Journal of Marine Systems 78 (2009) 351–362

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Interannual variation of the Polar Front in the Japan/East Sea from summertime hydrography and sea level data

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ARTICLE INFO

Article history:
Received 17 October 2006
Received in revised form 23 May 2008
Accepted 7 November 2008
Available online 20 February 2009

Regional index terms:
Northwestern Pacific Ocean
Japan/East Sea
126°E–142°E
34°N–52°N

Keywords:
Polar Front
Hydrographic data
Altimeter data
Numerical model
Interannual variation
Japan/East Sea

ABSTRACT

The Polar Front in the Japan/East Sea separates the southern warm water region from the northern cold water region. A merged TOPEX/POSEIDON and ERS-1/2 altimeter dataset and upper water temperature data were used to determine the frontal location and to examine the structure of its interannual variability from 1993 to 2001. The identified frontal location, where sea surface height gradient has a maximum about 10–20 cm over the horizontal distance of 100 km, corresponds well to the maximum subsurface horizontal temperature gradient. The front migrates more widely (36°N–41°N) in the western part of the sea than in the eastern part. The interannual migration induces large variability in upper water temperatures and sea surface height in the western region. Responsible physical mechanisms were studied using a reduced-gravity model. Differences between inflow and outflow change the total volume of warm water, and total warm water volume change in the warm water region uniformly pushes the front in the meridional direction across its mean position in the model simulation. Interannual variation of wind stress causes relatively wide migration of the modeled front in the western part.

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1. Introduction

The Polar Front marks an important climate boundary in terms of both water mass formation and air–sea fluxes. Accordingly, variation of the Polar Front in the Southern Ocean and the North Pacific Ocean has been studied extensively (Roden et al., 1982; Moore et al., 1999). The Polar Front of the North Pacific extends from 57°N in the Gulf of Alaska to 40°N off Japan. The front is relatively stable, except along 170°E, where it shifts north–south by 400 km every 6 years (Belkin et al., 2002). The western end of the Polar Front in the North Pacific extends into the Japan/East Sea, and is located between 38°N and 40°N (Tomczak and Godfrey, 1994; Belkin and Cornillon, 2003). The Polar Front in the Japan/East Sea is often referred to as the subpolar front in other recent studies (Park et al., 2004; Talley et al.; 2006).

The Japan/East Sea is a marginal sea of the North Pacific Ocean (Fig. 1a). Its dimensions are about 1600×900 km and the mean depth is about 1350 m. It communicates with the East China and Yellow Seas to the south, with the Pacific Ocean to the east, and with the Sea of Okhotsk to the north. Water is exchanged through narrow channels with sill depths not exceeding 135 m. Warm and saline water enters from the Kuroshio, flows through the southern part of the sea, and exits to the subpolar gyre with a throughflow transport of about $2.5\times10^6 m^3/s$ (Sv). The warm water occupies the depth range of 0–200 m and is characterized by a shallow salinity maximum at about 50 m depth in the warm southern Japan/East Sea (Talley et al., 2006). Below 200 m, the water is remarkably uniform with temperature of 0–1 °C and salinity of 34.1 (Tomczak and Godfrey, 1994; Preller and Hogan, 1998).

The Polar Front separates the southern warm water from the northern cold water in the Japan/East Sea. In Fig. 1a, solid lines with arrows indicate surface currents in the southern warm water region and dashed lines denote those in the northern cold water region. The dotted line is an approximate position of the Polar Front. A line of open circles represents hydrographic stations where upper layer temperature data were obtained to identify vertical structure of the upper water across the Polar Front in July 1993. The vertical section of upper ocean temperature along the north–south transect shows the structure of the Polar Front (Fig. 1b). Due to summer heating, the upper 50-m layer is highly stratified and the front submerges below the surface. There is a strong subsurface horizontal temperature gradient at depths of 50–150 m across 39.2°N. Horizontal maps of the

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doi:10.1016/j.jmarsys.2008.11.021

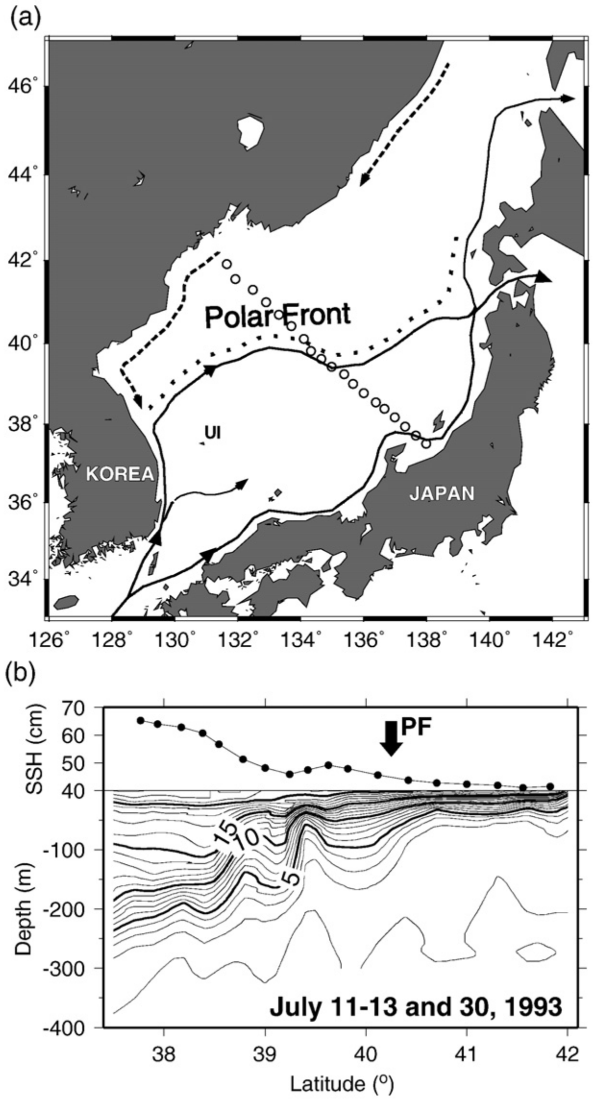

Fig. 1. (a) Schematic surface currents in summer and location of the Polar Front. UI stands for Ulleung Island. (b) Comparison of upper layer temperature and sea surface height. PF stands for the Polar Front in (b).

subsurface temperature give relatively better identification of the front position (Uda, 1938; Isoda et al., 1991; Talley et al., 2006). Once sea surface height measured from satellite altimeters is plotted on top of the vertical temperature section to compare with the upper layer heat content as in Fig. 1b, the sea surface height is closely related to the upper water heat content.

The front is identified by the maximum horizontal temperature gradient and, in general, it coincides with closely spaced zonally directed isotherms. It is about 100–150 km wide and is a boundary of physical and chemical properties such as temperature, salinity and dissolved oxygen (Kim and Kim, 1999) and nutrients (Talley et al., 2006). Sinking of water immediately north of the Polar Front forms the Japan/East Sea intermediate water (Senjyu and Sudo, 1994; Yoshikawa et al., 1999). Intrathermocline eddies may form through frontal convergence and subduction at the Polar Front (Ou and Gordon, 2002; Gordon et al., 2002). Migration of the front affects meso-scale circulations, water mass formation, eddy generation and nutrient distributions in the Japan/East Sea.

Sea level measured at Ulleung Island (130.9E°E, 37.4°N) has large interannual variations comparable to the mean seasonal variation, and the interannual variation in the southwestern part of the Japan/East Sea was found to be related to migration of the Polar Front from upper water temperature data (Kim et al., 2002). Statistical analysis of sea surface and upper water temperature in the Japan/East Sea revealed that interannual variation of the upper water temperature is larger in the western part than in the eastern part (Chu et al., 1998; Minobe et al., 2004; Choi et al., 2004a). A physical mechanism for the strong variability in the western part was thought to be the migration of the Polar Front. Seasonal variation of the Polar Front has been investigated using satellite sea surface temperature (SST) data (Isoda et al., 1991), climatological temperature and salinity data (Chu et al., 2001), and in numerical models (Kim and Yoon, 1996). Belkin and Cornillon (2003) examined thermals fronts of the Pacific coastal and marginal seas including the entire Japan/East Sea using the Pathfinder AVHRR SST data from 1985 to 1996. Park et al. (2004) identified the locations of the sea surface temperature front from an analysis of satellite SST images for the entire Japan/East Sea. Because of sparseness and irregularity of measured upper water temperature data, the interannual variability of the Polar Front over the entire Japan/East Sea has not been well investigated in previous studies.

Altimeter data have been used to examine seasonal variation of sea surface circulation and to determine meso-scale eddy variability in the Japan/East Sea. Twelve ground tracks of TOPEX/POSEIDON (T/P) pass over the Japan/East Sea with an orbit repeat period of 9.9 days. ERS-1/2 have forty-one ground tracks and their repeat cycle is 35 days. From T/P and ERS-2 altimeter data, Morimoto et al. (2000) found high root-mean-square (RMS) variabilities of sea surface height (SSH) in the Yamato Basin, the Ulleung Basin, east of North Korea, and the eastern part of the Yamato Rise. Morimoto and Yanagi (2001) showed variation of sea surface circulation by EOF analysis of the 3.5 years of ERS-2 altimeter data.

In this paper, we identify locations of the Polar Front from 1993 to 2001 and examine the structure of its interannual variability based on the merged altimeter data and hydrographic data in section 2. To seek possible responsible factors for the interannual variation, numerical simulations of the surface circulation are performed and the effects of the interannual variations in the wind stress and total warm water volume are investigated in section 3.

2. Interannual variation of the Polar Front

Before the satellite remote sensing era, locations of the Polar Front were observed by on-board temperature measurements, and the in-situ measurements were limited in time and space. Since satellite radiometers have sensed radiation emitted from the sea surface, the front has been easily identified in maps of SST inferred from composite infrared (IR) images (Isoda et al., 1991; Park et al., 2004). However, the measurements of SST from the satellite are frequently blocked by clouds in the mid-latitude. The data need to be interpolated in time and space to fill in the cloud-contaminated data. Additionally, the maps of summer SST do not capture the proper locations of the front because the seasonal surface heating in the upper 50 m of the water column reduces horizontal SST gradients. On the other hand, SSH measurements from satellite altimeters are not affected by cloud clover and SSH is closely related to the integrated heat content in the upper layer in the Japan/East Sea (Kim et al., 2002) so that maps of SSH are better to identify the Polar Front in the Japan/East Sea.

Satellite altimeters have provided sea level anomalies (SLA), but lack of accurate geoid information in the Japan/East Sea prevents the altimeters from providing the absolute SSH. Composite dynamic sea level (DSL) can be calculated by combining the mean sea surface steric height calculated from the long-term mean hydrographic data and SLA derived from the altimeters (Morimoto and Yanagi, 2001; Korotaev et al., 2003; Choi et al., 2004a). The mean sea surface steric height was calculated relative to 500 dbar using temperature and salinity climatological data from the Japan Oceanographic Data Center (JODC) and the Korea Oceanographic Data Center (KODC). SLA data

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