Circulation and currents in the southwestern East/Japan Sea: Overview and review

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Available online 19 August 2004

Abstract

A review is made of circulation and currents in the southwestern East/Japan Sea (the Ulleung Basin), and the Korea/Tsushima Strait which is a unique conduit for surface inflow into the Ulleung Basin. The review particularly concentrates on describing some preliminary results from recent extensive measurements made after 1996. Mean flow patterns are different in the upstream and downstream regions of the Korea/Tsushima Strait. A high velocity core occurs in the mid-section in the upstream region, and splits into two cores hugging the coasts of Korea and Japan, the downstream region, after passing around Tsushima Island located in the middle of the strait. Four-year mean transport into the East/Japan Sea through the Korea/Tsushima Strait based on submarine cable data calibrated by direct observations is 2.4 Sv (1 Sv = 10^6 m^3 s^{-1}). A wide range of variability occurs for the subtidal transport variation from subinertial (2–10 days) to interannual scales. While the subinertial variability is shown to arise from the atmospheric pressure disturbances, the longer period variation has been poorly understood.

Mean upper circulation of the Ulleung Basin is characterized by the northward flowing East Korean Warm Current along the east coast of Korea and its meander eastward after the separation from the coast, the Offshore Branch along the coast of Japan, and the anticyclonic Ulleung Warm Eddy that forms from a meander of the East Korean Warm Current. Continuous acoustic travel-time measurements between June 1999 and June 2001 suggest five quasi-stable upper circulation patterns that persist for about 3–5 months with transitions between successive patterns occurring in a few months or days. Disappearance of the East Korean Warm Current is triggered by merging the Dok Cold Eddy, originating from the pinching-off of the meander trough, with the coastal cold water carried Southward by the North

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Korean Cold Current. The Ulleung Warm Eddy persisted for about 20 months in the middle of the Ulleung Basin with changes in its position and spatial scale associated with strengthening and weakening of the transport through the Korea/Tsushima Strait. The variability of upper circulation is partly related to the transport variation through the Korea/Tsushima Strait. Movements of the coastal cold water and the instability of the polar front also appear to be important factors affecting the variability.

Deep circulation in the Ulleung Basin is primarily cyclonic and commonly consists of one or more cyclonic cells, and an anticyclonic cell centered near Ulleung Island. The cyclonic circulation is conjectured to be driven by a net inflow through the Ulleung Interplain Gap, which serves as a conduit for the exchange of deep waters between the Japan Basin in the northern East Sea and the Ulleung Basin. Deep currents are characterized by a short correlation scale and the predominance of mesoscale variability with periods of 20–40 days. Seasonality of deep currents is indistinct, and the coupling of upper and deep circulation has not been clarified yet.

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Keywords: Circulation; currents; Korea/Tsushima Strait; Ulleung Basin; East/Japan Sea

1. Introduction

The East/Japan Sea (the East Sea hereafter) is a semi-enclosed deep marginal sea in the northwestern Pacific. The total area and average depth of the East Sea are $1.01 \times 10^6$ km$^2$ and 1684 m, respectively (KORDI, 2002). It consists of three basins deeper than 2000 m: the Japan Basin in the northern half which is almost 4000 m deep, the Ulleung Basin (UB) in the southwest, and the Yamato Basin in the southeast (Fig. 1). The East Sea is connected with the East China Sea through the Korea/Tsushima Strait (KTS), with the North Pacific through the Tsugaru Strait, and with the Sea of Okhotsk through the Soya and Tartarskiy Straits. As these straits are shallower than 130 m, water exchanges with adjacent seas are very limited (see Sugimoto (1990) for a review of the physical characteristics of the straits). Warm and saline equatorial waters (TCW: Tsushima Current Water) are transported into the East Sea by the Tsushima Current through the KTS. The TCW occupies the upper 150 m in the UB and the Yamato Basin, and is bounded by cold waters in the north forming the polar front at about 40°N. The general upper circulation of the East Sea consists of the cyclonic cold water circulation in the Japan Basin, and north or northeastward flowing TCW circulation south of the polar front. The TCW inflow through the KTS mostly exits to the North Pacific through the Tsugaru Strait and partly to the Sea of Okhotsk through the Soya and Tartarskiy Straits. The remainder recirculates within the East Sea (Moriyasu, 1972). Below the upper surface layer, intermediate and deep water masses are formed, modified, and circulate within the East Sea. Deep water formation occurs in the Japan Basin (Seung & Yoon, 1995) leading to a thermohaline circulation that transports deep, cold water southward towards the UB and the Yamato Basin. The intermediate waters are also formed in the Japan Basin and along the polar front, and spread southward.

The UB, which is about 2300 m deep, is surrounded by shallow topographic features; the KTS shallower than 200 m to the south, Oki Bank shallower than 1000 m to the east, the Korea Plateau shallower than 1500 m to the northwest. The 2000 m isobath from the Japan Basin continues into the UB through a narrow constriction between Ulleung and Dok Islands called the Ulleung Interplain Gap (UIG). The UIG is about 90 km wide, and serves as a unique passageway for the exchange of deep waters below 1500 m depth between the UB and the Japan Basin. North of Ulleung Island the narrower (~5 km) Ulleung Trough, deeper than 2000 m, splits the Korea Plateau into two. Three water masses are found in the UB: the TCW, the East Sea Intermediate Water (ESIW), and the East Sea Proper Water (ESPW). The UB receives the TCW through the KTS, and both the ESIW and ESPW from the Japan Basin.

Studies on the circulation and currents in the UB have been focused mainly on the upper layer circulation by mapping observed water properties. Uda (1934) proposed the general circulation features and...
named the major currents in the East Sea. Satellite-tracked surface and subsurface drifters have been used to understand the quantitative nature of the circulation since the end of 1980s (e.g., Beardsley, Limeburner, Kim, & Candela, 1992). Long-term moored current measurements began in 1996 (Chang et al., 2002b). Monitoring of the volume transport through the KTS has been carried out since 1997 using an acoustic Doppler current profiler (ADCP) mounted on a ferryboat along a cruise line between Pusan and Hakada (Takikawa, Yoon, & Cho, 2003) and by measuring the voltage on an abandoned submarine cable (Kim et al., 2004). Recently high-resolution continuous moored measurements in the KTS and UB were completed in cooperation with the United States Japan/East Sea (JES) program (see http://sam.ucsd.edu/onr_jes for more details on the JES program) and Linkages of Asian Marginal Seas (LINKS) program, the Korea Ocean Research and Development Institute (KORDI), the Pukyong National University in Korea, and the Research Institute of Applied Mechanics of Kyushu University in Japan (RIAM).

Reviews of physical oceanographic studies of the East Sea until mid-1990s can be found in Seung (1992b), Lie and Seung (1994), and Preller and Hogan (1998). A comprehensive list of publications on the oceanography in the East Sea since the last century to the year 1994 with special reference to works

Fig. 1. Geographic map of (a) the East Sea and (b) the Ulleung Basin. Isobaths are 200, 1000, 2000, and 3000 m for the East Sea, and 100, 200, 500, 1000, 1500, and 2000 m for the Ulleung Basin. UIG, KP, and UT in (b) denote the Ulleung Interplain Gap, Korea Plateau, and Ulleung Trough, respectively.
of Russian scientists is also available in Danchenkov, Hong, Kim, and Yu (1996). This paper reviews studies on the circulation and currents in the KTS and UB, including those recently published and submitted. Special focus is made on the results from data obtained during the JES and LINKS programs between 1999 and 2001, as the data provide an unprecedented opportunity to study the circulation and currents quantitatively with their temporal variations. We also include some analyzed results that have not been published yet (Figs. 17, 18, 21–23, 27–31). The review made here cannot be completely thorough, although attempts are made to include as many relevant works as possible. The paper is organized as follows. Data used in the paper are described in Section 2. Section 3 covers the exchange through KTS. Reviews of mean circulation and variability in the upper and deep layers of the UB are made in Sections 4 and 5, respectively. Section 6 introduces recent results on flow through the UIG followed by summary and discussions in Section 7.

2. Data and methods

Data used in the paper are listed in Table 1 with references describing their characteristics and methods of processing. Figs. 2 and 3 show locations of measurements during 1996–2002. Only some of CTD stations referred to in the text and occupied by KORDI during 1999–2002 are shown in Fig. 2 (see Chang, Kim, Suk, & Byun (2002a) for the map of entire CTD locations). Serial oceanographic data obtained by National Fisheries Research and Development Institute (NFRDI), Korea are also used.

An extensive array of bottom-mounted ADCPs, moored from May 1999 to March 2000, was deployed in the KTS for the LINKS program (LINKS data hereafter). RIAM has been carrying out long-term ADCP observation since February 1997 six times a week using the ferryboat Camellia along a track between Pusan, Korea and Hakata, Japan (Camellia data hereafter). Analysis of tidal currents was made using the Camellia data (Takikawa et al., 2003), and subtidal variations of currents and volume transport are under investigation. Cross-strait cable voltage measurements provide a cost-effective alternative to current meter deployments for determination of transports over very long time intervals. According to Faraday’s law, when seawater possessing electric conductivity flows through a strait under the geomagnetic field, an electric potential difference is induced proportional to the volume transport through the strait (Larsen, 1992; Sanford & Flick, 1975). Voltage induced by the Tsushima Current on an abandoned submarine telephone cable between Pusan, Korea and Hamada, Japan (Fig. 2) has been measured since March 1998 in order to monitor the volume transport through the KTS (Cable data hereafter). Kim et al. (2004) found that voltage has a good linear relationship with the transport estimated from LINKS and Camellia data.

KORDI has been maintaining current meter moorings in the UB since 1996 to investigate characteristics of deep currents in the UB. One of the objectives for the moored current measurements is to monitor the flow through the UIG. Five mooring lines are currently in operation in the UIG. Continuous acoustic travel-time and bottom current measurements were conducted in the UB for two years between June 1999 and June 2001 by an array of pressure-gauge-equipped, inverted echo sounders (PIES) and current meters (PIES data hereafter). The travel-time data are converted into a three-dimensional synoptic time-series of temperature fields using a technique called GEM (Gravest Empirical Mode)/MODAS (Modular Ocean Data Assimilation System), which utilizes a relationship between the travel time and the vertical thermal structure (Mitchell et al., 2004). The current meters are deployed 20–40 m off the bottom at water depths ranging from 1200 m to over 2000 m.

Tides and tidal currents are generally weak in the interior of the East Sea. Tidal currents in the shallow KTS, however, are as strong as or stronger than subtidal currents. The strongest subtidal currents (~100 cm s⁻¹) are often observed off the coast of Korea in the KTS, and the total currents are nearly 170 cm s⁻¹ if tidal currents are included (Teague et al., 2002). Tidal currents account for about 25%, 50%, and 70% of the eddy kinetic energy near the surface layer, at mid-depths, and near the bottom, respectively. Four tidal current constituents (M₂, S₂, K₁, O₁) are dominant in the KTS with an amplitude ratio of 1:0.45:0.59:0.51.
<table>
<thead>
<tr>
<th>Measured items</th>
<th>Period of measurement</th>
<th>Area covered</th>
<th>Methods</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume transport</td>
<td>1998–present</td>
<td>Korea/Tsushima Strait</td>
<td>Cable voltage measurement</td>
<td>Kim et al. (2004)</td>
</tr>
<tr>
<td>Current</td>
<td>March 1999–May 2000</td>
<td>Korea/Tsushima Strait</td>
<td>ADCP</td>
<td>Perkins et al. (2000a),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Teague et al. (2002)</td>
</tr>
<tr>
<td>Deep current</td>
<td>October 1996–present</td>
<td>Ulleung Basin, Ulleung Interplain Gap</td>
<td>Moored current meter</td>
<td>Chang et al. (2002b)</td>
</tr>
<tr>
<td>Temperature and salinity</td>
<td>1999–2001</td>
<td>Ulleung Basin</td>
<td>CTD</td>
<td>Chang et al. (2002a)</td>
</tr>
</tbody>
</table>
Amplitudes of the major constituents are about 1.4–2.1 times larger in the western channel than those in the eastern channel of the KTS. For the most dominant $M_2$ tidal constituent, tidal velocities for depth-averaged currents range from 17 to 25 cm s$^{-1}$ northeast of Tsushima Island (Teague, Perkins, Jacobs, & Book, 2001). Clockwise rotation of tidal currents with time is dominant except for deep layers below 90 m. Tidal currents are largely barotropic at mid-depths but exhibit varying degrees of depth-dependence in the near-surface and near-bottom layers. More details on the characteristics of tidal and inertial motions from the LINKS and Camellia data can be found in Book et al. (2004), Teague et al. (2001), Jacobs, Book, Perkins, and Teague (2001a), and Takikawa et al. (2003). Variability described in these papers focuses on the low-frequency variations that have periods longer than tidal and inertial peri-

![Map of tidal current moorings and stations](image_url)
ods. To do so, current data are low-pass filtered using a 40-hour cutoff filter in order to remove tidal, inertial, and other higher frequencies.

3. Currents and transports in the Korea/Tsushima Strait

The Tsushima Current flows persistently through the KTS after the separation from the Kuroshio west of Kyushu, carrying water from the East China Sea into the East Sea. The Tsushima Current is a major contributor to the circulation of the East Sea and to the transport of heat and salt from the Pacific Ocean to the East Sea (Cho & Kim, 2000; Lee, Niiler, Lee, Kim, & Lie, 2000; Moriyasu, 1972). Numerical experiments show that the variability of the circulation in the East Sea depends largely on the transport variation through the KTS (e.g., Kim & Yoon, 1999).

Determination of the Tsushima Current in the KTS is made difficult by unsuitability of geostrophic methods in shallow waters (Shim, Wiseman, Huh, & Chuang, 1984), by strong tidal and other short-term variations, and by seasonal and interannual variability. Short-term (~25 h) current measurements in the KTS date back to the 1920s (e.g., Nishida, 1927), and the general strength of the currents has been demonstrated from many short-term measurements (Egawa, Nagata, & Sato, 1993; Hase, Yoon, & Koterayama, 1999; Isobe, 1995; Isobe, Tawara, Kaneko, & Kawano, 1994; Katoh, Teshima, Kubota, & Tsukiyama, 1996; Mizuno, Kawatate, Nagahama, & Miita, 1989). Long-term measurements from moored current meters in the KTS, however, are rare, in part because of the hazard to equipment posed by intense fishing and trawling (Kawatate, Miita, Ouchi, & Mizuno, 1988). Improved techniques for ocean
measurement have recently enabled long-term measurements that are largely unaffected by fishing activity, and these have led to advances in the study of the Tsushima Current and its variability. Mounted either upward-looking from the sea floor (Perkins, de Strobel, & Gualdesi, 2000b) or downward-looking from ships (Takikawa et al., 2003), ADCPs provide full-depth profiles of current over much of the KTS. Voltage differences measured from permanent, cross-strait cables have long been used to detect transport variability. Such cables, after being calibrated by arrays of ADCPs, can provide accurate estimates of absolute transport over many years (Kim et al., 2004). Surface-drogued drifters have proved to be practical, and Lagrangian paths of the surface waters of the KTS and its surroundings have been mapped by extensive drifter deployments (Lee et al., 2000; Lie & Cho, 1997; Lie, Cho, Lee, Niiler, & Hu, 1998).

The LINKS data provide an unprecedented view of currents in the KTS. Several aspects of the low-frequency components of this dataset have been presented (Perkins, Teague, Jacobs, Chang, & Suk, 2000a; Teague et al., 2002). The average spacing between LINKS ADCPs is 25 km and their sampling interval is generally 30 min. The horizontal and vertical decorrelation length scales for measured velocities are 20–40 km and 10–20 m, respectively (Jacobs, Perkins, Teague, & Hogan, 2001b). Here we consider the mean currents in the KTS and their spatial and temporal variability, the latter dominated by seasonal effects, subtidal pulsations, and tides. Volume transports through the KTS estimated from indirect and direct methods and some dynamical studies relevant to the transport parameterization are also reviewed.

3.1. Mean currents and variability

Spatial structure of the vertically averaged currents with standard deviation ellipses at the ADCP sites is shown in Fig. 4 for the months of maximum and minimum transports (see Section 3.2). The center of the standard deviation ellipse is at the tip of the arrowhead and reflects the area that is within one standard deviation of the mean. There is a broad similarity between the two months in the spatial distribution of the current patterns upstream and downstream of Tsushima Island. In both cases, the upstream flow varies smoothly across the channel, with a maximum at mid-channel. At all sites south and west of Tsushima Island except the near-shore site S6, depth-averaged mean currents are larger than the RMS variability. Downstream of Tsushima Island, the situation is reversed: strongest barotropic currents are found near the coast, while those in mid-channel (N3 and N4) are weak and variable. The northern section thus consists of two streams, one on each side of the strait. Between the two is a regime of highly variable flow with

![Fig. 4. Barotropic currents and their corresponding standard deviation ellipses for (a) October 1999 and (b) January 2000.](image-url)
weak mean. This separation around Tsushima Island occurred throughout the measurement period and is presumed to be a permanent feature. It is presumably one of the mechanisms that leads to formation of distinct branches of the Tsushima Current in the East Sea (Cho & Kim, 2000; Kaneko, Byun, Chang, & Takahashi, 1991; Katoh et al., 1996).

Monthly mean currents for months of maximum and minimum transport are given in Fig. 5 at depths near the top, center, and bottom of the water column. Strongest currents are found during October north of

Fig. 5. Monthly mean currents and their corresponding standard deviation ellipses. Panels (a)–(c): top, center and bottom of the water column for October. Panels (d)–(f): same information for January.
Tsushima Island near the Korean coast (sites N1 and C1) at the surface (Fig. 5(a)). The three principal streams, that is, the inflow core southwest of Tsushima Island and the two near-coastal currents northwest of it, decrease substantially between October and January at the top and central levels, whereas those near the bottom change less (Fig. 5(c) and (f)). Near the Korean coast (at S1 at all depths and at N1 near the bottom), there is a current component toward the coast.

3.2. Volume transports

The Tsushima Current originates mainly from the Kuroshio west of Kyushu (Lie et al., 1998; Teague, Jacobs, Ko, Chang, & Suk, 2003) and partly from the Cheju Strait (Chang, Suk, Pang, & Teague, 2000; Lie, Cho, Lee, Lee, & Tang, 2000). The volume transports through the KTS and the Cheju Strait were 3.17 Sv (1 Sv = 10⁶ m³ s⁻¹) and 0.59 Sv, respectively, according to concurrently obtained current data in the KTS and Cheju Strait between October and December, 1999 (Teague et al., 2004). Hence about 20% of the total transport through the KTS come from the Cheju Strait and remaining 80% from the region west of Kyushu.

Estimates of the transport through the KTS vary widely depending upon methods and time. Ranges for the annual mean are 0.5–4.2 Sv with a seasonal variation of 0.7–4.6 Sv (Table 2). Yi (1966) estimated the transport through the KTS using a dynamical calculation with a reference level at the bottom, which cannot give a good estimate because of the shallow bottom. The transport was also calculated from the sea level difference (SLD) across the strait (Mizuno et al., 1989) based on an assumption that the current is vertically barotropic. However, it was reported later that the baroclinic effect on the sea level difference is significant in the KTS (Isobe, 1994; Isobe, 1995; Lyu & Kim, 2003). Attempts have been made to quantify the transport using data from short-term current measurements lasting a few days (Isobe et al., 1994; Katoh et al., 1996; Miita & Ogawa, 1984). As these methods, however, provide instantaneous current fields, it is difficult to remove the contribution of short-term variations, such as tidal currents, to the subtidal transport.

The LINKS data provide, for the first time, the directly observed long-term transport through the KTS. Time-dependent transports across the two principal ADCP mooring lines, S1–S6 and N1–N6, have been estimated by an objective interpolation technique (Jacobs et al., 2001b). Results, based on 40-hour low-pass filtered current observations, are given in Fig. 6. Estimates of monthly mean transport through the KTS made from the ADCP array vary from a maximum of 3.4 Sv in October 1999 to a minimum of 1.7 Sv in January 2000, with a mean of 2.7 Sv over the 10 months of observations. EOF analyses indicate transport variations in summer are due mainly to variations near the coast of Korea, while contributions to transport variations in winter are distributed more uniformly across the strait (Teague et al., 2002).

![Table 2](image)

<table>
<thead>
<tr>
<th>Study</th>
<th>Summer &amp; Autumn</th>
<th>Winter &amp; Spring</th>
<th>Mean Transport</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yi (1966)</td>
<td>2.21</td>
<td>0.33</td>
<td>1.35</td>
<td>Hydrographic data ⇒ Geostrophic calculation</td>
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<tr>
<td>Byun and Seung (1984)</td>
<td>0.83</td>
<td>0.16</td>
<td>0.5</td>
<td>Hydrographic data ⇒ Geostrophic calculation</td>
</tr>
<tr>
<td>Miita and Ogawa (1984)</td>
<td></td>
<td></td>
<td>4.2</td>
<td>Current meter</td>
</tr>
<tr>
<td>Tawara et al. (1984)</td>
<td>4.1</td>
<td>2.2</td>
<td>2.2</td>
<td>Current meter</td>
</tr>
<tr>
<td>Mizuno et al. (1989)</td>
<td></td>
<td>0.8</td>
<td></td>
<td>Sea level difference (Eastern channel)</td>
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<tr>
<td>Isobe et al. (1994)</td>
<td>5.6</td>
<td>1.0</td>
<td>2.3</td>
<td>Towing ADCP</td>
</tr>
<tr>
<td>Katoh et al. (1996)</td>
<td>2.3</td>
<td></td>
<td></td>
<td>Towing ADCP</td>
</tr>
<tr>
<td>Takikawa et al. (1999)</td>
<td>3.4</td>
<td>1.6</td>
<td>2.6</td>
<td>Vessel-mounted ADCP</td>
</tr>
<tr>
<td>Teague et al. (2002)</td>
<td>3.5</td>
<td>1.7</td>
<td>2.7</td>
<td>Bottom-mounted ADCP</td>
</tr>
</tbody>
</table>
Climatological temperature profiles (Jacobs et al., 2001a) indicate the strait to be well mixed in January–March, to be fully stratified in July–September, and to shift gradually between these two conditions during the intervening months. An atlas of the strait (Kwak, 1996) is consistent with this temporal pattern and provides an estimate of its spatial extent. There is, therefore, a rough correlation between transport and the degree of vertical stratification, although no causal connection has been established. The seasonal variation of the transport from the 10-month long ADCP data coincides with the tendency inferred from the indirect methods in Table 2. Longer-term observation, however, indicates the seasonality of the transport variation is not repetitive, as will be shown shortly.

A large amount of variability with scales of several days is also evident in Fig. 6. These fluctuations are generally coincident in time on both N and S lines and so appear to be real. Since the storage capacity of the strait is not significant in the present context, differences between the two transport time series in Fig. 6 are expected to be small. Some difference can be attributed to measurement errors, caused primarily by inadequate spatial sampling. The S line provides the better estimate because the distribution of moorings there is better able to define the current's spatial structure. The N line not only has a more complex cross-strait structure, but lacks data from a site close to the coast of Korea where the mooring was lost. The loss is only partially compensated during the final five months by data from N1. The reality of these transport variations is also confirmed by the Cable data described below.

The voltage-derived transport reveals temporal variations that have not been observed previously. The transport variations are 2–3 Sv on subinertial time scales of 2–10 days (Fig. 7). It should be pointed out that these subinertial variations are larger than the seasonal variations known in the KTS (Takikawa, Yoon, Hase, & Cho, 1999; Teague et al., 2002). These subinertial variations also appear in the observed transport from the ADCPs as mentioned above (Fig. 6). Recently Lyu, Kim, and Perkins (2002) reported that there are non-isostatic subinertial variations with the range of 2–3 Sv on time scales of 3–5 days in the transport through the KTS and these variations could be derived from uniform atmospheric pressure over the East Sea acting like a forced oscillator constrained by friction. These variations are amplified at the period (~3 days) of a Helmholtz-like resonance between the East Sea and the Pacific Ocean through the straits. The transport variations are also large, up to 2 Sv, on time scales of about a month (Fig. 7).

The four-year long Cable data set shows that seasonal transport variations are not manifest and there appears to be a large interannual variation, although the data record may not be long enough to define the seasonality (Fig. 8). The transport has a mean of 2.4 Sv with a maximum of 3.4 Sv in October 1999 and a minimum of 1.2 Sv in January 2002. The monthly mean transports from the Camellia data (Takikawa et al., 1999) and the LINKS data (Teague et al., 2002) agree well with the voltage-derived transport within a 95% confidence interval. There seems to be a tendency that the transport becomes large in summer...
and autumn and small in winter and spring. However, interannual variations are prominent. The seasonal variation is very weak from spring 2000 to fall 2001 and annual mean transport reduces by 0.4 Sv from 1999 to 2000. The cable voltage measured between Pusan and Hamada provides an efficient means for long-time and continuous monitoring of the transport through the KTS and enables us to investigate various temporal transport variations and their driving mechanisms.

A strong linear relationship was found (Lyu & Kim, 2003) between the transport through the KTS and the cross-strait SLD between Moji, Japan and Pusan, Korea (see Fig. 3 for the locations) after a correction is applied to SLD using cross-strait hydrographic sections to remove baroclinic effects. The baroclinic effects lead to an overestimate of the transport by up to 40% in summer (Fig. 9). SLD between Moji and Pusan can provide good estimates of the absolute transport through the KTS continuously. Since the sea level data have been measured for about forty years, it is possible to investigate long-term transport variations in the KTS, which affect the circulation in the East Sea. The long-term variations can be related
to changes in the structure of the Kuroshio and the wind stress in the North Pacific, which will be described shortly. Studies on the long-term variation of the transport using the sea level data are underway.

Limited-area numerical models of the East Sea usually have open boundaries along the straits of the East Sea. The open boundary conditions adopted in the models mainly specify the constant (e.g., Hogan & Hurlburt, 2000) or the seasonal variation of the transport through the straits (e.g., Kim & Yoon, 1999). Because the subinertial and interannual variations are predominant, directly observed transport variations need to be used for the specification of the open boundary conditions, at least along the KTS boundary.

### 3.3. Korea Strait Bottom Cold Water

It has long been recognized that an outflow of cold water, called the Korea Strait Bottom Cold Water (KSBCW), takes place from the East Sea to the KTS (An, 1974; Lim, 1973; Lim & Chang, 1969; Nishida, 1927). The KSBCW is usually defined as a water mass with a temperature less than 10°C, and the widespread extent of the KSBCW in the KTS occurs frequently in summer (Lim, 1973; Lim & Chang, 1969; Yun, Kang, Cho, & Moon, 1992). Fig. 10 shows vertical sections of temperature and salinity across the KTS in July 1973. The KSBCW can be seen in the western end of the section from the coast of Korea to a deep trough northwest of Tsushima Island. Salinity of the KSBCW is less than 34.3, and it forms a strong thermocline together with overlying warm and saline TCW (14°C < T < 17°C, S > 34.3). The coldest water with temperature less than 4°C is found in the trough.

The subtidal southwestward velocity is about 5–15 cm s⁻¹ near the coast of Korea (Lim, 1973). Stronger southwestward velocity (>30 cm s⁻¹) is often found in the deep trough in the western channel of the KTS (Byun & Kaneko, 1999; Shinozaki et al., 1996). The southwestward flow in the trough is rather persistent (Kim, 2002; Park, Lee, Lee, & Byun, 1999). Long-term moored current measurement between May 1993 and March 1995 shows quasi-stable southward bottom currents in the trough, except in February and March 1994 (Fig. 11). Monthly mean southwestward velocities for year 1 and year 2 showed their maxima...
in June with speeds of $8 \text{ cm s}^{-1}$ in 1993 and $10 \text{ cm s}^{-1}$ in 1994. Northward currents were the strongest in March 1994 with a speed of $10 \text{ cm s}^{-1}$.

Lim and Chang (1969) suggested that the origin of the KSBCW is the ESPW partially mixed with the TCW. Kim and Kim (1983), Lim (1983), Kim, Lie, and Chu (1991a), and Cho and Kim (1998), however, suggest the KSBCW originates from the either the coastal (NKCW: North Korean Cold Water) or the off-shore mode of the ESIW above the ESPW (see Section 4.5). Two shapes in the structure of the KSBCW have been observed in the KTS: uplift of the interface between the TCW and the KSBCW at its western

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**Fig. 10.** Vertical sections of temperature and salinity across the Korea/Tsushima Strait in June 1993. Locations of CTD stations (●) are shown in the upper panel along with bottom topography in meters. + denotes the position of current meter mooring where the bottom current shown in Fig. 11 was measured.
Fig. 11. Vector time series of low-pass filtered currents at 205 m depth in the deep trough in the Western Channel of the Korea/Tsushima Strait. The location of current meter mooring is shown in Fig. 10 (+). Total depth of the mooring location is 220 m.
end towards the coast of Korea (Fig. 10; Byun, 1989; Lim & Chang, 1969; Lim, 1983; Seung, 1986), and an arch-shape interface (Cho & Kim, 1998; Isobe et al., 1994). The uplift of the interface towards the coast of Korea appears to be more commonly observed. The arch-shape interface occurs either in winter (Isobe et al., 1994) or in summer (Cho & Kim, 1998). The uplift of the interface may be a Rossby adjustment to a sudden increase of the Tsushima Current (Seung, 1986) or it may be the result of offshore Ekman transport due to alongshore wind (Byun, 1989). Park, Cho, and Kim (1995) and Cho and Kim (2000) suggest the KSBCW is hydraulically controlled such a way that the KSBCW flowing south separates from the eastern wall of the channel and hugs the coast of Korea to conserve the potential vorticity as the channel shoals downstream of the KSBCW.

The KSBCW does not seem to flow out to the East China Sea, and the southern limit of the KSBCW is known to be the southern end of the western channel of the KTS (Lim, 1973). It implies that the KSBCW returns to the East Sea again. Another possible way for the KSBCW to return is via an entrainment of the cold water into the upper TCW (Cho & Kim, 1998). Bottom currents and temperature from LINKS data show no distinct advective intrusion to southwest on a monthly averaged scale and only intermittent advective intrusion on a daily averaged scale with a speed of about 10 cm s\(^{-1}\) (Johnson & Teague, 2002). Instead, bottom currents tend to be directed toward the coast of Korea during low temperature episodes implying the existence of the return flow. Fig. 12 shows the distribution of low-pass filtered temperature and currents from LINKS data. Cold water with temperature less than 10°C appeared at N1 and N2 close to the coast of Korea almost all the year round. The bottom currents, however, are predominantly northward. Low temperature episodes with temperature less than 5°C occurred in May–June 1999 and December 1999–January 2000. Conceivable southward bottom currents were only observed in December 1999–January 2000. It is suggested that the appearance of the KSBCW affects the branching of the Tsushima Current in the KTS, which is reviewed in Section 4.7.

### 3.4. Dynamical aspects of the low-frequency transport variation

The branching of the Tsushima Current from the Kuroshio, beyond the scope of this paper, has been studied by Lim (1971), Huh (1982), Ichiye (1984), Ichiye and Li (1984), Yuan and Su (1988), Fang, Zhao, and Zhu (1991), Oey and Chen (1991), Katoh et al. (1996), Lie and Cho (1994), Hsueh, Lie, and Ichikawa (1996), Isobe (2000), and Ichikawa and Beardsley (2002). The mean transport and variability of the Kuroshio in the East China Sea remains controversial because most estimations are based on snapshots from hydrographic surveys. Estimates of the mean Kuroshio transport vary from 21 to 33 Sv (Bingham & Talley, 1991; Guan, 1983; Ichikawa & Beardsley, 1993; Nitani, 1972). The mean Kuroshio transport east of Taiwan was 21.5 Sv according to moored current meter observation spanning the entire Kuroshio section for 20 months (Johns et al., 2001). The mean transport of the Tsushima Current through the KTS is about 2–3 Sv based on LINKS (Teague et al., 2002) and cable (Kim et al., 2004) data. Hence, about 10% of the Kuroshio transport enters the East Sea.

Attempts have been made to understand factors affecting the Tsushima Current transport through the KTS (Minato & Kimura, 1980; Nof, 1993, 2000; Ohshima, 1994; Ou, 2001; Seung, 2003; Toba, Tomizawa, Kurasawa, & Hanawa, 1982). Ou (2001) suggests hydraulic control of the transport, which is dependent only upon upstream layer depth. Crude estimation for the Tsushima Current gives a large transport in summer and small in winter. Other studies attempted to investigate the transport of the Tsushima Current using a simple domain that consists of a marginal sea and an ocean basin.

Minato and Kimura (1980) (MK hereafter) extended the steady, linear, barotropic model of Stommel (1948) to a wind-driven ocean connected in the west to a shallow marginal sea through two narrow straits. In MK’s model, the Tsushima Current is generated by meridional pressure difference between the KTS and the Tsugaru Strait. The transport of the Tsushima Current is determined by bottom friction, depth ratio
between the marginal sea and deep ocean, width of straits, and the location of the straits on a $\beta$-plane. The MK's hypothesis was supported later by Toba et al. (1982) and Ohshima (1994).

Nof (1993) introduced a $\beta$-controlled, penetration-flux formula using a baroclinic, inviscid, non-linear model, which states that the transport of the Tsushima Current can be expressed as a function of the stratification in the North Pacific, the separation latitude of the Kuroshio, and the undisturbed thickness of the Kuroshio.

The applicability of the island rule of Godfrey (1989) was investigated to determine the transport of the Tsushima Current using a barotropic numerical model with an idealized domain that consists of an ocean and a marginal sea (KORDI, 1996). Godfrey's island rule assumes that Sverdrup theory is applicable. If the rule is applied to the transport through the KTS or the streamfunction around Japan (Honshu), it dictates that variations in the depth-integrated transport through the KTS result from variations of path integral of zonal wind stress over the North Pacific and along the west coast of Japan. The path integral starts from the
eastern boundary (west coast of USA) at the latitude of the northern tip of Japan, and ends to the eastern boundary at the latitude of the southern tip of Japan. Godfrey’s rule is a linear, baroclinic, and inviscid model developed to examine the flux of the Indonesian throughflow (e.g., Wajsowicz, 1993). In a weakly non-linear regime, the variation of the flux into the marginal sea is shown to be in phase with the variation of the wind stress field in the North Pacific, although the bottom friction and shoaling topography of the marginal sea significantly reduce the transport as compared to the predicted transport by the island rule. As the non-linearity increases, the temporal variation of the transport is amplified and has higher frequency than that of the wind-stress variation.

Nof (2000) investigated various models applicable to the estimation of the volume transport of the Tsushima Current, including Godfrey’s Island rule, Nof (1993, 1995)’s baroclinic models, a 1.5-layer isopycnal model, and the MK’s model. The baroclinic models are all inviscid and non-linear models, except for Godfrey’s island rule which is linear. At the latitude of the East Sea, the transport estimations using the baroclinic models give a similar value. On the other hand, the MK’s model gives about two times larger transport as compared to that in baroclinic models. The estimated transport from the baroclinc models, however, is about 10 Sv, which is much larger than the observed transport.

Seung (2003) considered both the baroclinicity and bottom friction, and showed that his formulation gives closer estimation (~2.5 Sv) for the transport of the Tsushima Current. According to him, the transport into the marginal sea is proportional to the Sverdrup transport in the North Pacific like Godfrey’s island rule, and inversely proportional to the bottom friction and the depth ratio between the ocean and marginal sea. The latter tendency is also shown by other barotropic models (Nam, Suk, Bang, Chang, & Seung, 1996; Seung & Nam, 1992).

The dynamical studies of the Tsushima Current suggest that the low-frequency variability of the transport results from the large-scale wind-stress in the North Pacific and the structure of the Kuroshio in the East China Sea. The models used to understand the dynamics of the Tsushima Current and to parameterize its transport adopted idealized basin configurations. It is required to use a realistic model that includes the North Pacific and the East Sea in its domain to assess the various parameterizations and to improve our understanding of the penetration of the Tsushima Current into the East Sea. Large-scale modeling of the North Pacific comprising the East Sea has been carried out (e.g., Kagimoto & Yamagata, 1997), but specific focus has not been made on the relationship between the large-scale wind field and the transport of the Tsushima Current, which deserves future study. The dynamical studies also imply that changes in the Kuroshio structure in the North Pacific due to climate change (e.g., Choi, Kim, & Kim, 2002) would result in long-term variation in the transport of the Tsushima Current, and thus also in the upper circulation in the East Sea.

4. Upper circulation in the Ulleung Basin

The Tsushima Current, entering the East Sea through both the eastern and western channels of the KTS, transports warm and salty TCW into the East Sea, which occupies the upper 150 m in the southern East Sea. The Tsushima Current has a profound impact on the upper circulation, and the formation of fronts and eddies in the East Sea. A strong seasonal pycnocline is formed in summer between the warm, low salinity water originating over the shelf of the East China Sea and high salinity water of the Kuroshio origin, both of which are carried by the Tsushima Current (Lim & Chang, 1969). The salty TCW can be traced by a salinity maximum layer that frequently occurs between 50 and 150 m depth south of the polar front, but the salinity maximum layer is not obvious north of the polar front (Hong & Cho, 1983a). The high salinity core of the TCW has low dissolved oxygen content (Hong & Cho, 1983a, 1983b).
4.1. Mean circulation

Mean flow patterns of the Tsushima Current have been proposed mostly based on analyses of property distributions and dynamic topography at around 100 m depth: branching pattern (e.g., Suda & Hidaka, 1932; Uda, 1934), single meandering pattern (e.g., Moriyasu, 1972), and the combination of these two patterns (e.g., Naganuma, 1977). Isotherms at 100 m depth have been thought to represent well the isopycnals and thus the streamlines for the upper circulation in the East Sea (e.g., Ichiye & Takano, 1988), because water masses in the East Sea are rather homogeneous except in the upper tens of meters (Moriyasu, 1972). The different views on the path of the Tsushima Current seem to suggest the strong variability of the upper circulation in the southern East Sea, or to arise from the limitation of the spatial and temporal coverage of data used. An example of the schematic mean circulation is depicted in Fig. 13, which shows three branches of the Tsushima Current as well as numerous mesoscale eddies and meanders.

The branching pattern is still widely accepted (e.g., Katoh, 1994), and the Tsushima Current splits into three branches downstream of Tsushima Island: the Nearshore Branch (NB), the Offshore Branch (OB), and the East Korean Warm Current (EKWC) or the first, second, and third branches, respectively. The Tsushima Current passing through the eastern channel of the KTS feeds the quasi-permanent NB that flows to the northeast along the Japanese coast, following the isobaths shallower than 200 m (Hase et al., 1999; Katoh, 1993; Katoh, 1994; Katoh et al., 1996; Lee, Lee, Lee, & Lie, 1997). The OB is fed by the Tsushima Current flowing through the western channel of the KTS (Lee et al., 1997), and flows to the northeast offshore of the NB, trapped along the continental shelf break and slope off the coast of Japan (Hase et al., 1999). It is shown that the OB can be traced by the thermal front at 100 m depth (Katoh, 1994).

Fig. 13. Schematic surface current chart by Naganuma (1977). C, cold-water region; W, warm-water region; H, relatively high temperature region. LCC, NKCC, EKWC, and NB denote the Liman Cold Current, the North Korean Cold Current, the East Korean Warm Current, and the Nearshore Branch, respectively. Although the Offshore Branch (OB) is not expressed in the Naganuma's chart, its existence flowing northeastward offshore of the NB is obvious in the chart.
The OB shows a strong baroclinic structure with underlying countercurrent, and it is suggested that the OB is highly variable and develops from spring to fall when the volume transport through the KTS is high (Hase et al., 1999; Kawabe, 1982). Part of the TCW passing through the western channel of the KTS forms the EKWC flowing northward along the east coast of Korea. The EKWC encounters the southward flowing North Korean Cold Current (NKCC) between 37°N and 38°N, where it separates from the coast. The EKWC splits into two parts after its separation from the coast. Part of it flows towards the east or northeast (Lie, Byun, Bang, & Cho, 1995), and part forms a large meander in the vicinity of Ulleung Island. The interior of the meander forms an anticyclonic eddy (Cho, Bang, Shim, & Yu, 1990; Lie et al., 1995) called the Ulleung Warm Eddy (UWE; Kang & Kang, 1990; Shin, Byun, & Kim, 1995). Thus, part of the EKWC retroreflects. We will describe the UWE more in detail shortly. The meandering of the EKWC can be seen in climatological temperature maps (see Fig. 15), and Tanioka (1968) reported that 80–90% of the volume transport of the EKWC returns southward around Ulleung Island based on the dynamic calculation.

The mean temperature field at 100 m from the PIES data indicates that the upper circulation of the UB is characterized by the northward flowing EKWC, the meandering of the EKWC, the anticyclonic UWE, and the OB in the southeastern UB (Fig. 14(a)). The EKWC flowing along the east coast of Korea separates from the coast at around 37.5°N to flow eastward, and part of it meanders to the southwest. The anticyclonic UWE is centered southwest of Ulleung Island at around 37°N and 130°45′E and forms an interior of the EKWC meander. A small-scale cold eddy appears south of Dok Island inside the meandering trough of the EKWC, which has been recognized in previous studies (e.g., Katoh, 1994; Tanioka, 1968), and is called the Dok Cold Eddy (DCE) by Mitchell et al. (2004). The formation of the DCE is associated with the meandering of the EKWC (Hirose & Ostrovskii, 2000; Tanioka, 1968). The eastward extension of the EKWC encounters cold waters in the coastal and offshore areas with the polar front in between them. The coastal cold water north of the separated EKWC is carried by the NKCC. A relatively cold coastal water also appears south of 36.5°N. The OB flows northeastward along the southeastern periphery of the UB.

Drifter data have been used to describe the surface circulation and eddy kinetic energy (EKE) in the East Sea (Lee et al., 2000; Lie et al., 1995). Recently, Lee and Niiler (2004) calculated daily averaged current data.
from 230 Argos surface drifters drogued at 15 m that traversed through the East Sea between 1991 and 2001 to prepare a horizontal map of surface currents in the East Sea. For the analysis of drifter data, velocity values were grouped in area (0.5° × 0.5° grid similar to the spacing of the PIES array) and time boxes to give distribution of mean current at the center point of each grid. The mean surface currents were deduced by averaging data in geographical boxes and the resulting values represent spatial-temporal averages over the box area and the period during which the drifter data were available in the box. In general, surface currents in the UB and Yamato Basin are stronger and more variable than those in the Japan Basin. Strong surface currents occur in East Korean Bay and off Vladivostok north of polar front (Lee & Niiler, 2004).

Mean current vectors in the UB based on the drifter data are shown in Fig. 14(b). All vectors in Fig. 14(b) have standard errors less than the mean, and the variability for the weak currents (blue vectors in Fig. 14(b)) defined by variance ellipses is large, especially in the center of the UB. The mean current distribution in the UB clearly shows the separation of the Tsushima Current into the EKWC and OB downstream of the KTS. The northward flowing EKWC can be recognized north of 38°N, but the mean velocity of the EKWC sharply decreases at around 37.5°N where the EKWC separates from the coast to flow eastward or southeastward. The mean speed of the northward EKWC is larger than 20 cm s⁻¹ at around 36.5°N. Strong (~8 cm s⁻¹) mean southeastward current appears between 37° and 37.5°N off the coast where the separation of the EKWC occurs. The southward NKCC along the coast is indistinct in the mean current map, and the surface current is weak west of 130°E and between 37.5°N and 38.5°N. Part of the eastward flowing EKWC forms the anticyclonic UWE south of Ulleung Island, and part of it continues to flow eastward which merges with a strong northeastward flow west of Yamato Rise.

Although the averaging periods are different, the mean circulation based on the drifter and PIES data shows similarity in the branching of the Tsushima Current and the generation of the EKWC and OB along the coasts of Korea and Japan, the separation location of the EKWC from the coast, and the formation of the UWE and its location.

The NKCC forms one of major currents in the East Sea originating from the Japan Basin off the Primorsky coast and flowing to the south along the western boundary (Kim & Seung, 1999) because of the positive wind stress in winter (Yoshikawa, Awaji, & Akimoto, 1999). It flows southward, at surface off North Korea (Uda, 1934) and at intermediate depths under the EKWC in the southern part of the East Sea (Kim & Kim, 1983). Short-term current measurements off the east coast of Korea evidenced the southward coastal currents at around 37°N (Lie, 1984) and 38°N with a 10-day long mean speed of 20–50 cm s⁻¹ (Lie & Byun, 1985). Deep southward currents will be discussed in Section 5. Trajectories of surface drifters also indicate the existence of the southward surface current along the inshore part of the EKWC in spring and summer (Lee & Niiler, 2004). A drifter deployed north of 38°N off the coast moved south to near 36°N along the coast with a speed range of 22–43 cm s⁻¹ in fall 1999. The width of the southward current appears to be narrow according to the trajectory of the drifter, which sharply turned to the north near 36°N and moved eastward at around 38°N. The existence of the southward flow along the coast, however, is not clear in the mean surface current distribution shown in Fig. 14(b), probably due to high variability of the coastal current and/or the paucity of data close to the coast.

### 4.2. Variability

Variability of the upper circulation in the East Sea has been examined using data from hydrographic surveys (e.g., Katoh, 1994), satellite-tracked drifters (Lee et al., 2000), and satellite altimetry (Hirose & Ostrovskii, 2000; Jacobs, Hogan, & Whitmer, 1999; Morimoto, Yanagi, & Kaneko, 2000; Morimoto & Yanagi, 2001). The typical length scale of an eddy in the East Sea is about 30–160 km (e.g., Park & Chung, 1999). Horizontal resolutions of tracks of TOPEX/Poseidon (T/P) and ERS-2 satellites are about 300 and 70 km, respectively. Hence, the basin-scale circulation and variability cannot be reasonably resolved using the T/P alone, although it provides more accurate sea surface height data as compared to
ERS-2. Inadequate removal of tidal signals and inaccuracy of geoid data further limit the use of altimeter data in the East Sea. Nevertheless, attempts have been made to investigate the variability of upper circulation along specific tracks of T/P (Hirose & Ostrovskii, 2000), and by combining T/P and ERS-2 data (Morimoto et al., 2000). A technique for blending or assimilating altimeter data with numerical models has also been attempted to examine the circulation (Morimoto & Yanagi, 2001) and variability (Hirose & Ostrovskii, 2000).

The southern half of the East Sea is characterized by high EKE for surface currents (Lee et al., 2000) and high RMS variability of temporal fluctuations of sea surface height (Morimoto et al., 2000). It suggests that the upper circulation is highly variable south of the polar front where warm water masses carried by the Tsushima Current prevail and surface currents are relatively strong as compared to those in the Japan Basin. The UB is one of the most energetic regions in the East Sea. Attempts have been made to examine the seasonal (Isoda & Saithoh, 1993; Morimoto & Yanagi, 2001), interannual (Katoh, 1994), and quasi-biennial (Hirose & Ostrovskii, 2000) variability of the upper circulation. Using composite sea surface height data combined with numerical model results between May 1995 and October 1998, Morimoto and Yanagi (2001) suggest that the Tsushima Current including the EKWC strengthens in summer and weakens in winter in phase with the seasonal variation of the transport through the KTS. They mentioned that the surface cyclonic gyre in the Japan Basin also exhibits the same seasonal tendency as the Tsushima Current, which is contrary to the trend from numerical model results (e.g., Kim & Yoon, 1999). Tanioka (1966) estimated the volume transport of the EKWC with its maximum in October and minimum in February. The seasonal variation of surface currents, however, is not obvious in the EKWC region along the east coast of Korea from a long-term drifter dataset (Lee & Niiler, 2004). Analyzing hydrographic data taken between 1970 and 1979, Hong and Cho (1983a) suggested two flow patterns of the Tsushima Current are possible in summer: one with the EKWC, and the other without the EKWC and the Tsushima Current only flowing to the northeast along the coast of Japan. Later, Katoh (1994) suggested five patterns of summertime (August) upper circulation based on temperature distribution at 100 m during 1976–1990. The patterns show different regimes of upper circulation that mainly arise from the strengthening and weakening of the EKWC and the path variability of the OB.

Bi-monthly climatological temperature maps at 100 m south of polar front and west of 140°E are shown in Fig. 15. The maps are based on 30-year mean data between 1961 and 1990 grouped in 0.5° × 0.5° grid (Naganuma & Ichihashi, 1993). Meridional gradient of temperature south of 36°N suggests the warm inflow through the eastern and western channels of the KTS forms the NB and OB. Zonal gradient of temperature off the east coast of Korea is due to the northward flowing EKWC. Some of isotherms turn to the east at around 37.5°N, indicative of the separation of the EKWC which then meanders to the south. The meander trough occurs around 132°E, and the UWE, which forms the interior of the meander, can be seen south of Ulleung Island. Deep southwestward penetration of the meander trough occurs in December. The minimum and maximum temperatures south of Ulleung Island occur in April and December, respectively, and the maximum temperature of the TCW in the KTS also occurs in fall. Coastal cold water is obvious throughout the year west of 130°E with the maximum temperature in December. The horizontal temperature gradients are stronger in summer and fall than in winter, indicative of the stronger upper circulation in summer as compared to the wintertime circulation.

Mesoscale variability of the upper circulation has been poorly understood due to the limitation of temporal coverage of data, although it is expected to be dominant. PIES data provide, for the first time, an opportunity to investigate the mesoscale variability of synoptic upper circulation in the UB. According to the evolution of the temperature field at 100 m from the PIES data, the variability of upper circulation in the UB arises from the path variability of the EKWC and OB, meandering of the EKWC, evolution of the UWE and DCE, and the fluctuation of polar front (Mitchell et al., 2004). At least five quasi-stable non-repetitive flow patterns have been identified during the two-year period (Fig. 16). Each pattern persisted 3–5 months with a period of the transition between successive patterns ranging from a few days to a couple of
Fig. 15. Bi-monthly climatological temperature maps at 100 m depth based on data averaged for 30 years 1961–1990 by Naganuma and Ichihashi (1993).
months. Hence, the mesoscale variability is dominant in the upper circulation during the two-year period between June 1999 and June 2001.

Pattern 1 observed during the first three and half months is characterized by the northward flowing EKWC, the UWE south of Ulleung Island, and the DCE south of Dok Island (Fig. 16(a)). The first pattern then evolved successively to an amplification of the UWE (Transition), shrinking of the UWE (Pattern 2), deep southwestward penetration of the DCE followed by the disappearance of the EKWC (Pattern 3), re-establishment of the EKWC (Pattern 4), and the formation of a large meander of the EKWC associated with a strong southward intrusion of the polar front (Pattern 5). The OB persisted for the observation period with high variability, and the horizontal temperature gradient increased in the OB region during Pattern 3 when the disappearance of the EKWC occurred, indicative of the strengthening of the OB. The UWE also persisted for about 20 months from June 1999 to March 2001 although it experienced changes its size and position. The observed patterns are more or less similar to the patterns classified by Katoh (1994) based on hydrographic data obtained in August, which implies that summertime circulation patterns classified by Katoh (1994) may be the expression of the irregularly evolving mesoscale variability of the upper circulation.

4.3. East Korean Warm Current

The EKWC has been recognized by Uda (1934) as a branch of the Tsushima Current flowing northwards along the east coast of Korea. Dynamic calculations using hydrographic data indicate that (1) the mean surface velocity of the EKWC ranges from 17 cm s\(^{-1}\) in winter to 50 cm s\(^{-1}\) in summer, (2) an annual mean

![Fig. 16. Mean temperature at 100 dbar (a, c, d, e, f) for each of the five quasi-stable patterns observed between June 1999 and June 2001, and (b) on November 21, 1999 during the period of transition between Patterns 1 and 2. (Redrawn from Mitchell et al., 2004).](image-url)
northward transport ranges from 1 Sv relative to 200 dbar to 3 Sv relative to 300 dbar with a maximum in fall, and (3) 80–90% of the northward transport returns back to the south as a countercurrent just east of the northward flowing EKWC (Tanioka, 1966, 1968). The main axis of the EKWC approaches the coast in winter and moves farther offshore in summer, and the NKCW appears between the coast and the EKWC in summer (Tanioka, 1968).

The EKWC has been thought to be a permanent feature, a western boundary current induced by the planetary $\beta$ effect (e.g., Morimoto & Yanagi, 2001; Yoon, 1982a, 1982b). It appears to be so according to climatological temperature maps shown in Fig. 15. However, disappearances of the EKWC have been reported. Isoda and Saithoh (1993) suggested that the EKWC is a manifestation of the episodic northward intruding eddy process rather than a persistent branch of the Tsushima Current, and that it disappears in winter. The disappearance of the EKWC was also reported to occur in April 1981 (Kim & Legeckis, 1986) and in winter of 1989–1992 (Cho & Kim, 1996). Cho and Kim (2000) suggested that the disappearance of the EKWC in winter and spring is a permanent feature, and it is related with the strengthening and weakening of the KSBCW. However, the disappearance of the EKWC also occurred in summer of 1970, 1971, 1974, 1977, 1981, and 1986 during the period between 1970 and 1990 according to Hong and Cho (1983a), Hong, Cho, and Yang (1984), and Katoh (1994). Katoh (1994) included the case of the disappearance of the EKWC as one of five patterns of summertime upper circulation in the southwestern East Sea. The above-mentioned studies on the EKWC are all based on hydrographic data from a single survey or snapshots of satellite-derived SST. The disappearance of the northward flowing EKWC occurred between mid-June and early November 2000 according to PIES data (Pattern 3 in Fig. 16(d)), so the EKWC was absent for five months. The UWE has remained south of Ulleung Island during this period but with its horizontal scale reduced. Horizontal distribution of temperature at 100 m depth using CTD data taken in August and October 2000 by NFRDI also evidences the disappearance of the EKWC during this period (Fig. 17). It is suggested that the disappearance of the EKWC results from the merging of the DCE with coastal cold water (Mitchell et al., 2004). The coastal cold water is regarded as the NKCW carried southward by the NKCC (Kim & Kim, 1983).

According to Hong et al. (1984) and Kim and Legeckis (1986), the disappearance of the EKWC occurred in spring and summer 1981. Fig. 18 shows temperature distributions at 100 m depth in 1981 based on NFRDI data. The UWE was located around Ulleung Island in February similar to the zonally elongated UWE observed in winter 1999 and 2000 (Fig. 16(b)). A wide area occupied by cold waters ($T < 4.0^\circ$C) occurred south of the UWE between 36° and 36.5°N. The cold waters were observed in February and April. The UWE shrunk in August 1981 with its center located southwest of Ulleung Island, which is very similar to Pattern 3 in Fig. 16(d). The thermal front north of the UWE moved to the north, the UWE core warmed up, and its size was enlarged in October as compared to that in August 1981. In December 1981, the coastal cold water retreated north of 37°N, and the EKWC has re-established. Both the 1981 data and PIES data suggest that the disappearance of the EKWC is associated with the development of a band of cold water between 36° and 37°N.

A disappearance of the EKWC, indicated from PIES data, began in mid-June 2000. Strong subsurface southward flow was observed between mid-July and mid-August 2000 in the UIG, and the deep southward flow during this period in the UIG was exceptionally strong during the entire period of current measurement between 1996 and 2002 (see Fig. 29). The bottom flow at EC3 in the central UB was also exceptionally strong during this period (see Fig. 25). The strengthening of the deep flow in the UIG does not seem to trigger the disappearance of the EKWC, because the strengthening of deep currents occurred after the disappearance of the EKWC. It is inconclusive whether or not the observed strong deep flows in
the UIG and central UB are associated with the disappearance of the EKWC. The bottom flow at EC4 over the continental slope off the coast of Korea was not especially strong during the period of the disappearance of the EKWC (see Fig. 25).

4.4. Ulleung Warm Eddy

Strong variability in the East Sea arises from numerous eddies and meanders (e.g., Ichiy & Takano, 1988; Sugimoto & Tameishi, 1992). Diameters of either warm or cold eddies in the East Sea range from 30 to 160 km (Ichiy & Takano, 1988; Matsuyama, Kurita, Senju, Koike, & Hayashi, 1990; Miyao, 1994; Park & Chung, 1999; Toba, Kawamura, Yamashita, & Hanawa, 1984). The UB is one of the regions where the quasi-stationary anticyclonic UWE, exists. The UWE forms the interior of the EKWC meander.

Fig. 17. (a) Temperature and (b) salinity in August 2000, and (c) temperature and (d) salinity in October 2000 at 100 m depth based on NFRDI data.
Kim and Yoon (1999) called the UWE the recirculation gyre of the EKWC, and suggest it is generated by the diffusion of the negative vorticity in the western boundary current. Trajectories of satellite-tracked drifters showed that the UWE was stationary in the UB for about 10 months between December 1992 and September 1993 (Lie et al., 1995). The surface expression of the UWE

(Cho et al., 1990; Lie et al., 1995). Kim and Yoon (1999) called the UWE the recirculation gyre of the EKWC, and suggest it is generated by the diffusion of the negative vorticity in the western boundary current. Trajectories of satellite-tracked drifters showed that the UWE was stationary in the UB for about 10 months between December 1992 and September 1993 (Lie et al., 1995). The surface expression of the UWE
is often characterized by a cold core wrapped by a warm filament (Fig. 19), while the subsurface structure across the UWE shows a warm core (Fig. 20). The horizontal scale of the UWE is between 50 and 150 km with the maximum depth of the thermostad of about 150 m at its center (Cho et al., 1990; Lie et al., 1995; Shin et al., 1995). It is suggested that the UWE is maintained in the UB due to the meandering of the EKWC, bottom topography, and the polar front north of the UWE (Lie et al., 1995; Lim & Kim, 1995; Seung, Nam, & Lee, 1990). It is shown that the development and disappearance of the EKWC affects the horizontal scale of the UWE (Cho et al., 1990; see also Fig. 16). When the EKWC disappeared in 1981 (Fig. 18), the UWE had a smaller size than that in 1982.

According to PIES data, the UWE had rested south of Ulleung Island for about 20 months from the beginning of the observation until the period of Pattern 4 (Fig. 16(e)). Highly-resolved upper ocean measurements were conducted using a towed, undulating vehicle (SeaSoar) along 37° 45’N (see Fig. 2 for the SeaSoar track) in May 1999, one month prior to the PIES deployment, and in January 2000 during the transition period between Patterns 1 and 2. Two eddies were captured by the SeaSoar both in May 1999 and January 2000 (Fig. 20). The eddy in the eastern part of the section is an intrathermocline eddy (ITE) (Gordon et al., 2002). The ITE water has elevated levels of dissolved oxygen as compared to those of the UWE, indicating that the ITE has been formed from winter mixed layer water along the polar front. The subduction of the ITE and associated circulation dynamics were investigated by Ou and Gordon (2002).
The eddies observed in May 1999 and January 2000 in the western part of the section are not the same. An SST image at the time of the SeaSoar survey in May 1999 (Fig. 19) indicates that part of the EKWC forms the UWE seen in Pattern 1 (Fig. 16(a)). Part of the EKWC water continued to flow north, turned eastward, and formed another warm eddy northwest of Ulleung Island. The SeaSoar survey crossed the eddy north of Ulleung Island, which is not obvious in Pattern 1 in Fig. 16(a), probably because the eddy was displaced or dissipated before the deployment of the PIES array. The eddy observed in January 2000 is the UWE which had been observed in PIES data for 20 months in the UB. The SeaSoar survey in January 2000 crossed the UWE during the transition period between Patterns 1 and 2 (Fig. 16(b)) when the UWE was located farther north and became zonally elongated as compared to that during the period of Pattern 1.

The warm eddy occupied the western half of the SeaSoar section in May 1999 with core potential temperature ($\theta$) between 9.0 and 10.0°C, salinity between 34.1 and 34.2, and potential density ($\sigma_0$) between 26.0 and 26.4 kg m$^{-3}$, respectively (Fig. 20(a)). The eddy core is capped by warmer and saltier surface waters above the weakly developed thermocline. The horizontal scale of the eddy is about 150 km and the maximum thickness of the thermostad at the center of the eddy is 150 m. Two troughs, about 50 km wide and 50 m deep, of high upper layer salinity water ($S > 34.3$) appear along the western and eastern rims of the eddy. This feature indicates a filament of the EKWC that extends northward to this latitude, separates from the east coast of Korea, and wraps around the edge of the eddy in an anticyclonic sense. A concurrently obtained velocity section using a vessel-mounted ADCP shows the circulation around the eddy is anticyclonic with a peak meridional velocity ($V$) of about 60 cm s$^{-1}$ near the surface (Fig. 21(a)). While the water
characteristics have symmetric features for the eddy, the velocity distribution is asymmetric. A strong vertical shear of $V$ occurs in the upper layer of the western part of the eddy, but the vertical shear is less prominent and strong southward flow greater than 30 cm s$^{-1}$ extends to the deeper layer below 200 m depth in its eastern part.

The UWE in January 2000 had a horizontal scale of about 200 km, larger than the scale of the warm eddy observed in May 1999. The seasonal thermocline had disappeared and the maximum thickness of the thermostad at the center of the UWE was about 150 m in January. A low salinity core ($S < 34.1$) occurred at the center of the UWE, and a thin layer of saltier ($S > 34.2$) and strongly stratified water forms the lower boundary of the UWE. The high salinity EKWC water that wrapped around the periphery of the UWE in May 1999 was not seen in January. The ITE could also be seen in the eastern part of the section, submerged below 140 m. Vertical sections of velocity components in January 2000 indicate an expansion of the high-velocity area (Fig. 21(b)). Strong vertical shear of $V$ in the upper 50 m observed in May 1999 in the western half of the UWE became reduced, and high velocity greater than 30 cm s$^{-1}$ extended to about 150 m. The zonal component of velocity was positive in the UWE and the magnitude is comparable to $V$ in January 2000 because the SeaSoar section crossed the UWE oriented northeast-southwest as can be seen in Fig. 16(b). Southward flow (NKCC) was observed off the coast of Korea both in May 1999 and January 2000, and the velocity was higher in January 2000 (>20 cm s$^{-1}$) than in May 1999.

A CTD survey, which was made along a zonal section at 37°35’N in May 2000 during the period of Pattern 2 in Fig. 16(c), also captured the UWE (Fig. 23(a)). Vertical sections of temperature, salinity, and density are similar to those observed north of the UWE in May 1999 (Fig. 20), and the core temperature and density in May 2000 were nearly the same as those in May 1999. The core temperature and
salinity of the UWE decreased and increased, respectively, in May 2000 as compared to those in January 2000. As the formation of the UWE is associated with the meandering of the EKWC, the property changes of the UWE would mainly arise from the interaction of the UWE with the EKWC. Local effects like the vertical mixing, however, would also affect the changes, which deserves future study.

4.5. East Sea Intermediate Water

The existence of an intermediate water lying between the TCW and the ESPW seems to have been noted first by Miyazaki (1953). He classified cold water \((T < 6.0^\circ C)\) into three water masses: Ci-water, Cm-water, and Cd-water. The Ci-water has a temperature range of 1–6°C and is characterized by a salinity-minimum (SML) and a dissolved oxygen-maximum layer. Kajiura, Tsuchiya, and Hidaka (1958) also identified a water mass similar to the Ci-water and called it a fourth water mass. The widespread presence of the SML between the TWC and the ESPW has been also observed in the UB (Kim et al., 1991a; Kim & Chung, 1984), and Kim and Chung named it the East Sea Intermediate Water (ESIW). The SML in the UB occurs between 100 and 300 m depth, and coincides with the maximum concentration of dissolved oxygen (Kim & Kim, 1983; Kim & Chung, 1984). Salinity of the ESIW is generally less than 34.06 with \(\theta\) between 1 and 5°C (Kim & Kim, 1999).

Reports were given of the bimodality of the ESIW in the UB (Cho & Kim, 1994; Kim et al., 1991a): a coastal mode along the east coast of Korea (Kim & Kim, 1983) and an offshore mode spreading to the UB from the north (Kim, Chung, & Yoo, 1991b). It is suggested that the offshore mode is brought into the UB from the polar front after subducting below the warm waters along the subpolar front (Kim et al., 1991b). Meridional sections across the polar front show the subduction of the ESIW below the saline waters (Kim, Kim, Cho, Takematsu, & Volkov, 1999; Yoon & Kawamura, 2002). The source water of the ESIW in the Japan Basin shows a cyclonic circulation (Kim & Kim, 1999; Senjyu & Sudo, 1994), part of which leaks southward above Yamato Rise (Isobe & Isoda, 1997). The coastal mode of the ESIW, which is also called the NKCW, has been thought to be carried southward by the NKCC (Kim & Kim, 1983; Kim & Chung, 1984). It is suggested that the coastal mode shifts ashore because of the development of the EKWC (Kim & Yoon, 1999; Shin, Byun, Kim, & Seung, 1998), and the anticyclonic UWE also plays a role to turn the coastal mode anticyclonically (Cho & Kim, 1994; Kim & Yoon, 1999). Thus the offshore mode found in the UB could be fed by both the coastal mode and the southward spreading of subducted water from the north.

Stable southward flows are observed on the continental slope off the coast of Korea (see Figs. 24 and 25; see also Lie, Suk, & Kim, 1989). A meridional velocity section in May 2000, estimated by combining observed currents and CTD data, clearly shows that the less saline ESIW (coastal mode) flows southward beneath the northward flowing EKWC like the western boundary undercurrent (Chang et al., 2002b). The estimated transport of the ESIW in May 2000 was about 0.8 Sv, which is comparable to the previous estimation of 0.3–0.5 Sv using the inverse method (Shin, Byun, Kim, & Seung, & Lee, 1999). The volume transport of the ESIW is estimated to be about 1.0–1.5 Sv in the Japan Basin (Isobe & Isoda, 1997).

Distributions of water properties indicate that deep southward penetration of the coastal mode occurs along the east coast of Korea in summer (Cho & Kim, 1994). Morimoto and Yanagi (2001) also mentioned that the NKCC strengthens in summer and weakens in winter. On the contrary, numerical models indicate that the southward current underneath the EKWC becomes stronger in winter due to the strong positive wind stress curl and weak development of the EKWC in winter (e.g., Kim & Yoon, 1999). Deep southward currents measured beneath the coastal mode of the ESIW (see EC4 in Fig. 25) tend to weaken in fall between October and December, but the seasonality is not obvious for the southward flows in an upstream region (see M1-1 in Fig. 25; Teague et al., 2004). Horizontal distribution of the minimum salinity in the ESIW layer is examined during the period of PIES deployment (Fig. 22). Although the ESIW has been identified by the SML in vertical sections of salinity (Kim & Chung, 1984), the SML cannot be found in
areas of no overlying saltier EKWC water and/or no underlying less saline ESPW on the shelf. This does not necessarily mean the ESIW is absent. The minimum salinity in water layer having temperature between 1 and 5°C is shown in Fig. 22. Salinity in the ESIW core layer ranges from 33.84 to 34.08. Potential density (\(\sigma_\theta\)) at the depth of the minimum salinity in Fig. 22 has a range of 26.9–27.2 kg m\(^{-3}\) that is consistent with Shin et al. (1998) and Kim and Kim (1999). Salinity of the ESIW core became lower over the entire UB including the UIG in September 2000 as compared to that in October 1999 and May 2000. The minimum salinity was less than 34.0 in a wide area in September 2000, while it was greater than 34.04 in May 2000. The low salinity (\(S < 34.0\)) ESIW core water rested in the UIG in November 2000, and salinity of the ESIW increased in April 2001. Low-salinity ESIW (\(S < 34.0\)) was also widespread west of 131°E and north of 36.5°N in September 2002, but salinity of the ESIW northeast of Ulleung Island was higher than 34.0. The period for the widespread occurrence of low-salinity ESIW both in coastal and offshore regions in September and November 2000 coincides with the period of the disappearance of the EKWC (see Fig. 16).

Fig. 23 shows vertical sections of potential temperature and salinity along a section from the east coast of Korea to Dok Island in May and September 2000. The anticyclonic UWE centered at Ulleung Island is obvious and the high-salinity EKWC (\(S > 34.3\)) prevails over the section in May 2000. The ESIW is found near the coast of Korea with minimum salinity of about 34.03, but it is not found below the UWE. The salinity minimum layer is absent at shallow coastal stations which are not affected by the EKWC. However, cold water having temperature 1–5°C is regarded as the coastal mode of the ESIW (Cho & Kim, 1994) or
Small-scale, patch-like salinity minimum layers were found east of Ulleung Island with minimum salinity of 34.05–34.06. The EKWC was not found between the east coast of Korea and Ulleung Island in September 2000, and salinity in the region has a range of 33.8–34.07. The area occupied by the ESIW with the temperature range of 1–5°C and salinity less than 34.06 became wider than that in May 2000 west of Ulleung Island, and the minimum salinity of the ESIW (~33.8) is also much less than that in May 2000. The freshening and wide spreading of the ESIW is also obvious in the UIG between Ulleung and Dok Islands in September 2000 as compared to that in May 2000. The ESIW whose salinity is less than 34.00 occurred in the middle of the UIG below a high salinity core. The relatively fresh ESIW in the UIG was also found in November 2000 (Fig. 22), and the minimum salinity of the ESIW increased again in April 2001 after the EKWC was re-established. The ESIW observed in the UIG in fall 2000 is regarded as the offshore mode of the ESIW, which is subducted along the polar front and spreads towards the south. There is also a possibility that the coastal mode along the east coast of Korea moves to the UIG by
the anticyclonic UWE. Salinity distribution at 100 m in August 2000 shows that water having salinity less than 34.0 extends offshore north of the UWE (see Fig. 17).

4.6. Transport through the Korea/Tsushima Strait and variability of upper circulation

Many studies suggest the variability of upper circulation of the East Sea is related to the transport variation through the KTS (e.g., Kawabe, 1982; Morimoto & Yanagi, 2001). In numerical models, the upper circulation of the East Sea is mainly controlled by the transport variation through the KTS, differential heating, and wind-stress field in the East Sea (e.g., Kim & Yoon, 1999).

The concurrently obtained Cable data during the period of the PIES measurements (Fig. 8) show an increase of the transport from June 1999 and an annual peak in October 1999 when the zonal amplification of the UWE was initiated. The transport sharply decreased in winter of 1999 and 2000 with a minimum in January 2000 followed by a slight increase in the transport in spring 2000. The transport remained at about the record-length mean value of 2.4 Sv afterwards with little variation until the end of the PIES measurement in June 2001. Hence, the upper circulation exhibited three different patterns, even though the transport variation through the KTS remained almost constant. The mean transport during the first year of the PIES measurement (June 1999–June 2000) was about 40% larger than that during the second year (June 2000–June 2001). The basin-averaged temperature at 100 m depth was also higher in the first year as compared to temperature in the second year. More careful examination of the relationship between the transport variation and the upper circulation variability is needed, but it seems that the observed mesoscale variability of the upper circulation in the UB does not arise solely from the transport variation through the KTS.

4.7. Dynamics of the upper circulation

Dynamical aspects of the branching of the Tsushima Current have been investigated through numerical (Hogan & Hurlburt, 2000; Kawabe, 1982; Yoon, 1982a, 1982b; Seung & Kim, 1993) and analytical (Cho & Kim, 2000; Ou, 2001) models. Numerical modeling investigations have used simple, intermediate, and realistic domains. It is suggested that the NB and the EKWC arise from the topographic and planetary $\beta$ effects, respectively (Yoon, 1982a, 1982b), while the OB is the surface expression of the propagation of a coastal trapped wave generated by the summertime increase in the transport through the KTS (Kawabe, 1982). Hogan and Hurlburt (2000) suggest that isopycnal outcropping in a nonlinear layered model is an alternative mechanism to generate the NB. It is not clear in numerical models (e.g., Hogan & Hurlburt, 2000; Kim & Yoon, 1999) whether the OB and NB coexist, as can be seen in the observation that shows two velocity cores (Hase et al., 1999). Ou (2001) theorized the coexistence of the NB and OB along the west coast of Japan using a reduced-gravity model. He suggested that the NB is the coastal boundary current and the OB is the flow along the layer outcrop. Friction and the stretching of the water column are two important effects in Ou (2001)’s model.

A relationship has been suggested between the generation of the EKWC and the appearance of the KSBCW (e.g., Cho & Kim, 1996). Attempts have been made to explain the strengthening of the EKWC in summer and the disappearance of the EKWC in winter due to the seasonal variation of the KSBCW in the KTS using hydraulic (Cho & Kim, 2000) and numerical (Isobe, 1997) models. Isobe (1994, 1997) suggests that the JEBAR (Joint Effect of Baroclinicity and Relief) in the KTS plays an important role in the partitioning of the transport of the Tsushima Current into the EKWC and coastal branches along the coast of Japan. The EKWC strengthens in summer due to an increase in the reduced gravity in the KTS caused by the KSBCW. In a two-layer hydraulic model, the Tsushima Current experiences shrinking of water column due to the southward flowing lower layer occupied by the KSBCW, which results in the generation of the EKWC in summer (Cho & Kim, 2000). Without the lower layer, representing the winter condition in
the KTS, the Tsushima Current experiences stretching of the water column and flows only along the eastern boundary resulting in the disappearance of the EKWC. However, the disappearance of the EKWC occurred in summer rather than in winter according to PIES data (see Fig. 16). Other studies also show the disappearance of the EKWC in summer (e.g., Hong et al., 1984; Katoh, 1994). Hence, the development and movement of the KSBCW may not solely explain the path variability of the EKWC. The above mentioned models assume the widespread extent of the colder KSBCW in the KTS in summer. LINKS data taken for 11 months between May 1999 and March 2000, however, contrasted with previous works on the seasonal trend in the appearance of the KSBCW in the KTS. Sustained intrusions of the KSBCW occurred in May/June and again in December/January rather than in summer (see Fig. 12), indicative of an interannual variability of the intrusion of the KSBCW in the KTS. Johnson and Teague (2002) hypothesize that when the transport through the KTS is low, the KSBCW intrudes and vice versa.

Separation of western boundary currents from continents in ocean basins has long been one of major issues in physical oceanography. Numerical models often fail to reproduce the separation, and an overshooting of the boundary currents is common (see Dengg, Beckmann, & Gerdes, 1996; for a thorough review on the Gulf Stream separation problem). One of the consequences of the inability of numerical models to correctly reproduce the separation is its impact on running a coupled ocean–atmosphere model for the prediction of climate change by exaggerating heat fluxes to the atmosphere (Haidvogel & Bryan, 1992). The separation of the EKWC has also long been a focal point in modeling the East Sea circulation. The overshooting of the EKWC was a common problem in numerical model studies (e.g., Seung & Kim, 1993). Seung (1992a) investigated the separation dynamics of the EKWC using a linear quasi-geostrophic model, and suggested that the separation of the EKWC is determined by the transport through the KTS, the surface cooling, and the wind-stress curl. It is shown that the separation latitude of the EKWC is sensitive to the parameterization of eddy-topography interaction, especially in coarse resolution models (Holloway, Sou, & Eby, 1995). In the layered model of Hogan and Hurlburt (2000), 1/32° horizontal resolution was required to resolve the baroclinic instability and to reproduce the separation latitude of the EKWC properly. Hogan and Hurlburt (2000) further suggested that the existence of the Korea Plateau is important in the separation of the EKWC. According to mean surface currents shown in Fig. 14, the separation of the EKWC occurs between 37° and 37.5°N over the Korea Plateau, where the coastline changes its orientation from the north to the northwest. After the separation, part of the EKWC retroreflects, forming the UWE, and meanders to the east. According to theoretical studies by Ou and De Ruijter (1986) and Da Silveira, Flierl, and Brown (1999), a similar type of separation occurs when the coastline tilts to the west from the north as is the case for the east coast of Korea. The separation of the EKWC may not be controlled by any one factor, but by the combined effects of the wind-stress in the East Sea, the transport through the KTS, the NKCC, the coastline tilt, and bottom topography. The eddy variability could be also a factor affecting the separation of the EKWC (Jacobs et al., 1999).

The variability of ocean circulation can be divided into two types: forced or external, and free or internal variability. The former is the response to changes in external forcing, especially in wind stress or in buoyancy fluxes, while the latter is due to the system’s intrinsic instability and nonlinearity. In a simple model with steady forcing, the circulation can undergo various scales of temporal variability ranging from a subannual period of 3–6 months to interannual and all the way to the interdecadal scale, depending on the degree of nonlinearity (Chang, Ghil, Ide, & Lai, 2001). Lee (1999) showed the possibility that the internal variability of the EKWC is not influenced by any perturbations in the forcing field using a multi-layer quasi-geostrophic model. Holloway et al. (1995) also showed an interannual variability of the East Sea circulation under seasonally repeating or annual mean external forcing using a primitive equation model. Analyses of satellite altimeter data revealed the quasi-biennial variability originating from the Yamato Basin, propagating westward, and affecting the variability of Tsushima Current in the southern East Sea (Hirose & Ostrovskii, 2000; Morimoto et al., 2000). The observed long-term periodic variability was conjectured to arise from the internal variability at low, constant wind-stress forcing, corresponding to
the conclusion of Jiang, Jin, and Ghil (1995) obtained in an idealized basin using a 1.5-layer reduced gravity model (Hirose & Ostrovskii, 2000).

5. Deep circulation and variability

The ESPW that is nearly homogeneous with temperature less than 1.0°C occupies a thick layer at depths greater than 400 m in the UB. The ESPW can neither be formed by local convection, since surface temperatures always exceed 1.0°C, nor originate through the KTS, since the sill depth is less than 200 m. The deep water in the UB is thought to originate from the Japan Basin, and is believed to flow into the UB through the UIG (Kim et al., 1991b) or over the Korea Plateau (Cho & Kim, 1994; Shin et al., 1998). Since the deep water is very homogeneous with distinctive properties, there must be a deep circulation to maintain these characteristics. However, direct measurements of the deep currents in the UB had been sparse before 1996 (e.g., Lie et al., 1989). Survival of moorings in the UB has been poor due to the intense fishing and crabbing.

Long-term current measurements began in 1996 in the UB (Chang et al., 2002b), and the JES data taken between June 1999 to June 2001 provide the basin-scale circulation and deep flow variability (Teague et al., 2004). The JES data are used to examine directly the deep currents and to examine indirectly the deep flow patterns through leveling of the pressure measurements, which, when combined with the inverted echo sounder measurements, form a three-dimensional mapping of the current field (Mitchell et al., 2004).

Two-year mean current vectors based on JES data are shown in Fig. 24. Except for moorings at M2-2, M4-1, EC3, and J1, the standard error for the larger current component is smaller than the respective mean value, indicating the mean currents using two-year-long data are well determined and reliable. Currents with speeds less than 2 cm s\(^{-1}\) account for about half of the observations. Largest mean current directed towards the south was observed on the continental slope off Korea at EC4 with a mean speed of 5.3 cm s\(^{-1}\). Before June 1999, deep currents at 770 and 1280 m were measured at a location (1380 m deep) about 10 km south of EC4 for seven months (Chang et al., 2002b), where stable southeastward currents were observed with mean speeds of about 2.5 cm s\(^{-1}\). The mean current at M3-1e, slightly east of EC4 located near the bottom of the continental slope, is also directed towards the south with a mean speed of 2.7 cm s\(^{-1}\), about half of the speed at EC4. Southward currents are also found north of EC4 on the continental slope at M1-1 with a mean speed of 1.6 cm s\(^{-1}\). Lie et al. (1989) measured deep currents at 620 and 790 m west of M1-1 at a water depth of 840 m for 70 days. The 70-day mean speed was 3.0–4.0 cm s\(^{-1}\), which is about two times stronger than the mean speed at M1-1. The mean current pattern shown in Fig. 24 and the previous observation by Lie et al. (1989) clearly indicate the existence of the relatively strong southward deep flow on the continental slope off Korea below the northward EKWC, like a western boundary undercurrent. The strong southward deep currents on the continental slope tend to weaken at the bottom of the continental slope. Upper current at 320 m was also observed for four months at EC4 between October 1997 and February 1998, and was a stable southward flow but with a smaller mean speed of about 3 cm s\(^{-1}\) as compared to the bottom velocity shown in Fig. 24 (Chang et al., 2002b). Although the mooring periods are different, the weaker flow at 320 m depth as compared to the bottom flow might be due to the fact that the mooring depth at 320 m was located in a shear zone between the northward EKWC and southward deep current.

Northward currents are found over the Korea Plateau at moorings located between M1-1 and Ulleung Island with the strongest current of about 3.8 cm s\(^{-1}\) at M1-2. A southwestward flow of nearly 2 cm s\(^{-1}\) is observed in the UIG. Mean currents are weaker in the interior and southern UB where the topography is relatively smooth. The mean currents often align with bathymetry. A cyclonic circulation pattern is suggested by the two years of current measurements for the Ulleung Basin, and yearly mean currents are similar to the two-year current patterns (Teague et al., 2004). The deep inflow from the northeast through the
UIG bifurcates: one branch circulates cyclonically in the UB and the other turns to north anticyclonically around Ulleung Island.

The observed deep currents for the two-year period are highly variable at most moorings. The mean current vectors in Fig. 24 are contained within their standard deviation ellipses and the EKE is larger than the mean kinetic energy (MKE), except for moorings at M1-2, M3-1, and EC4, where the mean currents are stable and best determined. The EKE for the two-year period ranges from 0.9 cm$^2$ s$^{-2}$ at EC2 to 7.5 cm$^2$ s$^{-2}$ at EC4, and the ratio between the EKE and MKE is larger than 30 at M2-2, EC3, M4-1, and J1, where the mean currents are weak and poorly defined. Vector time series of low-pass filtered currents at some selected moorings are shown in Figs. 25 and 27. Currents at M1-2, M3-1, and EC4 are strong and directionally stable with only a few reversals on short timescales during the two-year period. The bottom currents at M1-2 and EC4 sometimes exceed 10 cm s$^{-1}$ over periods of a week or more, and the maximum observed speed of 14.3 cm s$^{-1}$ at M1-2 and 18.5 cm s$^{-1}$ at EC4 occurred during winter 2001 and winter 2000, respectively. Southward currents at M1-1 are weaker and more variable than those at EC4 and M3-1e. Currents at M2-1n were weak and variable with frequent reversals towards the south at most times except for two events of strong and persistent northward current that occurred in fall 1999 and winter 2001. Visual correlation of current fluctuations between adjacent stations is poor, implying a short horizontal correlation scale for the observed bottom currents. Even the current fluctuations are only partially coherent between the moorings at EC4 and M3-1e which are only a few km apart and where the currents are stable. The

Fig. 24. Mean deep currents from near bottom current meters are shown for the time period of June 1999 to June 2001. Bathymetry units are meters.
fluctuations of southward deep currents observed upstream of EC4 at M1-1 are also not correlated with those at EC4. In general, weaker and more variable currents are observed in the interior and the southern UB where the bottom topography is smooth, and Fig. 25 indicates the eddy-like variability at those moorings (EC3, M4-1, J1).

The annual average deep currents are remarkably similar for the two years, being only slightly weaker in the second year, despite a 40% decrease in the transport through the KTS (Kim et al., 2004; Teague et al., 2002) and the quite different flow patterns observed in the upper layer circulation (Mitchell et al., 2004). It is apparent that the time series shown in Fig. 25 exhibit a wide range of time scales. There is some interannual variability, and seasonality is weak and evident at only a few moorings. Southward currents at EC4 tend to weaken in fall, and southwestward currents at EC1 tend to strengthen in summer (Figs. 27 and 29). Weak seasonality implies that the deep currents are not directly forced by surface winds or wintertime convection. Local wind events are not correlated with deep current events. In contrast with current fluctuations in the
UB, seasonal variations of deep currents are dominant in the Japan Basin with stronger currents in winter (Takematsu, Nagano, Ostrovskii, Kim, & Volkov, 1999). Observations show that renewal of bottom water occurred after the severe winter 2000–2001 (Kim et al., 2002), and strong deep currents appeared abruptly from mid-Feb. 2001 (Senjyu et al., 2002), indicative of deep current fluctuations driven by wintertime convection in the Japan Basin.

In order to form residual geostrophic pressures and hence geostrophic velocities from the JES data, the bottom-pressure records were first detided, and then a basin-wide oscillation of the free surface was subtracted from the records. Resulting RMS eddy currents and pressures ranged from about 1 to 6 cm s$^{-1}$ and 0.01–0.02 dbar, respectively, at different locations, with horizontal correlation scales of about 40 km, and integral time scales ranging from about 5 to 20 days. Average leveled pressure fields for each year and for the two-year measurement period are shown in Fig. 26. The deep circulation in the UB at seasonal (not shown) to annual time scales is clearly cyclonic with additional cyclonic and anticyclonic cells that occur on sub-basin scales. There are cyclonic cells (lows) along the continental slope off Korea and in the interior of the Ulleung Basin, and an anticyclonic cell (high) around Ulleung Island. Over the Korea Plateau, a northward deep outflow is observed that suggests an anticyclonic circulation pattern (high) further to the north. There is mainly southwestward inflow through the UIG, with a hint of outflow along the southeastern side of the UIG as is suggested in a high-resolution numerical model (Hogan & Hurlburt, 2000). Geostrophic currents are lower in absolute magnitude than measured point currents as expected, but are consistent in direction with the measured currents.

6. Flow through the Ulleung Interplain Gap

The maximum depth of the UB exceeds 2200 m, and the surrounding shallower topographic features hamper the exchange of deep water below 1500 m between the UB and adjacent deep Japan and Yamato Basins. Only the UIG serves as a conduit through which abyssal water originating from the Japan Basin enters into the UB. Moored current measurements at EC1 in the central UIG (see Fig. 2 for the location of EC1) were carried out between November 1996 and May 2002 with mooring turnarounds every five to seven months or one year. The mooring at EC1 has been typically equipped with three current meters at around 400 m, 1400 m, and near the seabed. An upward-looking ADCP was set at the top of the mooring line to measure the upper currents above 130 m during the mooring period between October 2001 and May
2002. Characteristics of observed deep currents at EC1 between October 1996 and June 2001 were described by Chang et al. (2002b) and Teague et al. (2004).

Subsurface currents below 400 m at EC1 show a predominance of southwestward (along-channel) flow (\( U, 50^\circ \) from north) with occasional reversals on short timescales (Fig. 27). Mean flows during each leg at EC1 below 400 m depths are directed towards the UB with a speed range of 0.8–2.7 cm s\(^{-1}\). The standard deviation of \( U \) is also higher than that in the cross-channel direction. Near-bottom mean flows at EC1 tend to be stronger than the flows at shallower depths, and the EKE is also higher near the seabed as compared to the EKE at shallower depths. Fluctuations of \( U \) below 400 m are mainly barotropic, and mesoscale fluctuations with a period range of 20–50 days are predominant (Fig. 28). Shown in Fig. 29 is the time series of \( U \) near the seabed. The deep currents tended to become strong in summer of 1997, 1999, and 2000. Especially, the strongest deep flow persisted for a couple of months in summer of 2000, when the disappearance of the EKWC and the widespread extent of low-salinity ESIW in the UB occurred.

Record-length mean currents in the upper 130 m depth at EC1 between October 2001 and May 2002 are directed towards the southeast, while concurrently measured deep currents below 400 m depths mainly flow to the southwest (Fig. 30(a)). Mean currents turn clockwise as water depth increases in the upper 130 m, and significant vertical shear of the mean currents occurs with a speed difference of about 6.0 cm s\(^{-1}\) between 16 and 128 m. Strong southward currents were observed in the upper 130 m in October 2001 and in winter 2002, while the strong southward deep currents occurred about one month later in mid-November 2001 and March 2002 (Fig. 30(b)). EOF analysis of concurrently measured upper and deep currents indi-
Fig. 28. Power spectrum for the along-channel (50° from north) velocity component at around 1500 m depth at EC1 based on 3.6-year long low-pass filtered 12-hourly data. Confidence level indicated by the vertical bar corresponds to 90% significance level.

Fig. 29. Long-term variation of along-channel (50° from north) velocity component near the seabed at EC1. Dotted and thick lines are based on 12-hourly and 30-day moving averaged velocities, respectively.
cates that current fluctuations are mainly barotropic, and the barotropic mode explains more than 85% of the variability (Fig. 31). Spectral analysis of the barotropic mode shows spectral peaks at 5 and 7 days for both the upper and deep currents. Most of spectral energy, however, is contained in the periods longer than 20 days for the deep currents, while a large portion of the spectral energy is contained in the periods around and shorter than 10 days for the upper currents.

Cold water with temperature less than 0.1°C (the East Sea Deep and Bottom Waters according to Kim et al., 1996) originating over the Japan Basin is observed in the UB at depths greater than 1500 m. It enters...
into the UB only through the UIG, as can be seen in Fig. 32, because the Korea Plateau is shallower than 1500 m. Assuming the deep net inflow to the UB through the UIG, mass and heat balances yield the vertical diffusivity of the order of $10^{-3} \text{ m}^2 \text{s}^{-1}$, suggestive of substantial diapycnal mixing across the top layer of the cold water (Chang et al., 2002b). The mean cyclonic abyssal circulation in the UB (Figs. 24 and 26) could be driven by the net inflow into the UB through the stretching implied at the top of the abyssal layer. To quantify an exact amount of inflow transport is important for understanding the deep circulation and diapycnal mixing in the UB. Especially, deep current measurements are required close to Dok Island since a fine-resolution numerical model predicts an outflow of part of the deep water near Dok Island (Hogan & Hurlburt, 2000).

Fig. 31. EOF analyses of (a) upper currents measured by ADCP and (b) deep currents measured by moored current meters. Upper panels show the vertical structure of Mode 1 and Mode 2 with their corresponding time coefficients in the lower panel. Power spectra for Mode 1 of (c) upper currents and (d) deep currents.
7. Discussion and summary

A review is made of the currents and circulation in the Korea/Tsushima Strait and Ulleung Basin with a special focus on describing some preliminary results from recent extensive measurements. The Ulleung Basin receives warm and saline Tsushima Current Water through the Korea/Tsushima Strait and cold water masses of the East Sea Intermediate Water and East Sea Proper Water from the north. The interaction between warm and cold waters both in the horizontal and vertical yields a high variability of circulation in the Ulleung Basin.

Mean cross-sectional flow shows a broad maximum at mid-channel southwest of Tsushima Island in the Korea/Tsushima Strait, while it splits into two strong cores hugging the coasts of Korea and Japan northeast of Tsushima Island. Four-year mean volume transport through the Korea/Tsushima Strait derived from cable voltage data is 2.4 Sv. Sub-tidal currents and transports exhibit a wide range of temporal variability from subinertial to interannual scale. Many studies suggest a well-defined seasonal variation, strong in summer/fall and weak in winter/spring based on the dynamic method. However, the seasonal variation in four-year long Cable data is inconclusive. The subinertial variation on time scales of 2–10 days has an amplitude of 2–3 Sv and is shown to be forced by atmospheric pressure disturbances. Factors affecting the lower-frequency variations, however, are not clarified. Dynamical models indicate the importance of remote forcing such as the large-scale wind-stress distribution in the North Pacific in driving the transport variation, which requires more careful investigation using realistic numerical models comprising the North Pacific and the East Sea in their model domains with reasonable resolution.
Mean upper circulation in the Ulleung Basin is characterized by the northward flowing East Korean Warm Current along the east coast of Korea, the northeastward flowing Offshore Branch along the coast of Japan, the anticyclonic Ulleung Warm Eddy in the central part of the Ulleung Basin, and the meandering of the East Korean Warm Current. The East Korean Warm Current separates from the coast at around 36.5°N, and forms a large meander with its trough (southward extreme) at around 134°E. The interior of the meander forms the Ulleung Warm Eddy. The horizontal scale of the Ulleung Warm Eddy is about 150–200 km, with maximum depth of thermostad as deep as 200 m at the center of the Ulleung Warm Eddy. The maximum velocity exceeds 50 cm s\(^{-1}\) around the Ulleung Warm Eddy and a high-velocity (>30 cm s\(^{-1}\)) core extends down to about 200 m.

Continuous acoustic travel-time measurements for the two-year period between June 1999 and June 2001 indicate that mesoscale variability of upper circulation is predominant. Five flow patterns have been identified with each pattern persisting 3–5 months and transitions between successive patterns occurring in a few days or months. The variability mainly arises from the interaction of warm water carried by the East Korean Warm Current with cold waters north of the polar front, which are carried by the North Korean Cold Current along the coast or brought into the Ulleung Basin by the meandering of the East Korean Warm Current. The meander trough often sheds a cold eddy, the Dok Cold Eddy. The meander is modest in Patterns 1 and 4, and is strong in Pattern 5 (Fig. 16). The coastal cold water extends to the region offshore at times like the transition period shown in Fig. 16(b). The disappearance of the East Korean Warm Current occurs when the offshore extension of the coastal cold water is connected with the Westward propagating Dok Cold Eddy. The disappearance of the East Korean Warm Current persisted for about five months between June and November 2000 during the period of continuous travel-time measurements. Freshening and wide spreading of the East Sea Intermediate Water occurred when the East Korean Warm Current disappeared. The disappearance of the East Korean Warm Current also coincides with the period when the transport through the Korea/Tsushima Strait was low and southwestward bottom current was strong in the Ulleung Interplain Gap. The amplification and shrinking of the Ulleung Warm Eddy appear to be related with increase and decrease of the transport through the Korea/Tsushima Strait. The upper circulation, however, exhibits high variability even when the transport shows little temporal variation. The movement of the coastal cold water and the frontal instability also appear to be important factors affecting the upper circulation variability, which needs to be further elucidated.

The velocity and bottom pressure measurements for two years during 1999–2001 show the deep circulation in the Ulleung Basin to consist of a series of anticyclones and cyclones with at least two cells, occurring on smaller than anticipated sub-basin spatial scales. During all seasons, northward flow is found over the Korea Plateau away from the shelf break. A relatively strong southward flow is found along the continental slope off the east coast of Korea. Horizontal coherence in the measured flows is small. Mesoscale variability with periods 20–50 days is predominant in observed current fluctuations while seasonality is indistinct at most moorings and evident only at a few sites. Bottom currents in the middle of the Ulleung Interplain Gap tend to strengthen in summer, and stable southward undercurrents on the continental slope off the east coast of Korea tend to weaken in fall.

A long history of physical oceanographic studies in the Ulleung Basin has contributed to our understanding of currents and circulation there. Especially, recent intensive, highly-resolved, and long-term observations have revealed quantitatively the nature of the circulation and its variability. The datasets from these observations are under investigation, and thorough analyses of the data will further elucidate the circulation dynamics in the basin. As mentioned earlier, the following issues especially need to be addressed in future: (1) dynamics of the low-frequency variation of the transport through the Korea/Tsushima Strait, (2) factors affecting the mesoscale variability of the upper, intermediate, and deep circulation, other than the transport variation through the Korea/Tsushima Strait, (3) coupling of upper and deep circulation, and (4) deep water transport through the Ulleung Interplain Gap with associated diapycnal mixing of deep water,
and its implication in climate variability of deep water in the Ulleung Basin. Overall, the three-dimensional circulation in the Ulleung Basin is yet to be discovered. More observational efforts should also be made because available observations indicate the correlation length-scale of the flow is short. Especially, high-resolution current observations off the east coast of Korea are required to delineate the spatial and temporal structure of the upper East Korean Warm Current and southward flowing undercurrent. Observations are also needed in the Korea Plateau and the Ulleung Interplain Gap to better understand the previously observed complex flow features and to quantify deep water flux. The modeling community should attempt to reproduce the recent observational results, to validate numerical mode results, and to test model forecasts. Attempts should also be made to understand the response of biogeochemical processes to the variability in physical forcing.

Acknowledgements

We wish to thank Dr. M.A. Danchenkov and an anonymous reviewer for their comments and suggestions. K.-I. Chang was supported by grants from KORDI’s projects (PE87000, PE89000, PG39300) and Ministry of Science and Technology, Korea (PN53500). K. Kim and S.J. Lyu were supported by the Agency for Defense Development of Korea through the Basic Research Program (UD030005AD). W.J. Teague, H.T. Perkins, D.R. Watts, D.A. Mitchell, and C.M. Lee were supported by the United States Office of Naval Research “Japan/East Sea DRI”. Basic Research Programs include the Japan/East Sea initiative under Grant N000149810246 and the Naval Research Laboratory’s “Linkages of Asian Marginal Seas” under Program Element 0601153N.

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