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Chemical and physical fronts in the Bohai, Yellow and East China seas

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ABSTRACT

Associated with strong mixing and stirring, as well as enhanced bioproductivity and ecotones, oceanic fronts have garnered worldwide attention in recent years. Research into oceanic fronts, especially thermal fronts, has gained momentum since the advent of satellites and their increased accessibility. Yet, studies of salinity and nutrient fronts —particularly those that are subsurface are few and far between. This study reviews the most widely accepted facts about surface and subsurface temperature and salinity fronts in the Bohai, Yellow and East China seas and their seasonal variations. The distribution of nutrients in the surface and bottom waters are mapped and nutrient fronts, for the first time, are identified systematically.

These fronts are generally strongest in winter when southward flowing coastal currents are influenced most by winter monsoons, and the contrasts between these cold, fresh, nutrient-rich currents and the northward flowing warm, saline but nutrient-poor Kuroshio are strongest. Surface fronts are generally weakest in summer when coastal currents may be weaker and temperature, salinity and nutrient contrasts are diminished. The existence of fronts and why some are disconnected are mainly related to oceanic features such as topography, boundaries between water masses and current flow patterns. Three latitudinal temperature and nutrient fronts in the southern East China Sea in winter may suggest eastward flowing currents. These currents have not been described previously.

1. Introduction

The study area, i.e., the Bohai, Yellow and East China seas, is bordered by China, Korea, Kyushu, the Ryukyu Islands and Taiwan (Fig. 1). The almost enclosed Bohai Sea (BS), with a surface area of 77×10^3 km^2, is the smallest and shallowest of the three seas with an average depth of only 18 m; maximum depth is 83 m and volume is 1.39×10^3 km^3. The Huanghe (Yellow River) is a major source of freshwater whereas the Yellow Sea (YS) is the source of salt through the Bohai Strait.

The semi-enclosed YS has a surface area of 380×10^3 km^2, an average depth of 44 m and total volume of 16.7×10^3 km^3. Maximum depth of the YS is only 140 m, and like the BS, it sits entirely on the continental shelf. The Changjiang (Yangtze River) at the southwest corner of the YS is the major source of freshwater for the YS and East China Sea (ECS) to the south.

The more open ECS, at 770×10^3 km^2, is the largest of the three seas, with an average depth of 370 m and volume of 285×10^3 km^3. The western three quarters of the ECS is occupied by the continental shelf, while the eastern part is deep; for example, the Okinawa Trough reaches a depth of 2,719 m (Zhang and Su, 2006). The near-surface waters of the ECS exchange with surface waters of the South China Sea (SCS) through the Taiwan Strait, with the West Philippine Sea (WPS) through several passages in the Ryukyu Islands, and with the Sea of Japan through the Tsushima Strait. Subsurface tropical (S_{max}) and intermediate (S_{min}) SCS and WPS waters only exchange with the ECS through the Okinawa Trough.

These relatively shallow seas are strongly affected by monsoons, massive freshwater outflows, tides and the Kuroshio. In winter, strong northerly winds carrying cold, dry air prevail over northeastern Asia and adjacent seas. River discharge in winter is typically low. In summer, mild southerly winds carrying warm, moist air prevail and lead to high river discharge as well as numerous estuarine and coastal fronts. Interactions among monsoon winds, cold air, bottom topography, large freshwater discharge and the Kuroshio intrusion result in various circulation regimes and different water masses. Generally, coastal waters flow southward, while offshore waters, especially those influenced by the Kuroshio, flow northward in winter. In summer, currents tend to flow northward except for the currents off the western coast of Korea flowing southward and the Changjiang Diluted Water (CDW) flowing north-eastward (e.g., Yanagi et al., 1998; Ichikawa and Chaen, 2000; Chen et al., 2001; Lee et al., 2002; Su and Yuan, 2005).

Oceanic fronts virtually function as boundaries separating two different water masses, where oceanographic parameters, such as temperature and salinity, change rapidly. For instance, a salinity front is formed when the warm Kuroshio water meets the fresher waters of the YS and ECS near the continental shelf break. In winter, the ECS water is markedly colder than the Kuroshio water; thus, the salinity front coincides with a thermal front (Chern and Wang, 1990; Qui et al., 1990; Oka and Kawabe, 1998; Lee and Chao, 2003; Chu et al., 2005; Chen and Wang, 2006). Close to the coastline, salinity fronts also form

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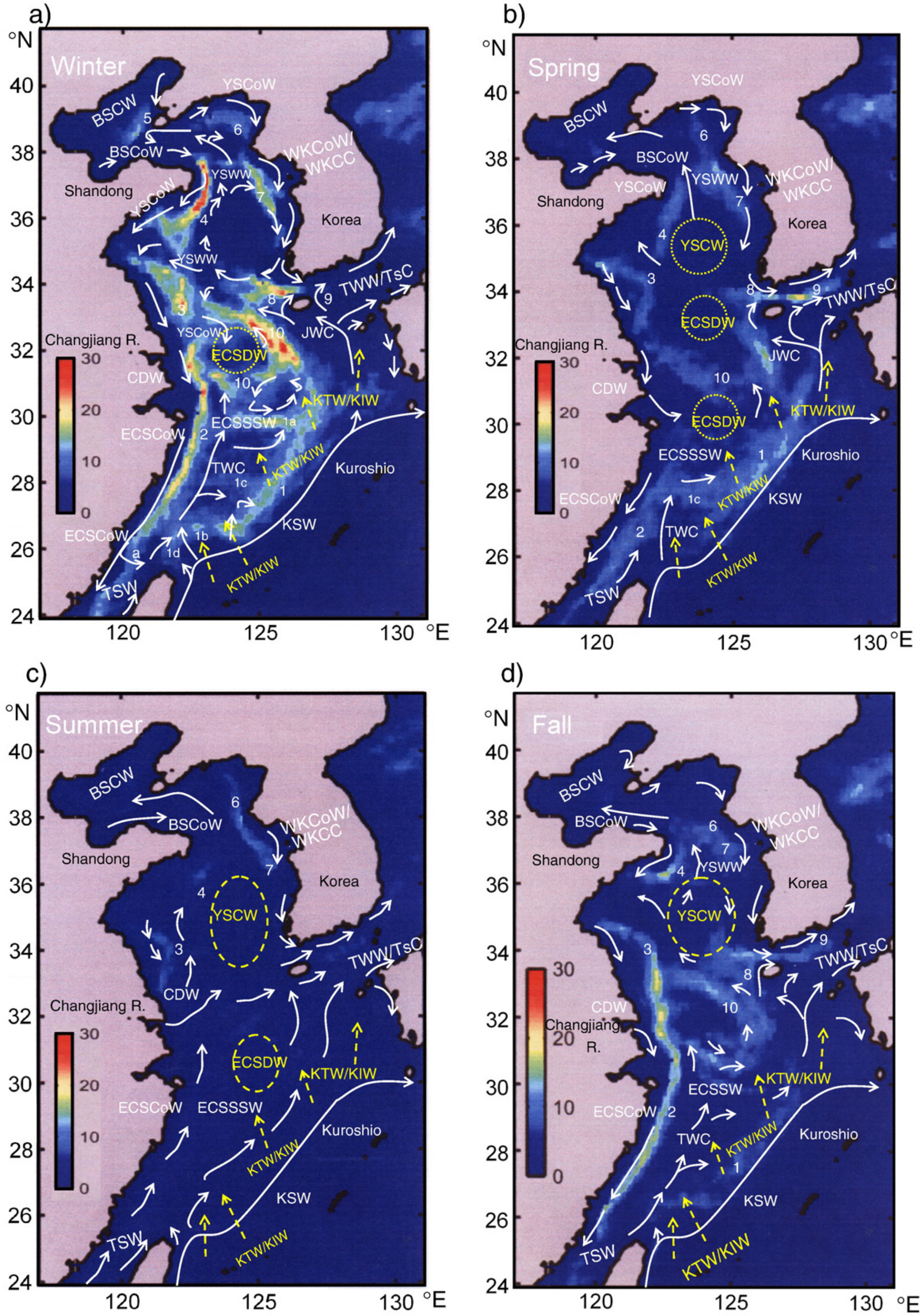

Fig. 1. Various water masses, currents, as well as seasonal probability maps of the thermal fronts in the Bohai, East China and Yellow Seas between 1985 and 1996 (Hickox et al., 2000; courtesy of I. Belkin; the colored bar code represents the seasonal frequency of appearance). The temperature fronts by number, as designated by Hickox et al., are also shown. Solid white lines show, schematically, major surface currents while yellow dashed lines show major subsurface currents. Fronts 1a, 1b and 1c were undesignated by Hickox et al. while Front 1d indicates the southernmost part of Front 1.

where low-salinity water is affected by land runoff meeting high-salinity water from the sea (Beardsley et al., 1983, 1985; Lie et al., 2003; Lee et al., 2004). In addition, subsurface cold water vertically mixed by bottom tidal mixing forms tidal fronts that are often coincident with thermal fronts (Zhao, 1987; Lie, 1989; Bi and Zhao, 1993; Yanagi, 1999). These fronts are mostly characterized by strong