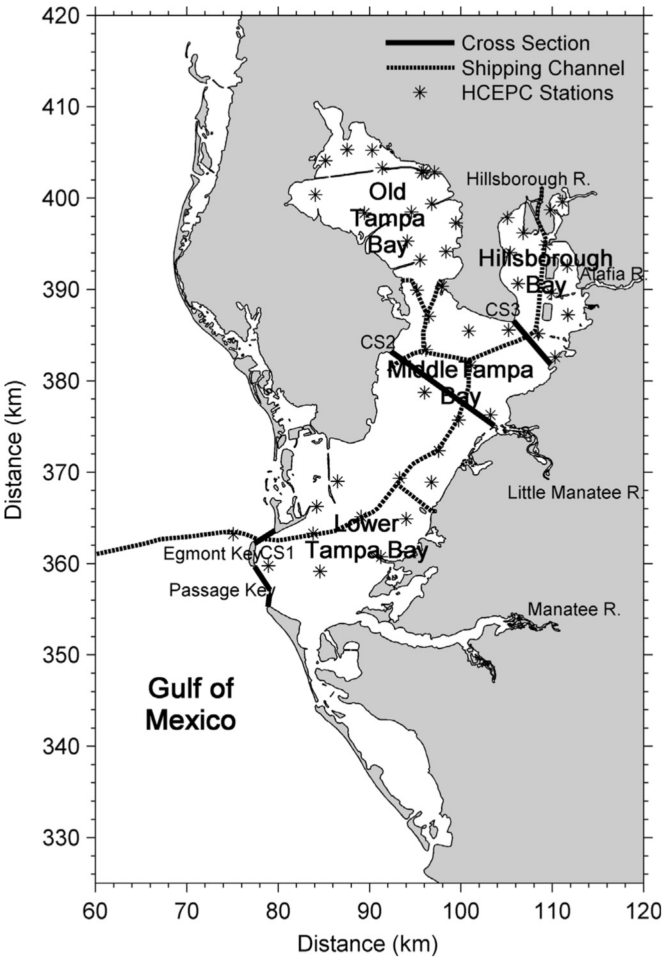

Fig. 1. Tampa Bay and vicinity. The dashed black lines are the shipping channels; the solid black lines (CS1, CS2, and CS3) are the cross sections used in later analyses. The stars are the HCEPC measured stations.

oscillations in velocity and salinity also being of importance. Similar studies were completed by Bowden and Sharaf El Din (1966a, 1966b) and Hansen and Rattray (1965). These studies, by integrating over depth or cross-section, tended to mask the vertical variations in the salt balance mechanisms, including the vertical advection of salt.

A more complicated method, further subdividing each variable into transverse and vertical components, extended the salt transport diagnoses to include the across estuarine axis direction, e.g., Dyer (1974), Dyer et al. (1992), Fischer (1976), Hughes and Rattray (1980), and Rattray and Dworski (1980). Subsequent to these, such decompositions were also applied to analyses of observations, e.g., Becker et al. (2009), Fram et al. (2007), and Lerczak et al. (2006) and model simulations, e.g., Bowen and Geyer (2003), Chen and Sanford (2009), Gong and Shen (2011), MacCready (1999), Ralston et al. (2010), Simpson et al. (2001) and Wu et al. (2010).

These studies in their composite show that estuary salt fluxes are complex, depend on tidal ranges, river inflow magnitudes, and varying bathymetry. For instance, based on velocity profile observations and a simplified frictional balance to extrapolate the flow fields to an entire cross-section, Simpson et al. (2001) found that the salt flux in a tidally energetic, well-mixed estuary is controlled by the seaward salt flux due to the river inflows and the landward salt flux by tidal pumping. In contrast, for the stratified Hudson River estuary, using 43 days of observations, Lerczak et al. (2006) found that the salt flux is mainly controlled by the mean advective and diffusive salt fluxes, except in a region of the lateral constriction where the tidal pumping is also important (Geyer and Nepf, 1996). By combining observations and model simulations for the salt wedge characterized, Merrimack River estuary, Ralston et al. (2010) found the salt flux within the deep channel to be influenced mainly by the tidal asymmetries in halocline elevation and thickness, a form of tidal pumping, whereas the mean advective salt flux was of lesser importance.

In a numerical model study of the Albemarle-Pamlico Sound, a shallow, weakly stratified lagoonal estuary, Jia and Li (2012) decomposed the salt fluxes through selected sections into three terms: sub-tidal (vertically averaged) barotropic, gravitational convection (vertically varying) baroclinic, and tidal pumping. For the inlet connecting the estuary with the inner shelf, the salt flux consisted primarily of tidal pumping (bringing salt in) and the sub-tidal barotropic salt flux (transporting salt out), whereas within the estuary the baroclinic gravitational convection tended to counteract the sub-tidal barotropic salt flux (tending to decrease salt).

All of the above studies diagnosed from one to a few cross sections, or a limited control volume; none of these considered the entire water body or the flux divergences within the water body. Investigations including the vertical salt flux and how this may apportion between the mean flow and the tidal pumping are also limited (Soltaniasl et al., 2013), and the role of turbulent diffusion and how this may apportion between horizontal and vertical contributions remains not well documented.

Studies on the mechanisms that affect Tampa Bay material property balances are particularly sparse. Circulation studies with baroclinicity (and hence estuarine circulation) include Galperin et al. (1991a, 1991b), Weisberg and Williams (1991), Vincent et al. (2000), Weisberg and Zheng (2006), Meyers et al. (2007), Zhang and Wei (2010), and Zhu et al. (2014a). Salt transport is touched upon by Weisberg and Zheng (2006), and flushing either through gravitational convection or the sum of all contributions in aggregate are addressed in Burwell et al. (2000), Weisberg and Zheng (2006), Meyers and Luther (2008) and Zhu et al. (2014b). Unlike transports and flushing based on salinity there are no prior attempts at diagnosing the salt balance for Tampa Bay.

Our paper offers a systematic, point by point, three-dimensional analysis of the Tampa Bay salt fluxes and salt flux divergences comprising the estuary-wide salt balances, including the contributions made by the horizontal and vertical advective salt flux divergences and the horizontal and vertical diffusive salt flux divergences. Our approach is similar to numerical model simulation-based analyses of momentum, e.g., Chen et al. (2001); energy, e.g., Weisberg and Zheng (2003), and temperature, e.g., He and Weisberg (2002, 2003) as applied to other water bodies. Given the non-linearity of the salt balance, we also examine how the advective salt flux divergence apportions into contributions by the experimental duration (three month) averaged mean products and the Reynolds averaged deviations about the mean (primarily due to tidal pumping) and their relative importance to the overall salt balance. Finally, being that Tampa Bay possesses geometries that are typical of the complexities found in many of nature's estuaries, we address the spatial distributions of the salt fluxes per unit area by the mean flow and the tidal pumping at selected cross sections.

The reminder of the paper is organized as follows. Section 2 describes the model and the experimental design. Section 3 defines the analyses based on the salt conservation equation. A decomposition of the advective salt flux divergence into mean and tidal pumping contributions and the three dimensional nature of the salt flux components are given in Sections 4 and 5, respectively. A summary and conclusions follow in Section 6.