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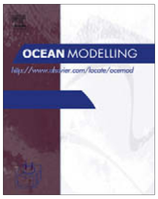

Modeling river plume dynamics with the HYbrid Coordinate Ocean Model

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ABSTRACT

The dynamics of large-scale river plumes are investigated in idealized numerical experiments using the HYbrid Coordinate Ocean Model (HYCOM). The focus of this study is to address how the development and structure of a buoyant plume are affected by the outflow properties, as impacted by processes within the estuary and at the point of discharge to the coastal basin. Changes in the outflow properties involved vertical and horizontal redistribution of the river inflow and enhanced vertical mixing inside an idealized estuary. The development of the buoyant plume was evaluated in a rectangular, *f*-plane basin with flat and sloping bottom conditions and in the absence of other external forcing. The general behavior of a mid-latitude river plume was reproduced, with the development of a surface anticyclonic bulge off the estuary mouth and a surface along-shore coastal current which flows in the direction of Kelvin wave propagation ("downstream"); the momentum balance was predominantly geostrophic. Conditions within the estuary and the outflow properties at the river mouth (where observed profiles may be available) greatly impacted the fate of riverine waters. In flat bottom conditions, larger mixing at the freshwater source enhanced the estuarine gravitational circulation, promoting larger upward entrainment and stronger outflow velocities. Although the overall geostrophic balance was maintained, estuarine mixing led to an asymmetry of the currents reaching the river mouth and to a sharp anticyclonic veering within the estuary, resulting in reduced upstream flow and enhanced downstream coastal current. These patterns were altered when the plumes evolved in the presence of a bottom slope. The anticyclonic veering of the buoyant outflow was suppressed, the offshore intrusion decreased and the recirculating bulge was displaced upstream. The sloping bottom impacts were accompanied by enhanced transport and increased downstream extent of the coastal current in most cases. No major changes in the general properties and especially the vertical structure of the plumes were observed when the vertical coordinates were changed from cartesian–isopycnal, to sigma or to sigma–isopycnal. The findings offer a benchmark for coastal studies with HYCOM, where plume dynamics should be examined in tandem with additional circulation forcing mechanisms, resulting in transitions of the vertical coordinate system that are dictated by the prevailing dynamics.

1. Introduction

The dynamics of large-scale river outflows (affected by the earth's rotation) have been widely investigated in the literature. It is acknowledged that in the absence of external forcing (such as winds, tides, and ambient currents) and if a river buoyant plume is large enough to be affected by the Coriolis force, riverine waters will turn anticyclonically when they reach the shelf, and move away from their land source as an along-shore buoyancy driven coastal current, in the direction of Kelvin wave propagation (hereafter referred to as "downstream direction"). Observations of large river plumes on open shelves such as along the US east and west coasts include: the Delaware (Münchow and Garvine, 1993a,b) and the Chesapeake (Boicourt, 1973; Marmorino and Trump, 2000) Bays, the Columbia (Hickey et al., 1998, 2005; Horner-Devine, 2009), the Hudson (Chant et al., 2008) and the Niagara (Masse and Murthy, 1992; Horner-Devine et al., 2008) Rivers, and the low salinity coastal band in the South Atlantic Bight (Blanton et al., 1994). Satellite and field studies have also shown evidence of a bulge-like region in the vicinity of the river inflow, where plume waters recirculate before feeding the coastal current (Masse and Murthy, 1992; Hickey et al., 1998; Chant et al., 2008; Horner-Devine et al., 2008; Horner-Devine, 2009). Similar behavior has also been observed in laboratory studies (Stern et al., 1982; Griffiths and Hopfinger, 1983; Whitehead and Chapman, 1986; Avicola and Huq, 2003a,b; Horner-Devine et al., 2006).

In addition to observations, numerical and analytical models have been used to understand and clarify the dynamics of coastal buoyant plumes. Many studies have been conducted in idealized scenarios. Rectangular basins were employed with simplified

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bottom topography, with buoyancy forcing only or with additional simple external forcing, such as constant and unidirectional winds, along-shore ambient current and single component tides. Such idealized studies revealed many features of river plume dynamics generally hard to extract from observations, where complex circulation forcing mechanisms impact the plume behavior. Early studies recognized the importance of non-linearity, rotation and friction in the development of the frontal structure of large buoyant discharges (Kao et al., 1977; Kao, 1981; Ikeda, 1984; Garvine, 1987). Pioneering numerical modeling studies demonstrated the impact of vertical mixing, bottom drag and sloping bottom on the spin-up, maintenance and dissipation of river-forced plumes (Chao and Boicourt, 1986; Chao, 1988a,b) as well as the coastal current variability associated with barotropic and baroclinic instabilites (Oey and Mellor, 1993). The variability of the bulge and the coastal current from a river-forced plume was also demonstrated by Kourafalou et al. (1996), who ellucidated the effects of buoyancy-induced stratification versus available mixing in determining the expansion of the bulge and the coastal current meandering.

The importance of the river mouth conditions to the variability of the bulge and coastal current transport has been reported by several studies. Yankovsky and Chapman (1997) developed a theory which relates properties of the estuarine discharge and cross-shore bottom slope to the bulge and coastal current structure. Garvine (1999) verified that the estuarine volume transport, scaled by the associated outflow geostrophic transport, controlled the greatest variance of the downshelf and across-shelf plume penetration. Fong and Geyer (2002) demonstrated that river mouth conditions affect the amount of freshwater transported by the coastal current relative to the bulge, which can accumulate low salinity waters, become unsteady and grow in time. They observed that when river outflows with larger Rossby number were simulated, more plume water recirculated within the bulge and that decreased the coastal current freshwater transport. In a series of laboratory experiments, Avicola and Huq (2003a,b) demonstrated how the ‘‘outflow angle” (angle between the outflow and the coastal wall) and the ‘‘impact angle” (angle at which the buoyant flow reattaches to the coast) affect the formation of the recirculating bulge. They suggested that the two angles are related (the outflow angle determines the impact angle) and concluded that a coastal current formed at oblique impact angles, and the bulge recirculation increased as the impact angle approached 90°. Finally, Yankovsky (2000) and Garvine (2001) demonstrated that the implementation of the river boundary conditions may affect the near-field bulge circulation, more specifically the development of the plume upstream intrusion. Kourafalou et al. (1996) showed that the upstream intrusion was due to a non-geostrophic balance between the along-shore acceleration and the along-shore pressure gradient (due to low salinity waters near the river mouth and denser ambient waters up the coast). Yankovsky (2000) suggested that the upstream intrusion is enhanced by over simplified river boundary conditions that lack a baroclinic adjustment of the discharge (i.e., fixed uniform river inflow along the coastal wall). The blocking of the lower layer landward flow at the mouth promotes a strong cyclonic vorticity disturbance with corresponding upstream turning of the buoyant flow at the source, which enhances the upstream spreading of the plume. Yankovsky (2000) and Garvine (2001) concluded that the use of an inlet flow field that better mimics that observed at the mouth of estuaries (upper seaward buoyant flow on top of a lower landward undercurrent) reduces that impact.

In the study presented herein, a ocean general circulation model is employed in an idealized estuary-coastal basin system to examine the development and evolution of a river plume under buoyancy forcing only and to investigate the plume variability associated with changes in the conditions at the river mouth. These changes are shown to be the results of lateral and vertical spreading of the river inflow and variable mixing inside the estuary. These effects are expected to impact the estuarine circulation and the buoyant outflow, ultimately promoting changes in the recirculating bulge and the coastal current properties. Previous numerical modeling studies (Chao and Boicourt, 1986; Chao, 1988a; MacCready et al., 2009) have demonstrated the importance of the estuarine circulation to the development of the river plume. The focus of the study presented herein is to understand how the properties of the buoyant flow at the estuary mouth (which reflects the coupling between the estuarine and basin circulations) impact the development of the river plume in the receiving basin.

We employ the HYbrid Coordinate Ocean Model (HYCOM; Bleck, 2002; Halliwell, 2004; Chassignet et al., 2006), which is used for the first time to investigate the dynamics of river plumes and the offshore propagation of buoyant waters. HYCOM is a state of the art community model that has been designed as a finite-difference and hybrid isopycnal–sigma–cartesian vertical coordinate ocean model with the objective to provide a flexible vertical coordinate system that is quasi-optimal in all oceanic regimes. Although initially applied on large scale, open ocean processes, the philosophy behind the flexibility in the vertical coordinate system was based on the desire to fully address coastal to offshore interactions. Our methodology includes the use of innovative parameterizations within the HYCOM code which comprise: a river parameterization option that allows enhanced downward penetration of the buoyant input and/or enhanced lateral spreading of riverine waters; adoption of different vertical mixing schemes; changes in basin topography and in the choice of vertical coordinates. This paper is organized as follows: Section 2 gives a brief description of HYCOM, the model capabilities and parameterizations for this study. Section 3 provides a description of the domain where numerical experiments are performed. Results from flat bottom and sloping bottom basins are presented in Section 4 and are followed by a discussion in Section 5. Section 6 provides a summary of the results and conclusions.

2. Model description

HYCOM is a primitive equation ocean general circulation model supported by code development and operational global/regional simulations associated with the HYCOM Consortium for Data Assimilative Modeling (see technical details in the model manual at www.hycom.org). HYCOM has been used in several large scale and marginal seas studies (Chassignet et al., 2003; Halliwell et al., 2003; Shaji et al., 2005; Kara et al., 2005; Hogan and Hurlburt, 2006; Zamudio and Hogan, 2008), and it has been recently applied to the coastal ocean as well (Kourafalou et al., 2006, 2009; Olascoaga et al., 2006; Halliwell et al., 2009). A comprehensive discussion of HYCOM’s governing equations and numerical algorithms (including the hybrid coordinate grid generator) and the available vertical mixing schemes can be found in Bleck (2002) and Halliwell (2004). Here, HYCOM is briefly presented, with emphasis on the model aspects that are relevant for this study.

HYCOM is a finite-difference hydrostatic, Boussinesq primitive-equation model that solves 5 prognostic equations: one for each horizontal velocity component, a layer thickness tendency (mass continuity) equation, and two conservation equations for a pair of thermodynamic variables (salt, temperature or density). Here, salt and density are employed. Variables are stored on the Arakawa C grid. Thermodynamic variables and the horizontal velocity field are treated as ‘‘layer” variables that are vertically constant within layers but change discontinuously across layer interfaces. Other variables, such as pressure, are treated as ‘‘level” variables, defined on interfaces. These prognostic equations are complemented by a