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Effects of the Changjiang river discharge on sea surface warming in the Yellow and East China Seas in summer

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ABSTRACT

This study explores the effects of the Changjiang (also called the Yangtze River) river discharge (CRD) on the density stratifications and associated sea surface temperature (SST) changes using a global ocean general circulation model with regional focus on the Yellow and East China Seas (YECS). It is found that CRD increases the SST in summer through a barrier layer (BL) formation that tends to enhance stratification at the mixed layer base, and thus reduces both vertical mixing and entrainment. This process is effective, particularly in August, after the CRD reaches its maximum in July. The SST difference between the composites of flood and drought years confirms that the surface warming is related to surface freshening by the CRD. This result suggests that the BL induced by the CRD is an important contributor to the surface heat budget in the YECS.

1. Introduction

Freshwater flux and salinity changes can create a pronounced salinity-induced mixed layer (ML) above the top of the thermocline. The layer between the base of the ML and the top of the thermocline is called a barrier layer (BL), because it acts as a barrier that isolates the warm surface water from cold deep water (Godfrey and Lindstrom, 1989; Sprintall and Tomczak, 1992). The BL helps to maintain a higher sea surface temperature (SST) by inhibiting the cooling of the surface water through restraining heat exchanges between the surface and the thermocline (Miller, 1976; Vialard and Delecluse, 1998). Both numerical model experiments and observational data have supported the idea that the BL formation is responsible for sea surface warming. For example, numerical simulations of the Atlantic Ocean showed that freshwater inflow from the Amazon (Congo) River increases the SST by 0.25 (1.0 °C) (Carton, 1991). An analysis based on high vertical resolution data suggested that a higher SST in the Amazon River runoff region is associated with low surface salinity and a thick BL (Pailler et al., 1999). Also, the warming by the BL formation has been observed in the long-term moored buoy data in the central North Atlantic Ocean (Foltz and McPhaden, 2009), and measurements and numerical simulations in the western Pacific warm pool region (Vialard and Delecluse, 1998). Proper simulations of the BL in the southeastern tropical Atlantic are believed to be important for reducing warm SST biases that are commonly found in most coupled atmosphere–ocean models (Breugem et al., 2008). However, no complete consensus has been reached yet on the warming effects of the BL. For example, Howden and Murtugudde (2001) showed that the river runoff in the Bay of Bengal decreases the surface temperature and suggested that an enhanced entrainment cooling is responsible for the SST decrease. Masson and Delecluse (2001) demonstrated that the BL generated by the Amazon River runoff does not have a clear impact on the SST from ocean model experiments. Foltz and McPhaden (2009), on the other hand, pointed out that such a feature could be an artifact caused by the forced SST restoring to mean values.

The Changjiang (also called the Yangtze River), the fifth largest river in the world in terms of the discharge, is a major freshwater source in the Yellow and East China Seas (YECS) (Fig. 1a) (Shen et al., 1998). Fig. 1b shows the climatological Changjiang river discharge (CRD) by Senjyu and Enomoto (2006). The CRD has a distinct seasonal variation; it is largest in July (0.051 Sv) ($1\ \mathrm{Sv}=10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$) and smallest in January (0.011 Sv). The CRD contributes significantly to sea surface salinity (SSS) distribution in the YECS, which is evident from both analyses using measurement data (e.g., Lie et al., 2003; Chen et al., 2006b; Siswanto et al., 2008; Yan et al., 2008; Kim et al., 2009) and numerical experiments (e.g., Chang and Isobe, 2003; Lee et al., 2004; Chen et al., 2008a, Moon et al., 2009). Some studies have explored that Changjiang diluted water (CDW)

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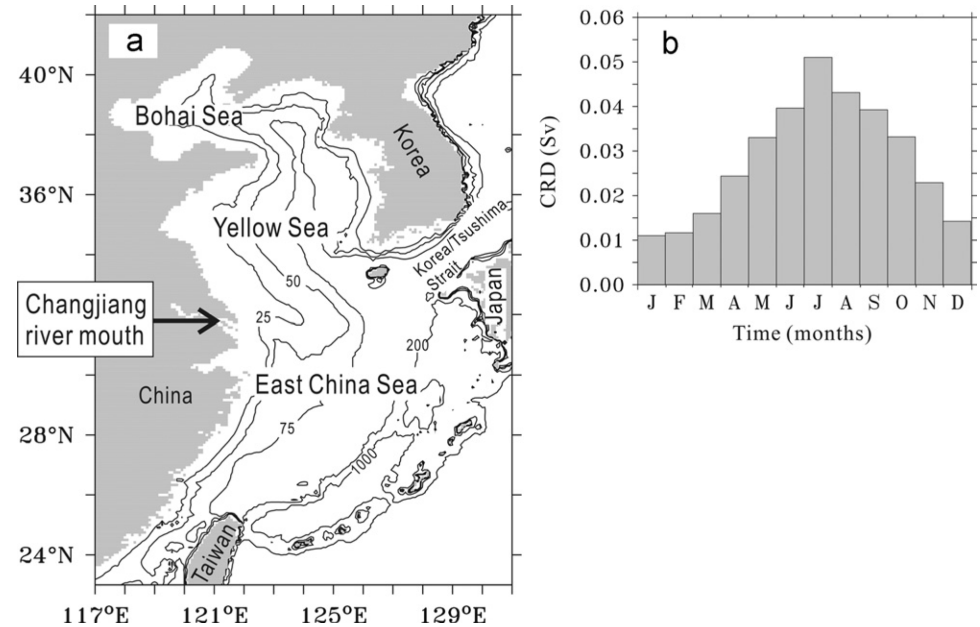

Fig. 1. (a) Geography and bottom topography (unit: meter) in the Yellow and East China Seas. (b) Seasonal variation of the monthly mean CRD (unit: Sv) averaged over 1960–2001.

reaches the Korea/Tsushima Strait (Isobe et al., 2002; Senjyu et al., 2006). The studies described above have focused on the behaviors of the CDW and physical processes responsible for SSS variations in the YECS.

However, few studies have investigated a thermal response to the CRD related to the BL dynamics in the YECS. Subsurface warming is observed off the Chinese coast in fall by Chen et al. (2006a). They suggested that the warming is attributed to the BL formation caused by the CRD retarding convective cooling in the subsurface. Recently, based on comprehensive in-situ data, Chen et al. (2008b) confirmed that the BL formation caused by the CRD is not a peculiar event, but rather a climatological one that occurs from spring to autumn. Nevertheless, the BL process in summer when the river water disperses most widely has received less attention. Delcroix and Murtugudde (2002) compared two experiments with and without the CRD using an ocean general circulation model (OGCM) and showed that the CRD leads to surface warming in August. They suggested that the warming is dominated by the northward advection of warmer water, whereas the BL has a negligible impact on the SST because the advection of waters with different temperatures inhibits the enhancement of the BL. On the other hand, Lee et al. (2004) carried out a similar work that compares results of experiments with and without CRD, using a high-resolution regional ocean model. In their simulations, both surface salinity and current differences indicate that the offshore extent of the CRD plume in summer is much narrower than that of Delcroix and Murtugudde (2002). Lee et al. (2004) attributes the discrepancy to low horizontal resolution and truncated coastal regions off the Chinese coast shallower than about 40 m in the OGCM conducted by Delcroix and Murtugudde (2002).

This study explores the effect of the CRD on the SST from the viewpoint of the BL processes, using an OGCM with regional focus on the YECS. Regional ocean circulation models that have been commonly used for this region have applied open boundary conditions mainly along the southern and eastern boundaries of the region and have taken into account the Taiwan Warm Current and Kuroshio system (Chang and Isobe, 2003; Lee et al., 2004; Moon et al., 2009). However, regional model limits its lateral boundary conditions mostly to the prescribed climatology data. Here, we construct an OGCM that holds higher resolutions in the YECS. The OGCM is a global ocean–sea ice model developed at the Max Planck Institute for Meteorology, MPI-OM, and the global grids are adopted to investigate the YECS, while avoiding artificial open boundaries. By no restoring of the surface salinity toward the climatology data in the northwest Pacific Ocean, year-to-year variabilities of salinity in response to the CRD variations over 42 years can be realized. Moreover an idealized experiment in which the CRD inflow is fully blocked can be carried out because the surface salinity is allowed to evolve freely without influence of the prescribed surface salinity.

The outline of the paper is as follows. Section 2 describes the ocean model and experimental design. Section 3.1 presents the results of a sensitivity experiment that takes into account year-to-year variations of the CRD to explain the role of the CRD on an SST with relation to the BL variation. Section 3.2 compares the results of simulations for flood and drought years to clarify the effect of the CRD on an SST, followed by an examination of the oceanic response to the exclusion of CRD in Section 3.3 and an analysis of mixed layer heat budget in Section 3.4. Sections 4 and 5 give a discussion and conclusions, respectively.

2. Model and experiments

2.1. Model characteristics

The major features of the MPI-OM formulation include primitive equations for a hydrostatic Boussinesq approximation, free surface elevation, vertical discretization of z-coordinates, horizontal discretization of a C-grid (Arakawa and Lamb, 1977), partial bottom grid cells at the lower boundary, and a bulk formula for the surface heat exchange. The along-isopycnal diffusion follows the Gent-McWilliams mixing parameterization (Gent et al., 1995) and the vertical eddy viscosity and diffusivity are calculated based on a scheme proposed by Pacanowski and Philander (1981). It is the oceanic part of the coupled atmosphere–ocean model, ECHAM5/MPI-OM, that was used for the IPCC fourth assessment report (AR4) simulations (Jungclaus et al., 2006). The details of the MPI-OM and its climatology in a global set-up are described in Marsland et al. (2003).

The model allows arbitrary locations of grid poles giving a locally high resolution in the region of interest by a conformal